# A STUDY OF SOLID LUBRICANTS USED TO PREVENT WEAR AND FRICTION IN POWDER METALLURGY PRODUCTION

by

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# SYNOPSIS

This research continues the earlier researches on wear friction and lubrication and its application to the powder metallurgy industries. A detailed study of the parameters involved in wear and friction has been made by using the "Pin and Disc" machine with cross cylinders technique. One iron powder was chosen and compacted over a range of densities with a series of metallic stearates as admixed lubricants for the purpose of examinations. These compacts were used as the "pins" for the wear and friction apparatus, the "disc" was made from high carbon high chromium steel which is one of the steels normally used in punches and dies in the powder metallurgy industries. The wear behaviour of these compacts was studied in relation to the following parameters: applied load between compact (or pin) and disc, sliding speed, travelled distance, density and hardness of compact. These were examined for a range of stearate lubricants and the wear rates determined, these data were then related to the possible industrial life for punches and dies in powder metallurgy presses.

Besides wear rate, friction forces between the compact (or pin) and disc were measured and these forces of friction were translated into coefficients of friction for each type of lubricant.

The thesis presents the results of these investigations with a survey of current theories on wear and friction of metallic systems relevant to powder metallurgy. Conclusions have been drawn and suggestions made on the most useful solid lubricant necessary in the pressing of metallic powders to reduce wear and friction in production presses. Calculations have been carried out using the data collected to estimate the possible press tool wear and accordingly a possible tool life was determined for pressing with each type of stearate lubricant. The overall conclusion was that zinc stearate is the best solid lubricant in the five metallic stearates (Al, Na, Mg, Ca and Zn) for use in iron powder compaction.

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# INDEX

# CHAPTER 1

## INTRODUCTION

# CHAPTER 1

# INTRODUCTION

The theme of this research work is: "Studies of solid lubricants to prevent wear and friction in powder metallurgy". Before introducing this research, an important question must be answered, that is: what is Powder Metallurgy?

## 1.1 WHAT IS POWDER METALLURGY?

Powder Metallurgy is the technology which is concerned with those industries which use powders or materials in particle form as their raw materials, from which they can make their products. The powders which are used in these industries could be metallic powders such as steel, iron, brass, bronze etc, or non-metallic powders such as carbides, nitrides, oxides or other ceramics. However, the production of ferrous and non-ferrous products from powders is one of the largest of these industries. There are many grades of powder for each metal and each of these types has some characteristics which might differ from the others, so that a powder which meets the needed requirements can be chosen. It has been found that for better performance of the tools which are used in the production and better quality of the products, an admixed solid lubricant must be used. The solid lubricants are being used in the forms of powders.

The powder technology for making engineering products is generally in four stages as follows:

1. Mixing of Powders. In this stage all the various powders needed to produce the component are mixed thoroughly in blending machines or mixers. This is the stage at which lubricants for metal powders are added. Generally the level of lubricant content is between 0.5 and 2.0 wt%.

2. Consolidation of Powders. The powder and lubricant mixture can be consolidated to form a product by a number of methods: pressing in a die, rolling, extrusion, isostatic pressing or hot isostatic pressing.

The most commonly used method for ferrous and non-ferrous products is compaction in a die using punches attached to a press. Such presses can have a capacity to apply forces from 30 to 500 tonnes. In this research we are considering the pressing of iron powders with stearate lubricants in an industrial press having a capacity to apply 35 tonnes maximum.

3. Sintering of Compacted Powders. This is done in a controlled reducing atmosphere for metals and the temperatures are around 1120$^{0}$C for ferrous components and between 550-1000$^{0}$C for non-ferrous components. Most sintering furnaces are of continuous operation using a mobile hearth often a moving heat-resisting belt.

The initial stage of the sintering is the burning out of the admixed lubricant. The sintering process is concerned with the diffusion of particle to particle, with the formation of grain boundaries, and with the closing of voids present in the green compacts. In spite of the sintering process, the resulting material has a substantial volume fraction of voids (interstices between powder particles) which limit its use to less heavy duty applications. One method used to enhance the properties of sintered materials involves deformation processing which simultaneously densifies the material and develops the final desired component shape. This is sometimes called "powder forging".

4. <u>Post Sintering Operations</u>. The porous components made by this technology often require a finishing process before delivery to the customer. Such finishing processes are listed as follows: painting, electroplating, steam-treatment, impregnation with resins etc. All these procedures are used to seal off the porosity in the component before its use in an engineering application.

Other finishing processes could involve the following: powder forging (as indicated above), "coining" or repressing to control the final shape and density, machining, and a whole range of heat treatment processes are possible if ferrous components are being made. For example, nitriding, carburising, quenching/tempering etc are possible.

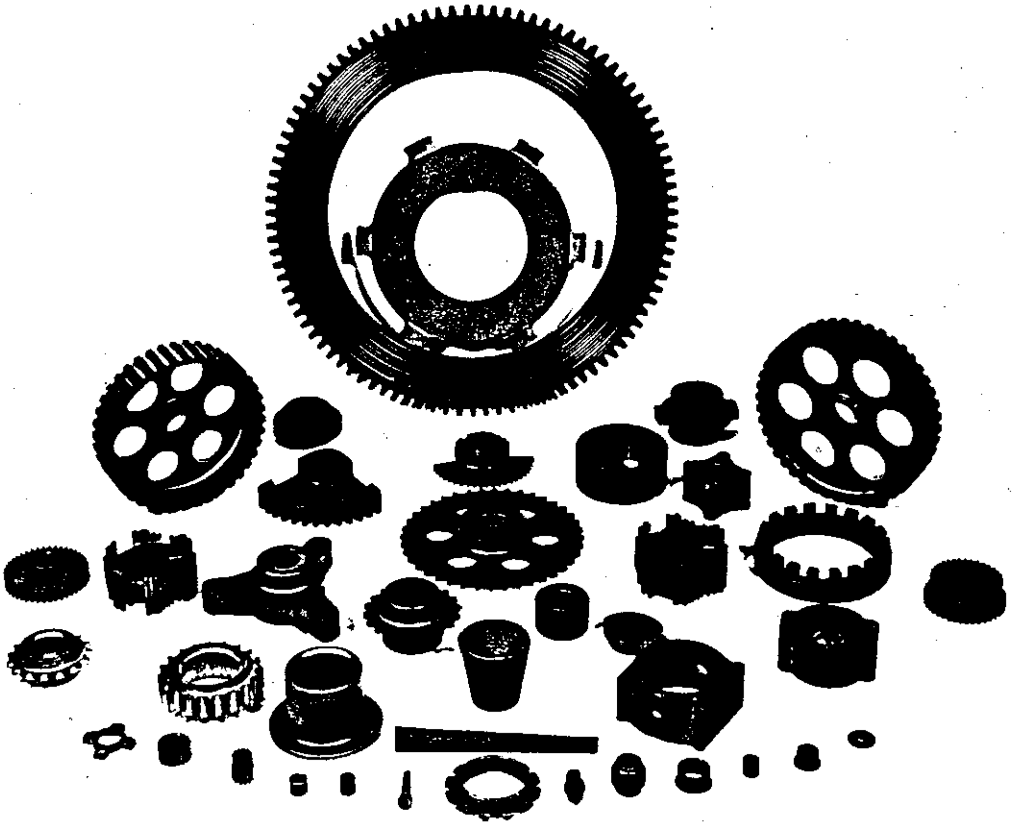
The interest of this research is therefore related to stages (1) and (2) above, that is the mixing of lubricants with powders and the subsequent consolidation of these mixtures within a punch and die tool set on a compaction press.

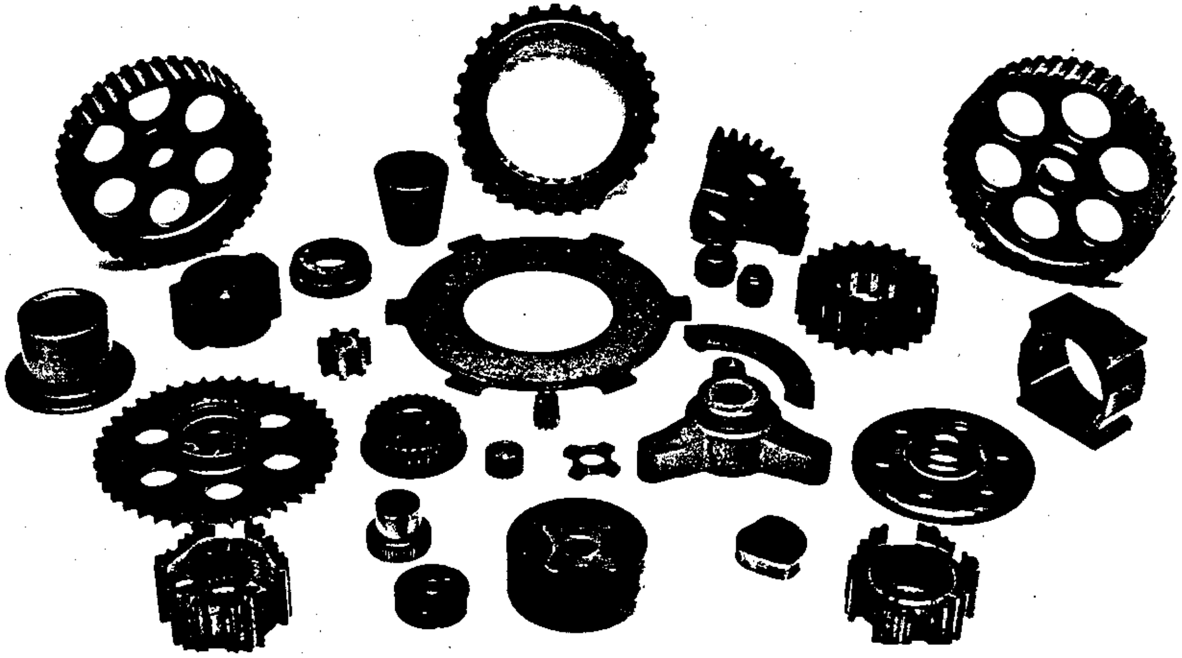
## 1.2 WHERE POWDER METALLURGY IS USED

The field of Powder Metallurgy is responding to demands from a number of the most important areas of industry. Among these areas are the atomic energy, aerospace, transport, domestic and business machine industries.

It is very noticeable that each of these fields is growing rapidly when compared with other industries, so that demands which are coming from them such as meeting the requirements of the physical and chemical properties of the materials, are growing very rapidly as well. Such demands have forced the metallurgists to turn to powder metallurgy techniques.

The use of Powder Metallurgy is very far from being restricted to the above mentioned fields. Because of the simplicity in the production, and the difficulties in producing some parts by other than Powder Metallurgy, a very wide range of types and shapes of components are produced. The use of these parts has been widened in so many industries. Many examples can be given to prove this point; the industries which are involved in producing cars, lorries, buses, motorcycles and many other





commercial machines besides the aerospace and atomic energy industries, which have been indicated earlier. Some industries are using the term "particle technology" which is concerned with any material of a particle nature such as ceramics included in some components used as tool tips for machine cutting tools.

The use of powder metallurgical techniques enables us to produce materials which are serviceable in very difficult circumstances, such as the situation of a very high temperature refractory. Materials which have special physical properties, such as the thermal conductivity, the thermal expansion, thermal capacity and emissivity can be produced by using powder metallurgical techniques; and also it is possible to produce parts with special characteristics, such as the porosity in filters and in pre-impregnated bearings. Metal powders are also playing an important role in producing solid fuels for rockets.

The figure opposite shows some components which are produced by using powder metallurgical techniques.

It is now generally appreciated that the powder metallurgy processing has some certain advantages over melting and casting processes of metals. There is an opportunity to start with special raw materials which have special characteristics of purity and uniformity, control of the manufacturing procedures to maintain these characteristics, control of the grain size, lack of stringing of segregated particles and inclusions, and improved properties, since directional elongation of grains from deformation processes are almost non-existent. In addition, the use of Powder Metallurgy techniques reduces the costs of the produced components and allows the production of many components which are impossible to produce by using other techniques of production.

## 1.3 WEAR PROBLEMS IN POWDER METALLURGY

In spite of the great attention which has been spent on the problem of friction during the compaction and ejection of powders, very little attention has been spent on the study of its closest associate, wear. The papers which have been published to deal with the problem of wear with powders are very rare. This has made the understanding of the wear problems of the tools which are used for the compaction and the ejection of powders very difficult.

However, some workers have done some experiments to study the wear problem of the compact which led to better understanding of this problem on the tools. Mallender and Coleman[1] assumed that Archard's equation 2 for the volume of wear is applicable to the powder situation, and they calculated the wear of the die according to this assumption.

## 1.4 FRICTION PROBLEMS IN POWDER METALLURGY

The friction generated during the compaction and ejection of powder can affect the density and the density gradient within the compact, the strength of the compact, the ease of ejection after compaction, the porosity of the compacts and the die wear.

The friction forces, which are usually generated when compaction and ejection take place, are due to several types of friction, such as the friction between the moving punch and the die wall; friction between the powder particles themselves; friction between the powder particles and the die wall; internal friction within the particles during deformation and friction between the compact and the die wall during the ejection of these compacts.

## 1.5 LUBRICANT AND LUBRICATION

Many problems can be caused in powder metallurgy due to the friction and wear which take place in the compaction and the ejection of the powders as has been stated before. Lubricants must be used to overcome the problems of density and density distribution within the compact, the strength of the compact, to ease the ejection, to control the porosity of the compacts and to overcome all the problems which can be caused by friction. The use of lubricants has an added advantage because they also extend the life of the press tools by controlling their friction and wear.

The normal method which can be used to reduce the wear and the frictional effects is to use admixed lubricants. Although many studies have shown that the die wall lubrication is quite satisfactory, this method is not widely used in powder compaction because of the engineering design difficulties with the lubricating system.

The use of admixed solid lubricants with the powder prior to compaction reduces the density variations within the compact and it also promotes less die wear. In some cases, the use of the admixed lubricants also give strength to the green components before sintering.

A large effort has been spent to study the problem of lubrication in powder processes. These studies were concerned with what type of lubricant to use, whether it should be solid or liquid, and what amount of this lubricant was required to give optimum results when compaction and ejection takes place. See references 3 and 4 for reviews of this area.

It is well known that to reduce the friction and wear between surfaces in contact, a separation of these contacted surfaces by means of lubricant must be done. The lubricant could be fluid or solid or sometimes gaseous. The ideal condition in eliminating wear and friction entirely is by using hydrodynamic lubrication, where the contacted surfaces are separated completely by a layer of oil or fluid. This condition is rarely maintained in practice and the film is squeezed out sooner or later, and then the two solids are pressed into contact with one another and boundary lubrication or lubrication by solids begins.

The general task of lubrication by solid lubricants is to prevent contact between clean surfaces by interposing low shear strength solid films rather than viscous fluid films. The use of solid lubricants can be advantageous under several conditions, such as high loads, where the oil films are squeezed out by the extreme pressure, or by movement, or by high temperature, or by the presence of dirt or abrasive. In our case the compacts can easily be freed from these solid lubricants by heating them to some certain temperature.

Solid lubricants may take many forms, such as stearic acids, metallic stearates and waxes. They can be used in many forms, such as powders, where they can be either mixed with the metallic powders, or by solution in solvents used as washes or sprays on one or both of the rubbing surfaces. They can be used in the form of pastes, bonded coatings or by corporation within porous dry bearing materials.

## 1.6 WEAR STUDIES IN THIS RESEARCH

It is generally agreeable that the wear volume of metals is directly proportional to the applied load, the sliding distance and inversely proportional to the hardness of the metal, that is to say that the wear volume obeys the Archard's equation more or less[2,15,16].

In powder metallurgy the situation is different because we have the case of powders which are pressed to give a porous component. This situation might be far from the original conditions to which the Archard's equation was applied, so without checking its applicability, the calculations of the tool wear in compaction of powders could be inaccurate.

By accepting the applicability of Archard's equation to the die and punch materials, it may be possible to examine this for the powder compacts, so that the calculations of the tool wear will be more accurate.

In these studies, the effects of applied load, sliding distance, sliding speed, hardness and density on the volume of wear of the materials involved will be examined.

The effect of the admixed solid lubricants on the wear volume will be examined as well. An optimum amount of lubricant ratio added to the powder to produce compacts will be derived and the lubricant with the best efficiency will be derived as well. The variation of the specimen density with wear volume and lubricant type and content can also be determined.

For the purpose of this study, specimens were examined with three different densities as follows: 6.3, 6.5 and 6.8 g $cm^{-3}$. Five stearate lubricants were used as follows: zinc, sodium, magnesium, aluminium and calcium stearate (see Table 1).

## 1.7 FRICTION STUDIES IN THIS RESEARCH

Many studies have been carried out by a number of workers to measure the friction forces generated during the compaction and ejection of the powder (see Chapter 3). Measurements of the friction coefficient between the die walls and the compacts have been carried out using different types of metallic powders.

In this study the friction forces between the die walls and the compacts will be simulated and measured for the specimens made from the five different admixed solid lubricants (see Table 1) and the values of the coefficient of friction between the die materials and the compact will be derived.

The solid lubricant which gives the lowest friction forces and consequently the lowest coefficient of friction will be sought.

## 1.8 THE PROCEDURE AND TECHNIQUE

It is very difficult to measure the effects of applied load, sliding speed, sliding distance, hardness, density and the friction forces between the tools and the compacts on the real production press. Instead, these will be done on a laboratory scale using established methods.

To carry out these studies a "pin and disc" machine using "crossed cylinder contact" was used. The disc was made from the same material as the die used in the real production presses in the factories. This material is a high carbon, high chromium die steel. The pins for this machine were made from one type of commercially available iron powder by pressing into small cylindrical forms on a production press.

The five solid lubricants (which indicated earlier) were used to produce the specimens (pins) for the experiments.

Specimens with different lubricant ratios and different values of densities were examined in this work (see Table 1).

## 1.9 THE RAW MATERIALS USED IN THIS RESEARCH

1. Iron Powder. As has been indicated before, the powder materials could be either metallic or non-metallic. In this work, metallic powders were considered for study. From the range of metallic powders available an iron powder was chosen. Since there are many types of iron powders, and every type has its own characteristics, the powder must be identified clearly and accurately. In this work the following iron powder was used:

Hoganas Atomised Iron Powder Type:

ASC. 100-29.

The characteristics of this type of iron powder are introduced in Table 2.

2. The Lubricants. In general, the addition of the solid lubricants to produce components by compaction is in fact wasteful, since later the lubricants are burned out in the first stage of the sintering process. At this stage, many residues of these lubricants are left in the component to the detriment of the properties of the compacts. The presence of these lubricants residues in the components is a certain factor in increasing the porosity of the

sintered compacts, so that it is better for the components to be produced without any lubricant if it were possible. But this case is not possible due to many reasons which were indicated earlier.

In our case the solid lubricants used in the admixed form within the iron powder are those being used in full-scale production.

The type of solid lubricants which are used the most is the metallic stearate. Each of the five stearates in Tables 1 and 3 have some advantages, however although zinc stearate is used most extensively, no real information is available as to why this is more efficient than say the stearates of sodium, calcium, aluminium or magnesium.

This research will attempt to determine this information, so that a critical assessment of lubricants can be made for the pressing of iron powders.

# CHAPTER 2

# REVIEW OF WEAR, FRICTION AND BOUNDARY LUBRICATION CONCEPTS

2.1 SURFACES
  1 Nature of Surfaces
  2 Geometrical Characteristics
    a) Error of form
    b) Waviness or macro-texture
    c) Roughness or micro-texture
  3 Surface Contact
    a) Contact of surfaces and surface interactions
    b) The area of contact

2.2 METALLIC WEAR
  1 Introduction
  2 Unlubricated Wear
    a) Effect of sliding distance
    b) Effect of sliding distance
    c) Effect of load, area of contact
    d) Effect of hardness
  3 Mechanisms of Wear
    a) Adhesive wear
    b) Abrasive wear
    c) Delamination theory of wear
  4 Lubricated Wear

2.3 FRICTION

1 Introduction

2 Theories of Dry Friction

- a) French geometrical theory
- b) Molecular attraction
- c) Materials deformation
- d) Composite theory of friction

3 Factors Affecting Friction

2.4 BOUNDARY FRICTION AND LUBRICATION

1 Introduction

2 Mechanisms of Boundary Lubrication

3 Factors Affecting Boundary Lubrication

- a) Effect of load
- b) Effect of speed
- c) Effect of surface properties
- d) Effect of temperature
- e) Effect of lubricant chain length

4 Wear in Boundary Friction and Lubrication

# CHAPTER 2

# REVIEW OF WEAR, FRICTION AND BOUNDARY LUBRICATION CONCEPTS

## 2.1 SURFACES

1. Nature of Surfaces: Before discussing wear, friction and boundary lubrication in metallic systems, it is advantageous to comment on surface topography of metals, since this is an essential step in the understanding of the interfacial interaction between the moving parts. It is this motion between surfaces in contact which leads to the wear and friction of such materials.

In general, the surfaces of solids are wavy and rough. The length of one wave varies from 1000 to 10,000 μm, and their height ranges from a few microns, to between 20-40 μm. For the range of surface irregularities between 0.01 - 0.2 μm for instance[5,6], coarse super finished surfaces can have irregularities of between 0.04 - 0.1 μm[7].

2. Geometrical Characteristics: Geometrical characteristics of solid surfaces fall into three categories[6,8,7] see Figure 1.

a) Error of form: Figure 1(b). The surface deviates from the desired shape due to error produced by manufacturing process. For instance the tapering of cylindrical bar.

b) Waviness or macro-texture: Figure 1(c) . This always takes the form of relatively long wavelength variations in the surfaces of the profile and it is often associated with the unwanted vibrations which always occur in machine tool systems.

c) Roughness or micro-texture: Figure 1(d) . This is the small scale roughness of the surface associated with the actual cutting or polishing process during its production.

## 3. Surface Contact

a) Contact of surfaces and surface interaction: The surfaces of solids are never perfectly flat. Flat surfaces are never achieved by the usual methods of surface preparations such as machining, grinding, lapping etc. Instead surfaces are wavy and rough, and have asperities or hills and valleys. Bowden and Tabor[9] and Holm[10] have studied the contact of the surfaces. They determined the real area of contact by using the method of electrical resistance techniques. The measurements indicated that when two solids are placed in contact the upper surface will be supported on the summits of the irregularities, and large areas of surfaces will be separated by a distance which is great compared with the molecular range of action. The real area of contact is very small when compared with the apparent area of contact, this means that the pressure at the real area of contact is very high, i.e. elastic deformation takes place if:

$$P_m \leqslant 1.1Y$$

where: $P_m$ = yield stress, and Y = elastic limit.
When the load increases:

$$P_m \geqslant 1.1Y$$

then plastic deformation takes place. At this stage adhesion between the plastic asperities takes place to form adhesion bonds. New contact areas are formed as the existing ones grow in size. Equilibrium occurs when the total contact area has increased sufficiently to carry the load at the mean yield stress of the contact[11,9]. This is very important to understand the theories of friction and wear of metals.
Kragelskii[6] calculated the real area of contact. He indicated that the roughness of surfaces subjected to compressive stresses changes because of inhomogeneity of its mechanical properties, when contact takes place, the area of contact depends upon the load and the roughness of the surface. The pressure will not be distributed uniformly over the contacts, but will depend on the surface configuration. Kragelskii[6] distinguished between a number of areas of contact:

i) Apparent area of contact which is outlined by dimensions of the contacting solids, it is independent of load.

ii) The counter area, which is the area constituted by deformation of surface undulation.

iii) The real area of contact which is the sum of the small areas over which the solids touch.

Halling[7] indicated the following points:

i) As the load increases the mean area of a contact spot remains constant.

ii) The total real area of contact is linearly proportional to the applied load, no matter whether the surface is deforming elastically or plastically.

iii) At the loads normally used in practice, the surface roughness will only be compressed by about ten per cent. At loads greater than this value, the underlying bulk material reaches the yield stress and deforms plastically.

When the load is removed there is a relaxation of elastic stress and the surfaces separate, then the contact spots which have been formed before will be destroyed. For clean metals, particularly soft ones, separation may be hindered by adhesion occurring between surfaces when the load is applied. With harder metals or contaminated surfaces, the junctions may break readily[3].

It seems agreeable that the surfaces of solids are rough and wavy, and when contact takes place elastic deformation occurs; when the load is increased, plastic deformation takes place. In spite of the formation of elastic contacts, there will be plastic ones at some asperities, and by increasing the load, plastic deformation dominates.

Under the action of combined normal and tangential forces, contact points are continually being made and broken. The contact points being referred to as adhesive bonds. The underlying material will deform and change compared with its original state. Friction and wear occur from the formation, existence and destruction of the bonds and the bulk deformation of the material.

b) The area of contact: The approach of two ideal smooth curved surfaces was first considered by Hertz[13]. If the surfaces are pressed together with a load (W) they will at first deform elastically according to Hertz. If an asperity can be considered as a portion of a sphere with radius (r) and this rests upon a flat surface and elastic deformation occurs, the region of contact will be bounded by a circle of radius (a) where:

$$a = 1.1\ [\frac{Wr}{2}\ (\frac{1}{E_1} + \frac{1}{E_2})]^{1/3} \qquad (1)$$

Here $E_1$, $E_2$ are the Young's moduli for the asperity and the surface respectively, see Figure 2. At this stage, therefore, the area of contact ($A = \pi.a^2$) will be proportional to $W^{2/3}$. However Bowden and Tabor[9] have indicated that for radii of curvature of the order of: $r = 10^{-4}$ cm, the load required to bring deformation up to the onset of plastic flow is extremely small. Indeed, in most cases the material around the tips of the asperities will be subjected to full plasticity, and for any given indenter, the area of contact is directly proportional to the load. Bowden and Tabor[14] have illustrated that the pressure that can be supported by two surfaces in contact under the action of a localised deformation is equal to the hardness of the softer metals, i.e. the indentation hardness.

However the elastic deformation has taken a great deal of attention of many researchers. Archard[15,16] has indicated that if a single spherical protruberance is deformed elastically, the area of contact (A) was also proportional to $W^{2/3}$ and thus the kinetic frictional force is also proportional to $W^{2/3}$. On the other hand, if the deformation is plastic, then A is proportional to W. This argument applies to a single contact, whereas for bodies touching in many regions, the situation may be very different. Using models to represent the multiple contact conditions, it has been shown[17] that even when deformation is entirely elastic, A is very nearly proportional to W and Amontons law[18] can be explained in terms of elastic theory of deformation.

A linear relationship between the area of contact and the elastically supported load is then proposed.

It has been mentioned that under the action of combined normal and tangential forces that adhesive bonds will be formed and broken. This phenomenon has been studied by a number of workers[9,19-22], who concluded that strong welded junctions result in a high friction and wear behaviour.

## 2.2 METALLIC WEAR

1. Introduction: Wear is often seen to be treated as something of a poor relation to its close associate friction. It is well known that Amontons [18] deduced the basic laws of friction as long ago as 1699, but it was another 127 years before the first mention of wear occurred. This took place in a paper by Rennie[5] when he related the fracture of asperities to the strength of materials, giving limiting loads at which "abrasion" took place for a wide variety of pairs of materials. Papers continued to be very sparse until 1946, when R Holm[10] published a book on electrical contacts and used the term "wear" for the first time. Holm suggested that the wear process was an atomic transfer which takes place when surfaces come very close together i.e. there will be a statistically constant probability of an atom from one surface to be pulled out to the other surface. Holm derived an equation for the volume of wear removed, which was:

$$V = Z \frac{W.x}{H} \qquad (2)$$

where Z = constant; W = load; x = distance of travel and

H = the hardness of the material.

Burwell and Strang[23] have discussed the existence of simple laws of wear, such as those forecast by Holm's theory. In the light of their experiments, they concluded that, under their experimental conditions, suitable combinations of materials can be found which show a simple wear behaviour of the expected type.

However, Holm's theory must be modified by replacing the concept of atoms removed at atomic encounters, by the removal of wear particles at asperity encounters.

Holm's suggestesion was examined by Rabinowicz and Tabor[24] using radio-active tracers. No evidence of Holm's suggestion was found. They indicated that wear takes place at asperity interactions, but it is in the form of fragments of material removed, rather than atomic transfer.

In 1953 Archard[15] published his theory on mechanical wear. It has in fact been the basis of nearly all subsequent studies on wear. A relationship between the extent of wear and the various factors affecting wear was derived without any special assumptions as to the nature of the sliding surfaces.

Indeed, there is now an abundance of theories on wear[25-27]. However, Tabor[28] has indicated that "there are no precise laws of wear". Wear could be divided into two groups:

i) Dry or unlubricated wear
ii) Lubricated wear.

2. Dry or Unlubricated Wear: Unlubricated wear seems to be a little remote from the real situation, but it has to be understood if an understanding of lubricated wear is required.

Research has been carried out by many workers to determine the wear laws or the mechanisms of wear by using either no lubricant or by using an inert lubricant.

Although the technical literature is full of reported data on wear, these are in almost all cases the results for particular industrial materials designed to simulate specific operations in service. As a result, it has not been possible to deduce any general laws of wear, in fact there are only three qualitative conclusions concerning wear to which those familiar with the field would all agree. These are as follows:

i) Wear increases in general way with distance of travel.

ii) Wear generally decreases with increasing the hardness of the rubbing surfaces.

iii) Wear depends on load, area of contact and many other factors, but these are less generally agreed.

a) Effect of sliding distance: It has been indicated by Holm[10] that the volume of wear is directly proportional to the travelling distance (see equation 2). Bowden and Tabor[9] have indicated that the measurements showed that, over a fairly wide range of experimental conditions, the wear at a fixed load is directly proportional to the distance traversed. A number of workers have illustrated the same result[8,29,24].

Burwell and Strang[29] indicated that wear increases in a general way with distance of travel, but not in linear fashion. There are always many variations, Archard and Hirst[2] showed that after an initial period, the wear increases linearly with sliding distance.

An equation similar to Holms has been derived by Archard[15] as long ago as 1953.

It seems that all researchers have agreed about the proportionality of wear with sliding distance in general terms[2,28,30,32].

b) Effect of sliding speed: This effect has been studied by a number of workers. Bowden and Tabor[33] illustrated that the mean effect of speed on wear arises from the increased surface temperature generated at the points of the rubbing contact. This may have several consequences of which the following four are probably the most important:

i) High hot spots will increase the reactivity of the surfaces and the wear fragments with the surrounding atmosphere or lubricant.

ii) The relatively rapid heating and cooling of the hot spots may encourage metallurgical changes, this greatly influences the wear process.

iii) High temperatures may greatly increase the ease of interdiffusion and alloy formation at the interface, such a process may crucially affect the wear behaviour.

iv) At high speeds of sliding, surface melting may take place and this is often accompanied by low friction and wear.

Quinn[34] has indicated that the wear rate will decrease with increasing the speed due to the high temperature which is produced during the run. However, the effect of speed on the wear rate has been examined by Lancaster[35], who indicated that, in general, the wear rate will increase for low speeds and it will decrease rapidly for high speeds. These observations will all depend on the ambient temperature.

It is essential to mention the fact that wear rate increases with increasing the speed (for low speeds) and decreases when the speed increases (for high speeds). These points have nearly universal acceptance.

c) Effect of load and area of contact: It has been indicated by Holm[10] that wear is directly proportional to the applied load (see equation 2). Rabinowicz and Tabor[24] introduce proof about this proportionality. They added that wear is independent of the apparent area of contact. Archard[15] derived the equation of Holm without any assumption to the nature of the sliding surfaces, he also indicated that wear rate is proportional to the applied load and independent of the apparent area of contact.

The transfer rate and the wear rate are proportional to the load and a similar relationship applies between the load and the size of transfer fragments and wear particles; i.e. it is not so much the number of individual transfer fragments or wear particles which increase with load, but rather their size[36].

It seems that most workers now accept that the wear volume (V) of an unlubricated system ideally obeys the relationship[2,23,37-40]:

$$V = \text{Constant}.\ \frac{W.x}{H} \quad \text{(see equation 2)}$$

It is also accepted that wear may take one of two forms, a mild or a severe form, and that for each the wear is independent of the apparent area of contact. The apparent area of contact may, however, be significant in determining the transition point from mild to severe wear. Hirst[41] and Bowden and Tabor[33] indicated that the more severe types of wear are associated with relatively greater contact stresses and surface deformations.

d) Effect of hardness: Material hardness is considered to be one of the most important factors governing the wear. Tonn[42] introduced the concept of the "relative wear resistance", which is the ratio of wear of a given specimen to that of reference sample. A linear relationship between the relative resistance and the hardness of materials has been achieved

$$\frac{B_2}{B_1} = aH + b \tag{3}$$

where: $B_1$, $B_2$ are ratios of wear resistance of the metals;
a and b are constants; and H = hardness.

Khrushchov and Babichev[43] for commercially pure and annealed metals established the following relationship:

$$\frac{B_2}{B_1} = K.\,\frac{H}{P} \tag{4}$$

where: K = proportionality constant; and P = nominal pressure.

Khruschov[44] reported experimental results for abrasive wear in supporting the proportionality between wear and the hardness. The real contact area is calculated as W/H where W is the load and H is the hardness of the softer material of the contacted pair[33]. Wear is assumed to be proportional to the real area of contact and hence is inversely proportional to the hardness as shown by Archard[15].

Rabinowicz[45] indicated that the harder metal will generate smaller wear particles than the softer material. The softer metal will wear more than the hard metal [6,71].

However, some workers have shown that wear is not always inversely proportional to the hardness. Egawa[46] showed that the transition from "mild" wear to "severe" wear became more acute as the hardness increased, but that hardness did not directly affect wear. Hogmark[47] showed experimentally, that under any conditions, the wear of soft martensitic steel (550 HV) was less than that of a harder steel (700 HV). Suh[48] proposed that the delamination theory of wear (in which the wear process consisted of three stages) and the effect of hardness on wear were inconsistent in each stage.

3. The Mechanisms of Wear: In spite of the lack of knowledge of any relation between the amount of wear and the simple operating variables, which will be necessary in order to deduce precisely what is the physical mechanism; still there are a number of mechanisms which may play a role in the wear process, although their relative importance is still in doubt. These mechanisms have been indicated by a number of workers as follows:

i) adhesive wear;
ii) abrasive wear;
iii) fatigue wear;
iv) corrosive wear; and
v) erosion, pitting, fretting, etc.

The first two mechanisms are the most important.

a) Adhesive wear: This mechanism of wear can be defined as the transfer~~r~~ance of metal from one surface to the other due to a process of phase welding[5,30].

Adhesive wear may be distinguished as the most fundamental of all other types of wear[5]. It occurs when surfaces slide against each other, and the pressure between the contacting asperities is high enough to cause local plastic deformation and adhesion[49]. The shear force required to break the interfacial junctions is primarily responsible for the frictional force[9,26,33].

Adhesion is favoured by clean surfaces, non-oxidising conditions and by chemical and structural similarities between the sliding couple[49]. Since the area of contact is inversely proportional to the hardness, wear decreases with increasing asperity hardness. Wear increases if the surfaces are chemically clean, because bonding and welding of the contacting asperities (true area of contact) are more likely due to the high load[30].

Archard[15] has related wear to a number of important factors in his equation (2), these being: LOAD, SLIDING DISTANCE and HARDNESS of the surfaces. Whether this equation can be used for adhesive wear is still in doubt.

Rabinowicz[12] related the adhesion of pure metals to their ability to form solid solutions. Metal adhesion and transfer may also occur due to harder surface asperities ploughing through the softer counterface. Metal debris then becomes trapped and embedded into the surface grooves on the hard surface[49].

In general, high temperature increases and accelerates adhesive wear, this temperature may be generated by frictional heat of rubbing. The strength of the bonds which have formed depends on the types of materials[30]. For dissimilar metals, the bond at the interface will generally lie between the bond strengths of the paired metals, i.e. for dissimilar metals the junction is generally stronger than the weaker of the two metals, so that when the junction is sheared it will detach a piece of the weaker metal. For similar metals, the junctions, because of work-hardening, are stronger than the parent metal, and when shearing occurs a lump is torn out of one or both surfaces[28].

However, the adhesive mechanism of wear seems to be almost impossible to eliminate completely[30].

b) Abrasive wear: It can be described as the displacement of material by hard particles or hard protuberances[5].

Burwell[30], Bowden and Tabor[33] and Richardson[39] indicated that in this type of wear, the removal of solid metals from a surface is accomplished not by its sticking to other surfaces and being pulled out, but rather by being ploughed out by a much harder surface or body. There are two general situations for this type of wear; in one case the hard surface in question is the harder of the two rubbing surfaces; and in the other case the hard surface is a third body. The primary requirement for its occurrence is that there be a great dissimilarity in hardness between the two rubbing surfaces. On the other hand, the removal of material through the abrasive mechanism by a small hard particle of grit caught between the rubbing surfaces is an extremely important factor in the total overall wear and is probably responsible for the largest amount of wear in industrial machinery.

Oberle[50] and Spurr and Newcomb[51] pointed out that the larger the elastic limit of strain, the better able should the surface be to resist damage by an abrasive or other harder surface.

Burwell[30] gave an equation for abrasive wear resistance as follows:

$$E_R \sim \frac{H^2}{2E} \qquad (5)$$

where: $E_R \sim$ wear resistance; $H$ = hardness; $E$ = elastic modulus.

Bowden and Tabor[33] assumed a pyramidal asperity and calculated the volume of wear as follows:

$$V = \frac{2\tan\theta}{\pi}\left[\frac{w.x}{H}\right] \qquad (6)$$

where: $\theta$ = the angle of pyramid; $w$ = load; $x$ = distance travelled. and $H$ is the hardness.

Lancaster[52] differentiated between two types of abrasive wear; two body abrasive wear, where there are only two surfaces sliding on each other; and three bodies wear when there is a third body (such as grit) in between the two sliding surfaces.

Khruschov[44] and Sin, Saka and Suh[53] indicated that the intensity of abrasive wear depends upon the size of the abrasive particle and on the hardness of the metal. Sin, Saka and Suh[53] pointed out that as the grit diameter is increased, the wear rate is increased rapidly until a critical grit size is reached. It then becomes independent of grit diameter or increases slightly.

A number of researchers have studied this mechanism and similar results have been drawn[28,49,54,55].

c) The "delamination theory of wear": This theory has been suggested by Suh[25]. Several factors have been considered in deriving this theory, such as the behaviour of dislocations at the surfaces, sub-surface cracks and void formation, and subsequent joining of cracks by shear deformation of the surface. Suh called this theory the "Delamination Theory of Wear". He indicated that this theory based upon the following facts:

i) during wear, the material near the surface cold-works less than that of the sub-surface layer;

ii) voids will form due to pile-up of the metal and by the time these will come together to form cracks.

An equation for the volume of wear has been given by Suh:

$$V = \frac{b}{4\pi} \left[\frac{K_1.G_1}{\sigma_1.S_1\ (1 - \nu_1)} + \frac{K_2.G_2}{\sigma_2.S_2\ (1 - \nu_2)}\right] L.S \qquad (7)$$

where: $\nu_1$, $\nu_2$ = Poisson's ratios for the two materials; $G_1$, $G_2$ = shear modulii; $K_1$, $K_2$ = constants depending on the surface topography; $\sigma_1$, $\sigma_2$ = friction stresses for the surfaces; $S_1$, $S_2$ = critical sliding distance.

Suh and colleagues[25-27, 48] indicated the following ideas:

i) The delamination theory of wear can explain many experimentally observed wear phenomena and give insights into the microscopic causes of wear.

ii) The so-called adhesive, fretting and fatigue wear are all caused by the same mechanisms.

iii) The wear rate decreases drastically when the shear deformation of the surface layer is prevented.

iv) Uncontrolled inclusion of hard particles in metals can accelerate the wear rate.

Abrahamson, Jahanmir, Suh and Turner[56] and Abrahamson, Jahanmir and Suh[26,27] supported this theory and they added that the delamination theory provides the theoretical basis for reducing wear through the development of a composite metal surface.

Tabor[28] reported that the repeated traversal of a surface, particularly in the absence of an effective lubricant, rapidly produces fragments, this has been renamed by Suh[25] as "delamination".

Delamination involves a fatigue mechanism. Although the details are still the subject of discussion among the practitioners of wear research (see Hirth and Rigney[57]), there is little doubt that the delamination process is of frequent occurrence, especially with materials containing local inclusions. This applies to metals containing hard particles. Tabor[28] added that there is some danger of classifying all wear processes, which yield flaky wear fragments, as part of a single delamination process.

4. Lubricated wear: It is almost certain that, in general, all types of wear can be eliminated or controlled by inserting a layer of lubricant between the rubbing surfaces. This depends on the surface topography and the film thickness of lubricant. However, this type of wear has been studied by a number of workers. Godfry[58] indicated that by using a convenient lubricant, wear rate can be reduced. Some additives can be added to the used lubricant for more effectiveness. Certain additives do have an effect on the area of the wear spot and on the occurrence of surface films during fretting wear. Rowe[59] has suggested that the following equation can be used for wear under lubricated conditions:

$$w_L = (K_L.a).A \tag{8}$$

where: $K_L$ = constant; A = real area of contact; $a = A_c/A$.
$A_c$ = area of real contact without lubricant.

Rowe[59] suggested that wear rate constant ($K_L$) for the lubricated case can be calculated by the following equation:

$$K_L = \frac{Z}{v\ t_o} \exp. \left(- \frac{Q}{RT}\right) \qquad (9)$$

where: Z = distance between lubricant sites; v = sliding velocity; $t_o$ = period of vibration of an adsorbed molecule and Q = is the heat adsorption; T = the absolute temperature of the surface film; and R = gas constant.

Fairly good agreement is found between calculated and determined $K_L$ values.

Stolarski[60] pointed out that the breaking of junctions formed by adhesion between opposing surface asperities is accepted as being largely responsible for the observed friction under conditions of thin film lubrication.

The empirical relationship between the rate of adhesive wear and the ratio of load to hardness, which is known as Archard's equation[15] has been extended to consider the presence of lubricant film on the rubbing surfaces as follows:

$$v = k_m\ (1 + 3\ f^2)^{\frac{1}{2}}\ \beta \frac{w}{P_m}\ x \qquad (10)$$

where: f = specific constant for characteristics of lubricant;

β = specific constant for characteristics of sliding metal couple; $k_m$ = wear coefficient (related to Z in equation 2); $P_m$ = yield stress related to the hardness H; and v, w and x are the same as in Archard's original equation 2.

## 2.3 FRICTION

1. Introduction: Friction as resistance of motion has been known for a long time ever since people tried to move large statues and building blocks in Egypt and Syria. They used lubricants, rollers and wheels to reduce the amount of friction.

The concept of friction started to be considered as a scientific matter as long ago as 1400 AD. The first man who worked on this concept was Leonardo da Vinci (1452-1519 AD). He pointed out the first two laws of friction.

Amontons[18] rediscovered Leonard's two laws of friction as follows:

i) The friction force (F) is independent of the apparent area of contact.

ii) The friction force (F) is directly proportional to the applied load (W).

Coulomb[61] distinguished between "static" and "kinetic" friction. He indicated that static and kinetic friction phenomena were almost identical for metals. He also discovered the third law of friction:

iii) The friction force (F) is independent of the sliding velocity (v).

Euler[31], Ewing[62], Hirn[63], Morin[64], and Rennie[65] extended the interest in friction and developed studies of asperities interaction, adhesion and rolling friction.

Hardy[66] investigated the adhesion theory of friction which has been pointed out by Tomlinson[67]. Hardy did an important experimental investigation on friction, particularly for the static friction of solids lubricated by very thin films of hydrocarbon compounds. He showed the important part which is played by a single molecular layer of lubricants in reducing friction.

The molecular interaction between two surfaces in contact and the elastic and plastic deformation of the asperities have been investigated by a number of workers[10,17,68,69].

Bowden and Tabor[33,70-72] and McFarlane and Tabor[19] studied the friction between two metals in contact, and established the so called "theory of adhesion friction".

Kragelskii[6] illustrated that the friction resistance is not only due to adhesion friction, as suggested, but it is due to two actions:

i) mechanical ploughing, and
ii) molecular adhesion.

He also suggested that the friction force is as follows:

$$\text{Friction Force:} \quad F = F_{\text{mechanical}} + F_{\text{molecular}} \qquad (10)$$

Forrester[73] studied the kinetic friction in or near the boundary region and the influence of sliding velocity and other variables on kinetic friction in or near the boundary region.

2. The Theories of Dry Friction: Various views have been put forward regarding the mechanisms of friction. It has been explained in terms of: lifting micro asperities over each other; molecular attraction forces between the two solids; deformation of a volume of one material by the asperities of the second; and various other composite theories. Some further details will be given here.

a) French geometrical theory: This is in fact an early view of the 17th and 18th centuries. It is a geometrical explanation of the friction in terms of lifting surface asperities over each other. This theory has been developed by Belidor in France[5]. Mathematical analysis of friction between rough surfaces modelled for rigid spherical asperities have been given by Belidor.

b) Molecular attraction (adhesion theory): A number of workers have worked on this theory as long ago as 1700[5,66]. Tomlinson[67] studied the adhesion of the asperities of the surfaces which are in contact.

Bowden and Tabor[33,71] suggested that the frictional resistance results from the shear strength of metallic junctions formed under the effect of normal load (P) or in other words, the friction arises from the forces required to shear junctions of cold welded asperities resulting from molecular interactions; this is the force which is required to shear the junctions and maintain a constant sliding speed whilst forming and breaking asperity contacts during kinetic friction. This assumes a negligible force for bulk deformation of the material. In this case the following can be considered;

$$F = \Sigma S.a = S\ \Sigma a$$

$$W = \Sigma P_m.a = P_m\ \Sigma a \tag{11}$$

where: a = area of the single asperity of contact;

S = mean shear strength; $P_m$ = mean yield strength of all the junctions.

The coefficient of friction will be given as follows:

$$\mu_{\text{kinetic}} = \frac{F}{W} = \frac{S\Sigma a}{P_m\ \Sigma a} = \frac{S}{P_m} \tag{12}$$

Since the shearing occurs in the softer material, Bowden and Tabor suggested that the valuesof S and $P_m$ will be approximately equal to those of softer materials; then:

$$\mu_{\text{kinetic}} = \frac{S}{P_m} = \frac{\text{shear strength of softer material}}{\text{yield stress of softer material}} \tag{13}$$

This is in accordance with the two basic laws of friction first recorded by Leonardo da Vinci[5]. More recently Bowden and Tabor[33,72] have shown that a more correct relationship for the coefficient of friction is:

$$\mu_{\text{kinetic}} = \frac{\text{critical shear stress at the interface}}{\text{plastic yield pressure of the underlying material}} \tag{13}$$

Archard[15-17] suggested that entirely elastic deformation can explain the relation between the frictional force and the load. The frictional force between the sliding surfaces results from the energy required to elastically deform the real area of contact.

c) Material deformation (ploughing theory): When one surface is harder than the other, the asperities of the harder surface will plough out the softer material.

This term has been studied by Bowden and Tabor[33,72], they indicated that the ploughing force is proportional to the cube of the track width. However, for the harder materials the ploughing term is considered to be small.

An equation for the value of the ploughing force for a conical asperity has been derived as follows[5]:

$$F_p = \Sigma\tfrac{1}{2}.\ 2r.r.\tan\theta.P_m = P_m.\tan\theta\ \Sigma r^2 \tag{14}$$

and

$$W = \Sigma\frac{\pi r^2}{2}\ .\ P_m = \frac{\pi}{2}.\ P_m\ \Sigma\ r^2 \tag{15}$$

In this case, the coefficient of friction will be given by:

$$\mu = \frac{F}{W} = \frac{2\ \tan\theta}{\pi} \tag{16}$$

and for grooved track:[33,72]

$$F_p = \frac{1}{12}.\frac{d^3}{r}\ P_m \tag{17}$$

where: $r$ = radius of the circle of the penetration in the surface of the softer material; $\theta$ = slope angle of the side of the asperity measured from the mean of the surface; $P_m$ = the pressure required to displace the metal in the surface and $d$ = the track width.

d) Composite theory of friction: A number of workers have indicated that in practice possibly both mechanisms (the mechanism of adhesion and the mechanism of ploughing) occur to a greater or less degree depending upon the sliding conditions[5,3]. In this case the value of the friction force is:

$$F_{total} = F_{adhesion} + F_{ploughing} \qquad (18)$$

Depending on the shape of the asperity, an appropriate equation for the value of the coefficient of friction must be used; for example for a conical asperity:

$$\mu = \frac{S}{P_m} + \frac{\tan\theta}{\pi} \qquad (19)$$

3. Factors Affecting Friction: It has been stated by Bowden and Tabor[70] and Forrester[73] and other workers, that there are some factors which affect the frictional behaviour of the surfaces. These factors play an important part in controlling the value of the coefficient of friction.

Forrester[73] pointed out that at velocities between the limits (0.01 - 2.25) cm/sec for clean metal surfaces, certain combinations of materials show a decrease in friction with increasing velocity when unlubricated.

The strength of interatomic bonds, which may be held responsible for mechanical properties of metals, is thought to play a significant role in dictating frictional behaviour. Soft metals show low frictional resistance while hard metals exhibit high frictional values. The experimental findings indicate that for unlike metals the coefficient of friction is lower than that obtained with similar metals interacting together[74].

Bowden and Tabor[9,33,70] showed the dramatic effect of surface films in reducing the coefficient of friction of perfectly clean surfaces. Reduction of friction between clean metals can be achieved by depositing a very thin film of soft metal on the hard surface.

Some work has been done on the effect of thin films of oxide with special reference to titanium. A reduction in the coefficient of friction has been noticed[9,69].

Soaps, waxes, greases and oils are often used to reduce the friction coefficient, since they produce thin films (on the surfaces of the metals) with low shear strength. Fatty acids, stearates, oxides and several other types are used for this purpose.

## 2.4 BOUNDARY FRICTION AND LUBRICATION

1. Introduction: Boundary lubrication and its mechanisms are very complex subjects involving surface interactions and reactions. If the surfaces of solids are not completely separated by lubricant and contact takes place over an area comparable to that which develops in dry contact, this condition is called "Boundary Lubrication". Since the frictional characteristics are determined by the properties of the thin films of molecular proportions which govern the contact characteristics, the properties of the bulk lubricant are of minor importance and the coefficient of friction is essentially independent of viscosity. Boundary lubrication is of considerable engineering importance, since it controls the behaviour of most sliding systems. In fluid film lubrication when two surfaces are separated by fluid film, the load which can be carried by this system is proportional to the speed and inversely proportional to the thickness of the film:[5]

$$P_z \propto \eta \frac{u}{h^2_{min}} \tag{20}$$

where: $\eta$ = viscosity; $u$ = speed; $h_{min}$ = minimum film thickness. When the speed is very low, and the load is increased then $h_{min}$ will be very small, and if:

$$h_{min} \leqslant R_{n_1} + R_{n_2} \tag{21}$$

where: $R_{n_1}$, $R_{n_2}$ are the roughnesses of the two surfaces. In this case boundary lubrication exists[5].

Boundary lubrication reduces the friction coefficient very greatly[75]. For example two clean metal surfaces in contact have a coefficient of friction of about, $\mu = 1.0$; whereas the coefficient of friction for surfaces lubricated by boundary film is about, $\mu = 0.1$[73,76-78]. Good boundary lubrication will prevent "stick-slip" motion and will allow the surfaces to slide over each other. Long chained molecules, such as fatty acids, stearates etc, exhibit good boundary lubrication.

A considerable amount of work has been done to understand the mechanism of boundary lubrication and friction between solids.

2. The Mechanisms of Boundary Lubrication: It has been indicated by Hardy and Doubleday[79] that when surfaces of solids are near enough to influence directly the physical properties of lubricants, then this condition is called the "boundary condition". Hardy[66] added that the friction was not only influenced by the chemical nature of the lubricant but also by the chemical nature of the underlying surfaces. Bowden, Gregory and Tabor[80] demonstrated that the boundary lubrication condition is due to metallic junctions which form between some asperities of the surfaces in contact, so the friction is governed by the properties of the lubricant and the surfaces. Bowden and Tabor[9,33] indicate that the Hardy's theory of boundary lubrication was an over-simplification. They added that the theory must include the influence of the bulk properties of the metals concerned. The theory must take into account the metallic adhesion which occurs through the lubricant film due to

the high pressure over some asperities and when welding takes place. In this case the friction force will be:

$$F = A\ [\alpha\ S_m + (1 - \alpha)\ S_\ell] \tag{22}$$

where: A = area which supports the load; $\alpha$ = the fraction of this area over which breakdown of the film has occurred; $S_m$ = shear strength of the junctions at the metal-metal contact; $S_\ell$ = shear strength of the lubricating film.

Another equation for friction force has been set by Deryaguin, Kavassev, Zakhavaeva and Lazarev[81] as follows:

$$F = \mu\ [W + S\ P_o] \tag{23}$$

where: $\mu$ = true coefficient of friction; W = load; S = area of real or molecular contact; $P_o$ = adhesion force per unit area of real contact.

The difference between equations (23) and (22) appears in inclusion of the value of the load (W). The resistance of shear in a thin boundary lubricating film is brought about by a normal load on the film, and appears and disappears with load[81].

A new mechanism of boundary lubrication has been suggested by Cameron[82]. He illustrated that the mechanism of boundary lubrication is due to molecular forces between hydrocarbon molecules adbsorbed on the surfaces rather than to welding and tearing of the opposing surface roughness as suggested by Bowden and Tabor. He evaluated the friction coefficient from:

$$\mu = \frac{F}{P} \tag{24}$$

where: F = force required to move the surfaces under boundary lubrication; P = yield stress which is considered to be equal to the vertical force.

A number of other workers have worked on the subject of boundary lubrication[6,83,84].

## 3. Factors Affecting the Boundary Lubrication:

a) Effect of load: The effect of load has been investigated by a number of researchers. Hardy and Bircumshaw[85] established that when the load increases, the coefficient of boundary friction decreases and tends towards a constant limiting value. Tabor[86] and Forrester[73] illustrated that with high loads and low speeds, a boundary lubrication condition is obtained. Bowden and Tabor[9,33] and Lancaster and Row[87] indicated that at very low loads (below 10g) the coefficient of friction decreases with increasing magnitude of the applied force. Nevertheless, for loads above 10g, the frictional behaviour is independent of the loads. Other researchers[9] used the value of load to calculate the friction force. They pointed out that the resistance to shear in a thin boundary lubricating film is brought about by a normal load on the film and appears and disappears with load. Kragelskii[6] gave an explanation for the decreasing of the coefficient of friction with increasing load by saying that when the load increases, the film thickness decreases, and thin lubricant films exhibit greater shearing resistance and therefore the friction force increases. At high loads, the coefficient of friction increases when loads increase due to transformation of the boundary friction at the individual contact points to dry friction. Similar results were obtained by a number of researchers[5,55,88].

b) Effect of speed: Forrester[73] indicated that friction may increase when the velocity increases. This is due to partial destruction of the boundary film. Forrester added that with increasing the sliding speed, an increased tendency may be expected for boundary friction to be replaced by dry friction over part of the contact area, and higher value of coefficient of friction observed.

Bowden and Tabor[9] showed that for fatty acids the friction coefficient does not alter significantly with the speed of sliding (in the range 0.001 - 20 cm/s). Paraffins and alcohols show a decrease in the friction coefficient when the speed increases down to limited value.

Clayton[89] has shown that in the range from zero to 0.3 cm/s, there are two types of relationships between the coefficient of friction and the speeds as shown in Figure 3.

Type A is concerned with pure mineral oils and bearing materials. Type B is for fatty acids, which do not give rise to mechanical relaxation oscillations ("stick-slip") in the system. Such oscillations occur when the friction decreases with increasing the speed.

Kragelskii[6] indicated that the A types will hold for a frictional contact into which rheological properties enter. The decrease in the coefficient of friction is explained by a reduction in the time of localized contact and, in turn, by a decrease in the contact area. The area will not increase when the surfaces are at rest with respect to each other. Type B curves are obtained for conditions in which interpenetration of the surfaces is reduced to the minimum.

Other workers studied the effect of speed on the boundary lubrication and similar results have established[90-92].

c) Effect of surface properties: Hardy and Doubleday[79] and Hardy[66] pointed out that in boundary lubrication, the friction depends not only on the lubricant, but also on the chemical nature of the solid boundaries and the nature of the underlying surfaces, which may in many cases react to produce lubricant soaps[93]. Hardy established the following relationship between the coefficient of friction and the nature of surfaces, see Figure 4:

$$\mu = a - bM \tag{25}$$

where: a = constant which depends on the nature of the solid surfaces; b = constant which depends upon the molecular weight M.

The results show that the properties of these lubricants depend very markedly upon the nature of the material[9,33,73,80].

Forrester[73] and Barwell[76] indicated that in friction, many combinations of materials and lubricants will be influenced by many factors, such as "running-in", surface finish and the degree of working of the substrate material. Even the breakdown of the boundary film may be caused by the extent of the deformation of the underlying metal during sliding[92,94].

d) <u>Effect of temperature</u>: Hardy and Doubleday[79] demonstrated that the coefficient of friction decreases when the temperature increases until the melting point of the lubricant is reached, when the coefficient of friction suddenly increased. Tabor[86] and Bowden, Gregory and Tabor[80] indicated that a lubricant which behaves well at room temperature, may have poor lubricating properties at quite moderate temperatures. Above the critical temperature, damage results to the boundary film and the surfaces. Kingsbury[95,96] and Cowley, Ultee, and West[11] added that, when increasing the speed and load, the failure temperature of boundary lubricants may markedly decrease.

Kingsbury derived an equation to calculate the temperature where the transformation from good lubrication conditions to poor conditions occur.

Bowden and Tabor[33] and Tabor[83] indicated that some lubricants react at high temperatures to form new boundary lubricants. When reaction occurs, however, the increase in friction and transfer take place at higher temperatures, which corresponds to the softening point of the soap. Above the melting temperature, the friction and transfer are characteristic of unlubricated metals. Figure 5 explains the region of the effectiveness of the lubricant as an example[5].

e) Effect of lubricant chain length: This term has been investigated by Hardy[66]. He pointed out that the boundary lubrication depends on the lubricant and on the chemical nature of solids (see equation 25). Working with homologous series paraffins, alcohols and some fatty acids on various surfaces, Hardy found that the friction was a function of the separate contributions by the solid surfaces, the chemical series of the lubricant and the number of carbon atoms in its chain. To interpret these data, Hardy assumed that the friction between unlubricated surfaces is due to the surface fields of force. When the lubricant is added, the molecules are physically adsorbed and orient themselves to each of the solid surfaces to form a unimolecular film. The solids sink through the lubricant layer until they are separated by only the unimolecular adsorbed film. Since the polar groups adhere to the metal surfaces, contact takes place, not between metal surfaces, but between the non-polar groups at the other end of the molecules. Slip takes place between these non-polar molecular sheets. The efficiency of a boundary lubricant is measured by the extent to which these films can mask the field of force of the underlying surfaces. The temperature which converts the lubricant from good to useless depends on the chain length of the lubricant. There is a fairly rapid decrease in friction coefficient to a constant value (about 0.1) as the chain length increases[9,33,80,86].

Bowden and Tabor [9,33] pointed out that the relationship between the chain length and the coefficient of friction is not linear, see Figure 6, and there is no zero friction coefficient as suggested by Hardy[66].

A number of other workers established similar results[81,82,6].

4. <u>Wear in Boundary Friction and Lubrication</u>: Lunn[97] indicated that the addition of oily additives, such as fatty acids or fatty materials, will decrease the coefficient of friction. Experience shows, however,that such additives often cause an increase in wear. It is suggested that this is due to the corrosive action of the additives. Lunn has shown that additions of oleic acid increases the amount of metallic contact, thus producing considerable metallic wear, even if the coefficient of friction is decreased.

Kingsbury[95,96] and Kragelskii[6] illustrated that there is no relationship between the friction factor and wear, but usually high friction is accompanied by high wear.

# CHAPTER 3

## REVIEW OF WEAR AND FRICTION IN POWDER METALLURGY

3.1 SOLID LUBRICANTS

1. Introduction
2. Types of Solid Lubricants
    - a) Metallic film lubricants
    - b) Polymeric films
    - c) Soaps, fats and waxes
    - d) Chemical conversion coatings
    - e) Lamellar solids
    - f) Miscellaneous soft solids
3. The Lubricating Action
4. Methods of Use
    - a) Powders
    - b) Pastes
    - c) Bonded coatings
    - d) Incorporation in dry bearing materials

3.2 WEAR IN POWDER METALLURGY

1. Introduction
2. Factors Affecting the Wear of Compacts

3.3 FRICTION AND LUBRICATION IN POWDER METALLURGY

1. Introduction
2. Powder Consolidation Theories and Friction Effects
3. The Effects of Lubricants During Compaction of Powders
4. The Effects of Lubricants During the Ejection of the Compacts.

## 3.4 APPLICATION OF MODERN TECHNIQUES IN WEAR AND FRICTION STUDIES

1. Optical Microscopy
2. Scanning Electron Microscopy
3. Taper Sectioning
4. Replica Technique
5. Profilometry

# CHAPTER 3

# REVIEW OF WEAR AND FRICTION IN POWDER METALLURGY

## 3.1 SOLID LUBRICANTS

1. Introduction: Solid lubricants can be defined as any material in the solid phase which, when interposed between two sliding surfaces, can cause an improvement in the sliding conditions[113]. In fact the most effective way to reduce friction and wear is to separate the two sliding surfaces by means of a viscous fluid, such as a film of oil, or gas. This ideal situation is known as hydrodynamic lubrication. It provides a coefficient of friction of the order of 0.003 or less[5], depending on the sliding velocity, load and viscosity of the fluid. It eliminates the wear entirely, since the solids do not touch or collide with each other[75]. Gyroscope bearings are one example where the ideal conditions of hydrodynamic lubrication are substantially achieved[98].

Ideal conditions of hydrodynamic lubrication can rarely be maintained in practice. Starting, stopping, misalignment, heavy loads and other service conditions can cause the fluid film to be squeezed out or allow the surface asperities to break through the film, so that the two solids are pressed into contact with one another. Then ideal hydrodynamic lubrication ends and boundary lubrication, or lubrication by solids[75] begins.

The general task of lubrication by solids is to prevent contact between clean metal surfaces by interposing low shear strength solid films rather than viscous fluid films. The effectiveness of this film depends on the degree of its weakness on shear[99]. These solids can be particularly advantageous under several conditions, such as high loads, where the oil films are squeezed out by the extreme pressure; low speed; high temperature environment; and where dirt or abrasive solids exist[100]. On the debit side solid lubricants do not cool; unlike oils, solid lubricants cannot carry away any heat generated during operation. Also, although the coefficient of friction provided by solid lubricants are low[113,101] typically of the order of 0.04-0.25, they are not as low as those provided by hydrodynamic films (typically of the order of 0.001-0.003)[5]. However, the coefficients of friction provided by solid lubricants can be lower than those provided by oils operating under conditions of boundary lubrication. They have finite wear lives and replenishment of lubricant is more difficult.

2. Types of Solid Lubricants: Solid lubricants may be grouped into six classes as follows[102,103]:

a) Metallic film lubricants: Because these show the most advantages under very heavy loads, this method is sometimes used in metal working operations, such as drawing[103]. A fairly thick film of this lubricant can be applied to one of the two surfaces in contact. The extent to which a thin film of soft metal on a hard metal substrate can reduce friction has been demonstrated by Bowden and Tabor[9,83], who have obtained coefficients of friction as low as 0.04. In practice, indium, lead, tin, zinc, copper and barium have all been used for this purpose[102].

b) Polymeric films: Organic polymers may be used instead of the metallic film to give lubrication under severe deformation conditions, provided that they have sufficient adhesion to the solid surface and have a moderate film strength[103]. It has been indicated that the mechanism of friction for plastic polymers is the same as that for metals, except for "Teflon", which has a very low coefficient of friction[102,104,105]. Polymers such as PTFE show very low friction coefficients in bulk form. The disadvantage of the material is its ability to flow slowly under heavy pressure, especially if the temperature rises. This problem can be overcome by reinforcing the materials[103].

c) Soaps, fats and waxes: These are the oldest known lubricants, but it can be shown that their action is again dependent on thin film characteristics. For example, a steel hemisphere sliding on a steel block coated with a thin continuous film of sodium stearate showed a value of $\mu = 0.1$. As the film thickness was increased, the friction increased until, when the steel block was replaced by a solid sodium stearate block, the friction reached $\mu = 0.2$, even after many traversals had established a constant groove in the soap[102]. Some materials in this class possess a self-heating ability, although the rate of repair of the film is much slower than with liquid lubricants and greases. The materials which are more chemically active give excellent wear and friction reduction even above their melting points on base metals by reacting with the surface[103]. Thus stearic acid gives very low friction and good wear reduction on a variety of metals up to temperatures corresponding to the melting point of the metallic stearate[103]. This type of lubricant is widely used in powder mixes for welding and forming operations with resins, ceramics, metal powders, tablet manufacture, textile fibres, wire drawing and metal forming industries. Examples of this class are metallic soaps, the most common of which are aluminium, calcium, zinc, magnesium, sodium and lithium stearate; waxes, solid fatty acids[102,103].

d) Chemical conversion coatings: The best known films in this class are sulphide, chloride, phosphide, phosphate, oxide and oxalate films. The first four types are generally formed in situ at points of incipient seizure as result of reaction between additives in extreme pressure lubricant and the surface of heavily loaded rubbing parts, their function is primarily to provide protection against seizure and pick-up when the lubricant breaks down. It has been observed that the friction for clean steel lubricated by an oil of poor boundary lubrication quality is lowered 40% by the presence of an oxide film and 60% by a sulfide film on the surface. The thin film of oxide acts as a solid lubricant, although it is not the best because of its poor elastic properties and relatively high shear strength. Nevertheless it prevents seizure and galling[9,33,106,107]. If the oxide film is thick enough and the load is low, the coefficient of friction is low and constant, following Amontons law of friction. At critical loads the friction will be high due to shearing of oxide bonds[108].

Phosphate and oxalate coatings are used as a supplement to other lubricants, both liquid and solid. They are widely used in the forming and working of metals[102,103].

e) Lamellar solids: Examples of this class are graphite, boron nitride, molybdenum disulphide, tungsten disulphide, vermiculite, mica and silver sulphate. Since the members of this class are almost all inorganic materials, most can withstand high temperatures, and several are unusually inert[102]. The best known are graphite and molybdenum disulphide.

In the case of graphite, the ease of slip between adjacent crystal planes has been shown to result from the presence on the surface of an adsorbed water or oxygen film. In nitrogen, at humidity lower than 5%, or in high vacuum, rapid wear with very high friction takes place[109-112]. If the graphite is "run-in" under normal conditions, so that sufficient water is adsorbed on the layers to give low friction, it becomes highly oriented with the slip-layers flat on the surface, then wear is very slow. The rapid wear of graphite in vacuum is readily reduced by incorporation in the powder mix or dispersion of a small amount of a variety of lubricants or activants[102]. Almost the same is true of boron nitride[103]. Some of these lubricants (e.g. $MoS_2$) show a low friction coefficient that is not dependent on the presence of vapours, and is unaffected by temperature, either above or below room temperature; provided that vapours do not cause decomposition such as hydrolysis and that temperatures are not sufficient to cause rapid volatilization, oxidation or decomposition[103].

f) Miscellaneous soft solids: A large variety of inorganic solids, which do not clearly fit into any of the classes above comprise this class. Examples are basic lead carbonate (or white lead) used in the threading compounds, lime, used as a carrier in wire drawing, talc and bentonite, used as fillers in greases for cable pulling.

3. The Lubricating Action: When two moving surfaces come into contact, the real area of contact (A) can be determined by:

$$A = \frac{W}{P_m} \qquad (26)$$

where: $W$ = applied load; $P_m$ = yield stress for metal-metal contact.

The friction force is given by:

$$F = A.S_m \qquad (27)$$

where: $S_m$ = shear strength of metal junctions.

The coefficient of friction can be given by:

$$\mu = \frac{F}{W} = \frac{S_m}{P_m} \qquad (28)$$

This means that the coefficient of friction is independent of the area of contact. Reduction in the value of the coefficient of friction can be done by reducing the value of $S_m$ or increasing the value of $P_m$. This can be achieved by depositing a very thin film of solid lubricant (or soft metal) on the surface of the hard metal. Provided the film does not break down, the shear strength $S_m$ will be that of the soft metal[103]. At the same time A will remain small even for heavy loads[9]. As a result, the friction force will be small, so that the coefficient of friction will remain small as well[103]. This is the case when a complete separation between the rubbing surfaces is presented. If the film of soft metal is broken and metallic junctions take place between the soft metal and the hard one, the friction force will be given by[9]:

$$F = A\ [\alpha S_1 + (1 - \alpha)S_2] \qquad (29)$$

where: A = area of real contact; $S_1$ = shear strength of the softer metal; $\alpha A$ = area of contact at the junction; S = average value of the shear strength of the regions where the films are unbroken.

Apart from the friction, the film may also be worn away if the slider traverses the same track a sufficient number of times[9].

Yue, Ting-Hong, Hang-Chaw and Rui-Zhong[120] indicated that by using a thick film of solid lubricant of $MoS_2$, the wear volume (V) of this film is directly proportional to the square of the load and inversely proportional to the contact area as follows:

$$V = k \frac{W^2 . L}{a} \qquad (30)$$

where: W = load; k = constant; L = distance; a = area of contact.

Sugishita and Fujiyoshi[114,115] showed that the coefficient of friction for cast iron, which contains graphite, decreases with a decrease in substrate hardness and it contributes to decreasing wear loss; but when the temperature is increased the coefficient of friction is increased due to the hardening of the graphite film. Friction and wear performance of cast iron are influenced by the surface graphite conditions.

Tanaka and Vchiama[116] used $MoS_2$ and indicated that the wear rate and coefficient of friction are decreased as the contact pressure and sliding velocity were increased. This variation of wear rate and friction coefficient could be explained by the frictional heat. It was found that the wear of the slider sliding on a steel plate was reduced by the use of a $MoS_2$ film in high vacuum and in air, and showed the environmental effects.

Milne[117] and Scott[118] indicated that the effectiveness of solid lubricants under conditions of heavily loaded rolling contact appears to be attributable to the formation of an adherent surface film and due to the molecular structure of some lubricants and the relative weakness of the bonds between the layers of the lubricant.

Solid lubricants can eliminate or reduce the wear[118].

4. Methods of Use : Solid lubricants can be used in many forms listed as follows.

a) Powders: The powder of solid lubricant is burnished or polished on to one or both of the solid rubbing surfaces, usually by means of hard wood; or it can be mixed with the powder metal itself as in this research.

b) Pastes: These are made by mixing a large proportion (up to 80%) of solid lubricant powder with a carrier, which may be oil or grease, but the mixture must have the properties of the solid lubricant itself.

c) Bonded coatings: This form is used where a completely dry lubricant film is needed. The solid lubricant is often mixed with a bonding agent. Such a coating may then be applied like a paint and when it is dry it forms an adherent lubricant coating.

d) Incorporation in dry bearing materials: The lubricating properties of a bearing material may be improved by incorporating a solid lubricant. In this case very effective components may be produced. Examples of this are, inclusion of graphite in bronze bearings, the presence of tin or lead in clutch or brake materials. All of these examples are made by the powder metallurgy process.

## 3.2 WEAR IN POWDER METALLURGY

1. Introduction: The economy of making structural components by powder metallurgy techniques depends to a large extent on the quality and the life time of the compacting tool, especially the die[119]. There are a number of factors which affect the die wear, such as powder properties, lubricants, tooling materials and design; and it is affected also by the compacting variables.

The evaluation of the lubricants with respect to the die wear rate is, therefore, of considerable importance; also as wear occurs, the surface finish of the die changes and this change will affect the compaction and the ejection force, as well as the compact properties[121].

A number of workers have worked on the subject of wear of the tool die, and a number of papers concerning this subject have been published carrying results which have been derived, but as far as the wear of the compact itself is concerned, the work which has been done is very little, and the papers which have been published are rare.

Bockstiegel and Svensson[157], who worked on the factors which affect the wear of the die during the compacting, indicated that it is not the properties of the iron powder that have the most critical influence upon the die-wear rates and the tool life. A number of other factors must be considered. The proper choice of the die steel type, its heat treatment, as well as the correct dimensioning of the punch-die clearance, appear to be much more critical. It has not been possible so far to make reliable predictions of die wear rate or die life from ejection force measurements.

2. The Factors which Affect the Wear of Compacts: Most of the work on wear of the compacts has been done for sintered compacts. However, Mallender and Coleman[1,3] did some experiments on the wear of unsintered compacts. They indicated that the wear rate of the unsintered compact is increased approximately in a linear way with an increase in the load on the sliding surfaces. The wear rate is also increased with increasing the sliding distance and the speed,

but it is independent of sliding velocity when high chromium-steel materials are involved.

Mallender and Coleman[1,3] applied the Archard Equation in evaluating the wear volume of the die and then attempted to predict the die life.

Casstevens[119] indicated that the wear rate is increased with increasing the velocity, and at the same value of velocity, the increase in wear rate is very sharp due to "edge breaking". The speed at which edge breaking begins appears to be partly a function of the grain size of the powder which is being used. The larger the grain size, the weaker the specimen and the edge breaking occurs at a lower speed.

Another factor which affects the wear rate is the grain size. Dufek and Jenicek[122] indicated that wear rate is increased by increasing the grain size.

## 3.3 FRICTION AND LUBRICATION IN POWDER METALLURGY

1. Introduction: In both powder metallurgy and in mechanical sliding systems, the problems of friction and lubrication are similar, since they are both concerned with the interactions between surfaces. The particular difficulties which friction presents in powder metallurgy have been examined by a number of workers[123-126], who have contributed towards a general appreciation of the important factors, but who have not fully analysed them.

It has been shown by Hausner and Sheinhartz[127] and Leopold and Nelson[158,128] that several types of friction have been observed as follows:

i) Friction between the moving punch and die wall. This type of friction is relatively small, the pressure loss caused by it is almost negligible.

ii) Friction between powder particles. This has been shown to play a fairly small part in compaction.

iii) Friction between powder particles and the die wall. This has been shown to be the primary cause of pressure losses during compacting and the magnitude of the effect depends upon the powder material, its size and size distribution, its shape and surface conditions and the interparticle pressures[129].

iv) Internal friction within the particles during deformation.

v) Friction between compact and the die wall during ejection. This depends upon the materials involved, the die finish and clearance and the compacting pressure.

Leopold and Nelson[158,128] indicated that these types of friction act to decrease the effectiveness of the applied pressure. The special problems of friction and lubrication in powder metallurgy are directly dependent upon the ratio of pressing area/die wall friction area[127].

The actual pressure losses, which mainly occur during the compaction, are caused by the friction forces between the powder particles and the die wall. The value of the maximum die reaction which occurs as a result of die wall friction, is the result of extensive cold welding between the compact and the die walls[3].

The normal method for reducing these frictional effects is to use admixed lubricants. Although many studies have shown that die wall lubrication is quite satisfactory[158,128] this method is not widely used in production because of engineering design difficulties with the lubricating system[130].

Die wall friction exerts a considerable influence, both during compaction and ejection, and upon the finished components. It gives density variations along the compact length. Application of lubricants lowers the die wall friction losses and gives more uniform components and better life for the die itself.

2. Powder Consolidation Theories and Friction Effects: It has been pointed out by Leopold and Nelson[158,128] that by increasing the punch pressure on the mass of powder within a die results in the density increasing. The pressure losses which mainly occur during compaction at a given pressure are caused by the friction between powder particles and the die wall[131], the number of powder particles in the mould, as well as the surface condition of both the powder particles and the die materials[127]. However, as pointed out previously, friction between the die wall and particles results in density variations along the compact length[3].

Train and Hersey[132] studied the cold compaction of indium and lead powders. Bowden and Tabor friction theory has been used to derive equations for the die wall friction of pressed powder.

These equations enabled them to calculate the shear strength of the examined materials. The results were similar to those determined by using a punch penetration test.

Sheinhartz, McCullough and Zambrow[131] and Duwez and Zwell[133] used a comparatively simple direct measurement method and determined a relationship between applied and transmitted forces. They showed that the majority of the total friction occurring during powder metal compaction develops along the die wall and the effect of the die wall lubrication was also evaluated. A number of workers[115,128,131,141] have carried out studies on the interrelation between applied and transmitted forces in which mathematical relationships have been proposed taking into account the effect of die configuration and frictional forces during the densification of compacts.

The majority of these theories during compaction use the concept of powder-die wall friction coefficient and a number of workers have shown that this friction coefficient may change along the length of the compact die wall interface.

It has been illustrated by Hechel[135] that the compaction occurs by a multi-stage process which includes:

i) densification during filling the die;
ii) densification by particle rearrangement at low pressures before appreciable interparticle bonding;
iii) densification by compact deformation after appreciable interparticle bonding.

The various stages which occur during powder compaction are difficult to see from a plot of pressure versus density. However by plotting pressure versus relative porosity, the stages become more clearly discernible[136]. Starting with the assumption that the powder mass could be treated as if it were a solid metal subject to isostatic compression forces, Shapiro[137] derived an equation between the relative density and the depth. Torre[138] starting with a classical stress analysis of the hydraulic compression of a hollow sphere and assuming fully plastic flow, also arrived at the same equation. Heckel[135] suggests a relation between the applied pressure P and the resulting density of the compact D as follows:

$$\log \frac{1}{(1 - D)} = KP + X \qquad (31)$$

where: K and X are constants.

Heckel evaluated the value of K and X, and suggested formulae to evaluate the values of K and X:

$$K = \frac{1}{3\sigma_0} \qquad (32)$$

$$X = \log \left(\frac{1}{1 - D_0}\right) + \tau \qquad (33)$$

where: $\sigma_0$ = yield strength of the powder material; $D_0$ = relative apparent density of the powder; $\tau$= accounts for the densification which takes place at low pressures before bonding takes place.

Kawakita[139] indicated an empirical relationship between pressure and density which is applicable to a large number of powdered materials. He suggests that the relative reduction in compact volume C is related to the compaction pressure P by the equation:

$$C = \frac{V_o - V}{V_o} = \frac{abP}{1 + bP} \tag{34}$$

where: $V_o$ = original powder volume; V = volume at pressure P; a,b = constants. The relationship between powder properties and the Kawakita constants and other fundamental aspects of powder consolidation have been fully reviewed by James[140-142].

3. <u>The Effects of Lubricants During Compaction of Powders:</u> The effects of die-wall lubrication and admixed lubricants on the compaction of sponge-iron powder have been investigated by Leopold and Nelson[128]. They indicated that die-wall lubrication gives higher densities at high compacting pressure, while at low compacting pressures, the density is higher for admixed lubricants. For the larger weight compacts, the density can be increased significantly by either die wall or admixed lubrication. The lubricant efficiency was assessed by measuring the difference between the applied and transmitted forces, $F_a$ and $F_t$ respectively. A linear relationship was found between $F_a$ and $F_t$ as follows:

$$K = \frac{F_t}{F_a} \tag{35}$$

Leopold and Nelson[128] indicated that only very small amount of lubricant is necessary to give a high K factor. Increasing the amounts of lubricants having little effect. This relationship has been used by a number of workers[127,131]. They found that there is an optimum lubricant level for a given combination of compact weights and pressing pressures. They also showed that at low pressure, a greater amount of admixed lubricant is required to provide optimum lubrication, because the pressure is insufficient to force it to the die walls. Die wall lubrication is more significant than admixed lubrication at high pressures, whereas at a low pressure the reverse applies. Comparisons have been made between die-wall and admixed lubrication, from which it was shown that die wall lubrication was superior, and that when both die wall and admixed lubricant are used together exudation of the lubricant from the compact was retarded and densification was inhibited by the retained lubricant.

Sajdak, McNally and Nasta[130] investigated the effects of lubricant content, application and iron powder type upon the value of K at various compact length to diameter ratios. They illustrated that little advantage is to be gained by increasing the lubricant ratio above 1.0 wt%, and that the punch force is more effectively transmitted when using electrolytic iron, than atomised or sponge iron. Very few investigations have been carried out into the effects of the lubricant particle size upon the compaction of powders. However, Hausner and Sheinhartz[126] and Bocksteigel and Svensson[143] find that in pressing electrolytic iron powder at a given compacting pressure, zinc stearate of fine particle size gives greater densities, than a zinc stearate of coarse particle size.

4. Effect of Lubricants During the Ejection of the Compact:

It has been shown that the increasing admixed lubricant content reduces the force necessary to eject the compact from the die[115,130].

However Leopold and Nelson[128,158] indicated that a small amount of die wall lubrication is much more effective in decreasing the ejection pressure than a large amount of admixed lubricant (i.e. 0.012 mg/cm$^2$ die wall lubrication is much more effective than 2.0 wt% of admixed lubricant). Sajdak, McNally, Nasta and Beddow[130] indicated that decreasing the size of sample, or increasing the percentage of admixed lubricant, decreases the ejection force required, and the larger the compact, the more marked the effect of lubricant. It has also been indicated that the ejection pressure increased during ejection of the compact from the die where admixed lubricants were employed and that this effect is reduced with increasing lubricant content[115,130]. Bockstiegel and Svensson[157], Hausner and Heinhartz[126] all showed that fine particle size lubricants are better than coarse lubricants in reducing ejection forces. An opposite effect has been shown by Geijer and Jamieson[144]. The lubricant type is of importance in determining ejection forces[126]. It has also been suggested that ejection force measurements are a useful indicator of the wear. However they demonstrated that lubricants, which yield low ejection pressures, do not necessarily give low die wear rates. They in fact found it impossible to correlate ejection forces and wear rates for different lubricants[145].

## 3.4 APPLICATION OF MODERN TECHNIQUES IN FRICTION AND WEAR STUDIES

There is a very wide range of instruments which have been used to study friction, wear and surface topography.

1. Optical Microscopy: This is in fact the best method to observe the surfaces. It reveals many of the finer features of the surfaces. Unfortunately it suffers from a number of disadvantages. The use of visible light restricts the resolution of the instrument insofar as light is unable to discriminate features which are smaller than 0.25 μm. Furthermore even at the highest resolution one obtains a picture of only a very small part of the surface, which is not helpful in the study of the character of surfaces. It is very difficult to obtain quantitative values of the surface size features by using optical microscopy[146,9].

2. Scanning Electron Microscopy: The main advantages of the Scanning Electron Microscope comes from its capability to give very high magnification to the surface under examination. SEM can enable the examiners to observe directly the worn surfaces, this is very useful and is an advantage, particularly when rough surfaces have to be examined.

When using the SEM, the specimen needs a minimum of preparation and sometimes no preparation at all is required. Greater depth of focus can be achieved by using this technique. However, this method can be used for small specimens only. These have to be cut from the bulk material, which is often not possible, as in the case of the disc surface examined in this research[146-149,9].

3. Taper Sectioning: It appears to have first been described by Nelson[150] and further developed by Moore[151]. This is in fact the only direct method which gives direct observations of the surface geometry by the simple process of taper sectioning. The studied surface is plated with another metal, then composite blocks may be carefully machined and polished at some taper angle ($\theta$). This sectioning reveals an interface which follows the pattern of the original surface profile and enhances the vertical magnification by a factor of $\cot\theta$[146,9].

4. Replica Techniques: These are usually a polystyrene plastic, and they have been used for a long time to examine surface topography. The advantage of using the replica comes from the fact that replica is non-destructive and very easy to use.

By using this technique, curved surfaces can be examined. The replica itself can be examined by using simple optical techniques. Replicas can be used in places which are difficult to reach, and which have different shapes as well.

Before examining the surface by replication, it has to be cleaned properly and degreased, then flooded with acetone. A piece of acetate film (about 0.125 mm thickness, and cut to the size required) is immediately placed on the flooded surface and gently pressed into position. The acetone will soften the film and this soft film will consolidate down onto the topography of the surface. Finally the acetone will evaporate. After a few minutes the acetate can be peeled off carefully and placed on a glass slide by using adhesive tape, then it can be taken to be examined, either by optical microscopy, or if coated with carbon or a metal, by TEM methods. It must be noted that the replica is in fact a mirror image of the real surface[152].

5. Profilometry: This method was introduced by Abbott and Firestone[153] as the most common method used to study the surface geometry.

In this method a very fine diamond stylus (tip radius ± 0.5 μm or less under a static load of less than 0.0007N) is drawn over the surface irregularities. The vertical movement of the stylus is measured and amplified electronically, and recorded outputs provide an actual picture of the surface.

The "Talysurf" is the best known instrument of these types of profilometers. One of the most attractive features of this instrument is its flexibility in controlling the horizontal and vertical magnification independently. The horizontal magnification is controlled by the speed of traversing and the speed of paper on which the profile record is produced. This magnification is typically X10 to X5000[5]. The vertical magnification is controlled electronically and may be varied from X100 to X100,000 according to the precision required. The typical ratio of horizontal to vertical magnification is 1:50[5,154].

Several other techniques have been used for these purposes such as Reflection Electron Microscopy[155], and radioactive tracers have been used for examining friction mechanisms under conditions of lubricated[24] and unlubricated[35,156] sliding and the same technique was used in engine wear investigations.

These techniques have provided results to give us an even better understanding of the processes involved in sliding and interactions occurring between surfaces mainly on a microscopic scale[3].

# CHAPTER 4

# DETAILS OF APPARATUS AND EXPERIMENTAL PROCEDURES

# CHAPTER 4

# DETAILS OF APPARATUS AND EXPERIMENTAL PROCEDURES

## 4.1 COMPACTION AND EJECTION OF IRON WEAR 'PINS'

1. General Description of the Press: To produce the compacts which are needed in this research, an industrial compaction press operated mechanically by a cam was used, as shown in Figure 7 . During the production of the compacts, the press was operated on a single cycle having a maximum load of 35 tonne. The lower punch is fixed and the table which carries the die is supported by springs which have enough strength to bear the weight of the table. When the compaction takes place, the die which is mounted in the table, moves downwards over the fixed bottom punch due to the frictional force which generates between the powder and the die wall, this is what is called "floating die tooling" and this gives the effect of double ended compaction.

When single cycle compaction is used as in this research, the feed shoe was removed and the die had to be filled by hand and levelled with a straight edge. When the compact is made, then the lower punch pushes it up and it is ejected from the die.

The pressing force which can be obtained on this press is up to 350 kN and if fully automatic operation is needed, then the production rate of this press can be up to 1500 compacts per hour.

The length of the stroke of the upper punch and consequently the thickness of the compact can be controlled by the main operating cam profile, but the position of the stroke can be varied by the adjustment of an eccentrically mounted roller, which raises or lowers the contact point of the operating mechanism relative to the main cam. Figure 7 shows a general view of this press.

2. Tooling Details: Figure 8 shows the arrangement of top, bottom punches and die which have been used in this work to produce the samples of iron powder compacts (or wear pins). These top and bottom punches and the die itself were made from high carbon, high chromium die steel. The compositions in this die steel metal were as follows:

Chromium: Cr = 13.0%

Carbon: C = 2.1%

Molybdenum: Mo = 0.5%

Silicon: Si = 0.3%

The hardness of the die and the top and bottom punches were obtained by heat treatment to the following specifications:

The die hardness = 60 - 62 HRC

The top and bottom punches hardness = 57 - 60 HRC

The surface finish of the die = 0.07 μm CLA

3. <u>Compaction and Ejection</u>: Depending upon the volume of the compact and the density which is required, the appropriate amount of the mixture of iron powder and lubricant was weighed and carefully poured into the die. The technique which has been used during the pressing was designed to make the compact move over the same surface of the die during the ejection. The wear pins (the compacts) were produced by using the same speed for all of them. When the amount or the type of lubricant within the mixture needed to be changed, then the punches and the die were washed properly by using acetone liquid to remove any lubricant which may be left in the die and punches.

4. <u>The Compact Density Measurement</u>: The density of each compact was determined by using the following formula:

$$\text{Density} = \frac{\text{weight}}{\text{volume}} \qquad (36)$$

The weights were measured by using an accurate balance having a sensitivity of ± 0.01 mg. Before weighing the compact, the "flashes" which may occur around the circumference of the compacts, were removed and the compacts were washed by acetone to remove any unwanted particles on the surface, which might affect the accuracy of the measurements. To determine the volume of the compacts, a micrometer was used to measure its dimensions, by using the above equation (36) the density can be easily determined.

## 4.2 MEASUREMENTS OF SURFACE FINISH OF THE WEAR/FRICTION DISC

The measurements of the surface finish of the disc used in wear and friction studies were made by using a "Talysurf". The surface topography of these materials is indicated by a stylus, which has been rested on their surfaces and was traversed across it. The movement of the stylus was recorded and integrated over the sample length (which is the length of profile selected for individual measurements of surface texture) and the "centre line average" (CLA) value was determined. The CLA value is the arithmetic average of the centre line throughout the prescribed cut off. The centre line is the line representing the form of the geometrical profile drawn parallel to the general direction of the profile through the sample length, such that the sums of the areas contained between it and those parts of the profile which lie on each side of it are equal[5].

In addition, the surfaces were examined by using the replica technique. A piece of cellulose acetate material film (0.005 inch thickness) is used for these measurements. Before examining the surface, it was cleaned and washed by acetone. Then the surface which required examination was flooded in acetone. The acetate film is immediately placed in position on the flooded surface and is gently pressed into position. The acetone first softens the film, the soft film is then consolidated down on to the topography of the surface, and finally the acetone evaporates away.

After a few minutes the acetate film is carefully peeled off the surface, inverted, placed on a glass slide, and attached to the slide with adhesive tape. This surface was coated with a thin layer of carbon by vacuum evaporation. After carbon-coating the replica was cut up into small squares (containing the impression of the area of interest) and placed on specimen grid with diameter of 3 mm. Then these were washed by acetone to remove the plastic backing. This left the thin carbon film on the supporting grid with the impression of the original surface.

Since the carbon film is of roughly the same thickness all over the surface, a replica like this may be a bit lacking in contrast. The contrast was accentuated by the shadowing process. A heavy metal (usually gold or a gold-palladium alloy) was evaporated under vacuum ($10^{-4}$ torr) from a tungsten filament at an angle of 45° to the surface of the carbon film. Areas where the height of the specimen changes then receive a heavy coating and appear dark in the transmission microscope while the specimens were examined. The results are shown in Figure 26.

## 4.3 THE PIN AND DISC WEAR/FRICTION MACHINE

This apparatus has been used in this research for wear and friction experiments. This machine was used to study the wear of pins (i.e. compacts) and the effect of load, speed, and travelling distance on the wear behaviour of these pins or compacts. It has been also used to study the friction between the surfaces of the compacts and the disc, and the effect of load on the friction force which is generated between these two surfaces.

1. Description of the 'Pin and Disc' Machine: As shown on Figure 10, this machine consists of a 'Pin' which in this research is made from the various iron powder and stearate mixtures as described in Section 4.1. The 'pin' is carried by a horizontal arm which is movable to allow the pin to rest freely over the rotating disc, so that they can rub against each other during the test in the 'crossed cylinders' mode. The disc was made from the same material as the pressing die which is high carbon, high chromium die steel. The horizontal force or the load can be applied to the pin by adding the weights to the hanger, which is supported by the horizontal arm carrying the pin. When the disc rotates a horizontal force will be generated due to the friction between the surface of the disc and the surface of the pin or compact. This frictional force can be measured by using strain gauges, which are fixed on a spring plate, which is in turn attached to the horizontal arm on the body of the machine. During the test, the horizontal arm is freed from any restriction but the spring plate, so that the friction force will pull the spring plate and the strain gauges will be affected. This effect can be magnified and recorded and then used to calculate the value of the friction force. The degree of inclination of the spring metal is about $20^0$ to the horizontal; two strain gauges were attached to each of the upper and lower surfaces of this plate to form a bridge circuit which was supplied from a stabilized DC power unit. The speed of the disc can be varied by means of the exchangeable pulley system as shown in Figure 10; hence the effect of speed on the wear can be studied. This system of pulleys was fed by a high

torque motor capable of running at 1500 rpm. The position of the pin on the disc can be adjusted by a special holder.

To measure the value of the speed accurately during the test, a very accurate tachometer was used and the speed was measured several times during the run, an average value then derived. An electronic high accuracy revolution counter was used for counting the revolutions of the disc directly without relying on the electrical motor and the pulley arrangement, which might introduce some error in the speed evaluations due to the slip factor of the pulleys. To measure the time of the run an electronic timer, which is connected to the motor starter has been used. All these are shown on Figures 9 and 10.

## 2. Calibration of 'Pin and Disc' Machine for Friction Force Measurements

The above mentioned system was calibrated by using a cord of nylon, which can be attached to the free end of the horizontal arm carrying the specimen and supported by the disc as shown in Figure 11. The nylon cord was passed around a very small and frictionless pulley. A pan of known weight was attached to the other end of the cord. It is very important to notice that this nylon cord must be horizontal, otherwise a vertical force component could be generated during the calibration. The first step in this calibration was to balance the circuit before applying or adding any load to the pan attached to the arm. Then the loads were applied in 100g increments up to a load of 1500g. The horizontal arm must be freed from any restrictions, but the inclined spring plate which carries the bridge of the strain gauges. When applying the loads, this plate will bend due to a bending force resulting from the load applied. This will produce a compression force in the upper gauges and tensile forces in the lower gauges, thus throwing the bridge current out of balance. This will be in the form of mV output and this can be magnified by an amplifier and then recorded by rapid response recorder. The mV output from the strain gauges was recorded after each addition of load and the same procedure was repeated for a decreasing load increment. A graph of horizontal arm load versus strain gauge output was produced and then formulated into an equation which has been used in deriving the frictional forces during the tests.

Since the horizontal arm is supported by the disc during the calibration, a frictional force can be generated in this case. To avoid such a possibility, the disc was vibrated after each incremental load. In addition some of the zinc stearate lubricant powder was inserted between the pin and the disc to avoid any contact between them. The friction force can be measured in this way to an accuracy of ± 2.0%.

## 4.4 TEST PROCEDURE FOR WEAR MEASUREMENTS

1. Introduction: To study the wear of the compacts and the effect of the applied load, speed, sliding distance and density on this wear, the above pin and disc machine (with a crossed cylinder arrangement) was used as shown in Figure 12. An electronic

timer, tachometer and revolutions counter were attached to the machine. The experiments were carried out for compacts which had zinc stearate with differing contents and different densities as shown on Table 1 and 3. As has been indicated (in Section 4.2) the surface finish of the disc was measured after rubbing it against abrasive paper of 600 grade. This operation was repeated after each reading. The same disc was used for both wear and friction studies, using materials as described in Tables 1 and 2. Before each test the surface of the disc and the pin (specimen) were cleaned and washed by acetone. Then the pin was carefully lowered over the disc. After finishing the zinc stearate experiment, other lubricant stearates have been followed. No powdered metal stearate lubricants have been separately used to separate the two rubbing surfaces from the contact. To determine the volume of wear after each reading the specimen was taken to a travelling microscope and the small diameter of the wear scar on the specimen surface was measured. By using the following equation, the volume of wear can be obtained:

$$V = \frac{\pi\ a^4\ \sqrt{R}}{64\ r\ \sqrt{r}} \qquad (37)$$

where: a = small diameter of the wear scar on the specimen surface as shown in Figure 12; R = radius of the disc; r = radius of the compact.

Full derivation of this equation is shown in the appendices.

Each of the experiments was repeated twice, and sometimes the experiments were repeated three times, depending on the situation and the result. The reasons for this will be discussed in Chapter 7. The value of the wear rate was always calculated by the computer. Sometimes, where it was necessary, photographs which show the surface topography of these scars were taken by scanning electron microscopy.

From Archard's wear equation (2):

$$V = Z. \frac{W.X}{H}$$

The effects of the following factors on the wear volume V and wear rate have been studied:

i) Effect of load (w)
ii) Effect of distance of travel (x)
iii) Effect of speed (S)
iv) Effect of hardness (H) and density ($\rho$)

2. Effect of Load: To study the effect of load on pin and disc arrangement, the speed was fixed for all the experiments at 190 rpm, which is $6.0287 \times 10^3$ cm/min; and the travelling distance was fixed by fixing the time of every run to five minutes. The load can be applied by adding the increments to the hanger which is attached to the horizontal arm. The increments of the load were 300g. The range of the load was: 300 to 2700g. Thus, eight readings on each specimen were taken for zinc stearate lubricant and these have been repeated for two or more specimens. For the other lubricants, it was not the same, only five readings were taken and the increments were

600g. The reason for that is the wide range of the lubricants, lubricants ratios and densities which have been examined.

When the value of the small diameter of the wear scar was obtained, then the value of the volume of wear and the wear rate can be obtained. Examinations of the wear scar surfaces were made by SEM where it was necessary.

3. Effect of Sliding Distance: The same arrangement which was used in the last section were used in this study. The speed was constant for all the experiments at $6.0287 \times 10^3$ cm/min, and the load was kept constant at 600g. The distance was varied between $3 \times 10^4$ and $28 \times 10^4$ cm. The increment steps were $3 \times 10^4$ cm. Nine readings were taken on zinc stearate compacts. The increment steps for the other lubricants were $6 \times 10^4$ cm and only five readings were taken for every compact. All the experiments have been repeated two or three times depending on the results. The compact and the disc surfaces were cleaned and washed before and after each reading. The surface of the disc was restored by rubbing with 600 grade polishing paper to remove the scar of the previous experiment. The volume of wear and the wear rate have been calculated in the same way as in the last section. SEM examinations for the scar surfaces of the disc and the compact were obtained where necessary.

4. Effect of Speed: The pin and disc arrangement which has been described before, was used in these experiments to study the effect of speed on the volume of wear and the wear rate. The load was kept

constant for all experiments at 600g. The running time for each reading was constant as well at 2 minutes for each reading. The speed variation used is shown in the following table:

For zinc stearates

| Reading | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Speed x $10^3$ cm/min | 6.0287 | 7.6152 | 10.1536 | 15.2304 | 18.2765 | 22.8457 | 30.4609 |

Seven readings were taken for zinc stearate and for the rest of the lubricants the readings were only four as follows:

For all lubricants

| Readings | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Speed x $10^3$ cm/min | 6.0287 | 10.1536 | 18.2765 | 30.4609 |

All these experiments have been repeated two or three times depending on the results. After each reading the surface of the disc was polished by 600 grade polishing paper, cleaned and washed by acetone liquid. The surface of the compact was washed after each reading. SEM examinations for the surfaces were carried out where necessary. The volume of wear and the wear rate were calculated as it has been indicated before.

5. Effects of Density and Hardness: These effects have been derived from the experiments which have been done to study the effects of load, speed and sliding distance which have been described above. All the readings have been taken for constant load and speed, or load and sliding distance, or speed and sliding distance. The constant load, speed and sliding distance were as follows:

load = 600g

speed = $6.0287 \times 10^3$ cm/min

sliding distance = $3 \times 10^4$ cm

There are three compact densities used in these studies; these are: 6.3, 6.5 and 6.8g $cm^{-3}$, for each type of lubricant. Hardness measurements were obtained for lubricants at each density level.

6. Effect of Other Factors: Effects of other factors, such as lubricant ratio and lubricant type, on the volume of wear and the wear rate were derived from determinations obtained in the above experiments.

## 4.5 TEST PROCEDURE FOR FRICTION FORCE MEASUREMENTS

Before starting the experiments, the surface finish of the disc was measured after polishing it with grinding paper of 600 grade. The surface of this disc was repolished by using this method after every run.

The measurements of the disc surface finish were carried out by using the "Talysurf", and the replica technique; these measurements were taken before fixing the disc on the pin and disc machine.

The disc was made from the same materials as the die i.e. a high carbon-high chromium die steel, and it had a diameter of 101.0 mm. The compacts tested on the pin and disc apparatus had diameters of 25 mm and thicknesses of about 9 mm. The surface finishes of these compacts (or "pins") were not measured using a Talysurf because of their high roughness due to their surface porosity. Scanning electron microscopy was used for the scars surface topography. The pin was mounted in the pin holder on the horizontal arm in a position to give a crossed cylinders relationship between the disc and the pin as shown in Figures 10 and 12. The two surfaces of the pin and the disc were thoroughly cleaned and washed by using acetone. Then the pin was very carefully lowered over the disc. The loads between the compact (the pin) and the disc were added using the appropriate weights to the hanger which is supported by the horizontal arm as shown in Figure 10. In these experiments, the applied load was varied between 300 and 2400g. Before the test was carried out, the horizontal arm was released from its spring retaining clamps, the strain gauges and the recorder adjusted to zero, and then the test was started. The running time of each experiment was 3 minutes for each reading. No powdered metal stearate lubricants were used to separate the two surfaces of the pin and the disc.

Three compact densities have been used in our experiments and different ratios of lubricants have been admixed in these compacts. Several types of powdered metal stearate lubricants have been used as well. All of these can be shown in Tables 1 and 3. By using one of this range of compacts, it is possible to study the effect of the density, the lubricant ratio and the types of lubricant; in addition to the effect of load on the friction force and on the coefficient of friction. Only one speed has been used in this work which was $6.02872 \times 10^3$ cm/min (190 rpm). The load was varied between 300 and 2400g, by increments of 300g. Readings were repeated for four compacts and an average value of friction force was derived for each increment of load.

## 4.6 MEASUREMENTS OF HARDNESS OF PINS/COMPACTS

1. Hardness Machines: A number of methods and machines can be used to study the hardness of metals. The most accurate apparatus for this purpose is Vickers Hardness Machine. The principles of all these machines are similar. They depend on penetrating the surfaces and measuring the dimensions of the impression, so that the hardness can be obtained. For our case the optical microscope microhardness technique cannot be used due to the porosity of the compact. Hence the Vickers diamond pyramid hardness tester was used.

2. General Description of the Tester: The Vickers pyramid hardness testing machine provides a simple and accurate method of studying the hardness. A general view of this machine is shown in Figure 13. Figure 14 gives the general arrangement of the apparatus. It works

by using calibrated weights acting through the medium of a simple lever system. As shown in Figure 14, the weight rod is loaded with 15 kg weight which is sufficient for the compacts. The surface to be tested is placed under a square-based pyramid diamond indenter with an included angle between opposide facets of $136^{0}$. This diamond is attached to the machine, and the distance between the diamond and the specimen can be adjusted by raising or lowering the table which carries the jig with the specimen. This can be watched by a microscope fixed on the machine. The table which carries the jig is movable to the left, right, backwards and forwards for easy adjustment. To load the machine the pedal should be depressed as shown in Figure 14, then the load will be automatically applied, maintained and released in a set time. To measure the impression the dimensions of the indentation, the attached microscope with accuracy of about ± 0.01 mm is used.

3. <u>Procedure for Hardness Tests</u>: Before doing the test, the compact was cleaned and washed by acetone. Then it was placed on the jig on the movable table of the machine. Then the distance between the indenter and the compact was adjusted and the machine was loaded. A very small impression was made on the compact surface by the diamond indenter as shown in Figure 15. The dimensions of this impression are then measured by the optical micrometer in the microscope on the machine, and the hardness determined, by referring to the appropriate tables. These tables have been set by the manufacturer and have been calculated with accordance to the following formula:

$$\text{Hardness} = \frac{\text{Load}}{\text{Impressed Area}}$$

The hardness distribution on both surfaces of the compact have been examined, Figure 16. Twenty readings were taken on surface 1 of the cylinder and ten readings were taken on surface 2 for each specimen. The experiments were repeated on four specimens and average value was calculated.

All the hardness experiments were carried out on the compacts which contained zinc stearate lubricant only. No experiments were done on the other compacts containing the other lubricants. Hardnesses were determined on the compacts having the following specifications:

| Lubricant Ratio for Zinc Stearate | Density g/cm$^3$ | | |
|---|---|---|---|
| 0.005 or 0.5 wt% | 6.3 | 6.5 | 6.8 |
| 0.010 or 1.0 wt% | 6.3 | 6.5 | 6.8 |
| 0.015 or 1.5 wt% | 6.3 | 6.5 | 6.8 |

The effects of density and lubricant ratios on the hardness distribution were also derived from these experiments.

## 4.7 OTHER MACHINES USED IN THIS RESEARCH

1. Travelling Microscope: This microscope has been used in this research to measure the dimensions of the wear scars on the specimen surface, which have been produced during the wear experiments.

These dimensions were used to determine the volumes of wear. The magnification which was used in this work is X10. For example, to measure the small diameter of the wear scar, the compact was held by a small jig placed on the table of the microscope under the objective lens. By moving the lens to each end of the small diameter of the wear scar, the dimension of this diameter can be obtained from a scale attached to the microscope. The accuracy of this scale is ±0.01 mm; see Figure 17 which shows a general view of this microscope.

2. The Balance: This balance was used to determine the values of the compact densities.

The capacity of this balance is up to 100g and could be read to five numbers after the decimal point, so that it had the accuracy of ±0.01 mg. The balance can be easily adjusted, levelled and its pan must be cleaned before the operation takes place. Any heat and dust will affect the accuracy of the balance, so it must always be checked before each weighing. When weighing the compacts, the door of the pan chamber must be closed to prevent any dust or air which may affect its operation. Any vibrations will affect its accuracy. Before weighing the compact, it was cleaned from "flash" around the edges and washed (to remove any unwanted particles on the compact) by acetone and dried by hot air drier. The operation has to be repeated a number of times to obtain accurate values. Figure 18 shows a general view of this balance.

3. The Powder Mixer: This is a double cone container rotated by a motor at about 40 rpm. Its capacity is around 5 kg at its maximum load. Figure 19 shows a general view of this pilot scale powder mixer.

The powders to be mixed are poured inside the container and the lid locked by three screws to prevent any leaking. The mixing time depends on some factors such as the amount of the mixture, the powder type and the particle size of the powder. For this work the mixing time was standardised at 1 hour, which is sufficient for this type of mixing machine.

4. Disc Centrifuge with Photosedimentometer: It is an apparatus for measuring the particle size of the lubricant powder. As shown in Figure 20, it works on the centrifugal force principle. It uses the buffered line start, or two layer technique, whereby a small volume (usually 0.5 ml) of 0.5 to 2.5 per cent solids dispersion is introduced via an entry port into the disc cavity to lie on top of a known volume of spin fluid or fill. This fluid has a higher mean density to prevent mixing. The interface between the sample and the fill is buffered by a layer which is then partially mixed with the fill. This technique is called the Buffered Line Start.

The particles in the dispersion will start to settle at a rate determined by their size. Particle settling is described by Stoke's equation:

$$T = \frac{6.299 \times 10^9 . n}{d^2 . N^2 . \rho} \log_{10} \frac{R_2}{R_1}$$

where: T = centrifuge time in minutes; d = particle size in microns; N = centrifuge speed (rpm); $\rho$ = density difference between particles and spin fluid in g/ml; n = spin fluid viscosity in poise; $R_2$ = radius to which a particle size (d) settles under the given conditions from a radius $R_1$; $R_1$ = starting radius of particles determined by the volume of spin fluid used in the rotor.

The accuracy of the apparatus is about 2%, and it is fully automatic.

# CHAPTER 5

# PRESENTATION OF RESULTS ON WEAR STUDIES

5.1 RAW MATERIALS

1. Iron Powder Properties
2. Lubricant Properties
3. Pin and Disc Apparatus
   a) Disc material
   b) The compacts (or wear pins) for pin and disc apparatus
   c) Surface topography of compacts

5.2 HARDNESS TESTS ON COMPACTS (OR WEAR PINS)

1. The Axial Surface
2. The Diametrical Surface
3. Interpretation of Hardness Results

5.3 WEAR STUDIES

1. Effect of Applied Load
   a) Zinc stearate studies
   b) Other stearate studies
   c) Wear scars in load studies
2. Effect of Speed
   a) Zinc stearate studies
   b) Other stearate studies
   c) Wear scars in speed studies
3. Effect of Sliding Distance
   a) Zinc stearate studies
   b) Other stearate studies
   c) Wear scars in distance studies

4. Effect of Hardness
    a) Hardness and load
    b) Hardness and speed
    c) Hardness and distance
5. Effect of Density on Variables
6. The Wear Rate
    a) Effect of density on wear rate
    b) Effect of lubricant content on wear rate
    c) Comparison of wear rates with density for different lubricants

# CHAPTER 5

# PRESENTATION OF RESULTS ON WEAR STUDIES

## 5.1 RAW MATERIALS

1. Iron Powder Properties: This work has been designed to be carried out on compacts made from iron powders. One type of iron powder has been selected for this purpose, Hoganas ASC 100.29 atomised iron powder.

The properties of this type of iron powder such as the values of apparent density, tapped density, flow and screen analyses are as indicated in Table 2.

Since the surface characteristics of the iron powder particles play very important part in the wear and friction behaviour of this powder, the iron powder particle surfaces have been examined by using the Scanning Electron Microscope (SEM); Figure 21 shows a typical sample of this grade of Hoganas Iron Powder.

2. Lubricant Properties: Five solid lubricants have been used in this research as admixed lubricants. They were: zinc stearate precipitated; calcium stearate precipitated; magnesium stearate precipitated; aluminium stearate 22, and sodium stearate fused. These five lubricants were mixed separately with Hoganas iron powder to produce a mixture for making the compacts or wear pins. Different contents of these lubricants were used as indicated in Table 1.

The properties of these lubricants were taken with accordance of the producer (Witco Co) data sheets and shown in Table 3, together with the lubricant contents which have been considered.

Figure 22 shows the curves of the particle size distributions for these five stearates versus their weight under size.

Figures 23 and 24 show photographs of the particles of these solid lubricants taken on the Scanning Electron Microscope. Mixtures with each stearate were examined under the optical microscope. The effects of mixing on each one are recorded in Figures 27 and 28. Figure 27 shows the iron powder and stearates after mixing at 1 wt% lubricant addition. Figure 28 shows zinc stearate after mixing with iron powder at levels of 0.5, 1.0 and 1.5 wt% contents.

## 3. Pin and Disc Apparatus:

a) Disc material: As it has been indicated in Chapter 4, the machine which was used in carrying out the experiments of this research was a "Pin and Disc Machine".

The disc was made from the same material as the die which was used in producing the compacts needed to carry out this work. This material is in fact one of the most used die materials in powder metallurgy industries. This material is high carbon, high chromium die steel which has a hardness of about 850 VHN. The surface topography of this disc had been examined before starting the test by using a Talysurf apparatus, the results of these examinations are shown in Figure 25.

Another examination for the surface topography of the disc has been carried out by using a replica technique. The results of the replica studies are shown in the photographs from the Transmission Electron Microscope in Figure 26.

The surface topography of the disc has also been examined in some cases after the test. This examination was also carried out by using the replica tecnnique and the Transmission Electron Microscope. These examinations were done after the wear experiments were completed. The results of these examinations were inconclusive since no complete replica could be made.

b) The compacts (or "wear pins") for pin and disc apparatus: These were all made with the Hoganas ASC 100.29 iron powder (Table 2). These were mixed with the various stearates as explained in Table 1, where the range of densities and lubricant contents are tabulated. It can be seen that for all the stearates, except the calcium stearate, 3 density levels were used: 6.3, 6.5 and 6.8 g/cm$^3$. For calcium stearate only, results for five density levels were possible: 5.5, 5.9, 6.3, 6.5 and 6.8 g/cm$^3$.

c) Surface topography of compacts: Figures 29 and 30 show typical surfaces of the compacts used in this research. Figure 29(a) and (b) shows the surfaces of compacts made with 1 wt% calcium stearate and the iron powder for each of the five densities 5·5 - 6.8 g/cm$^3$ for two magnifications X450 (Figure 29(a)) and X180 (Figure 29(b)).

Figure 30 compares the surfaces of compacts made with 1 wt% of each of the stearates and iron powder compacted to a density of 6.5 g/cm$^3$. Again, two magnifications are given, X180 (Figure 30(a)) and X450 (Figure 30(b)).

## 5.2 HARDNESS TESTS ON COMPACTS (OR WEAR PINS)

These tests were carried out to study the hardness distributions on the cylindrical (or axial) and the flat (or diametrical) surfaces of the compacts. Compacts with zinc stearate as admixed lubricant were used for this purpose. The compacts which were examined had three levels of densities: 6.3, 6.5 and 6.8 g/cm$^3$. The lubricant contents for these compacts were: 0.5, 1.0 and 1.5 wt%.

1. The Axial Surface: As shown on Figure 31(a) the axial surfaces of the compacts were examined. Ten readings were taken on each compact. The test was repeated four times for four specimens, then an average value was obtained.

The results of the hardness tests for these axial surfaces are recorded as follows. Figures 32-34 and Tables 4-12 show the hardness distributions on the axial surfaces for compacts with the three levels of zinc stearate content and three density levels.

Because of difficulty in understanding these results of this research, the above values (from Tables 4-12) have also been replotted in Figures 35-37, where the information has been gathered under the different density levels as opposed to the lubricant contents given in Figures 32-34.

2. The Diametrical Surface: These results are given in Tables 13-21 and are plotted in Figures 38-40 in the same manner as the axial hardness studies in Section 5.2.1 above. As before the results are compacted under the 3 levels of zinc stearate contents in Figures 38-40 and under the 3 levels of density in Figures 41-43.

3. Interpretation of Hardness Results: The relationship between axial hardness and density is shown in Figure 44, where average values (see Tables 22 and 24) from the previous results above are plotted for the 3 levels of lubricant content (or ratio). Figure 45 shows the same results replotted to show the relationship between axial hardness and lubricant content (or ratio) for the 3 density loads.

Exactly similar results for the diametrical hardness values are shown in Figures 46 and 47, which use the results recorded in Tables 23 and 25.

## 5.3 WEAR STUDIES

Wear experiments on the iron powder compacts described in Sections 5.2 and 5.3 were carried out. These studies included the study of the effect of normal applied load, sliding speed, sliding distance, the density and the hardness on the wear behaviour of these compacts.

The results of these studies were stored in tables and plotted in graphs as follows.

1. <u>Effect of Applied Load</u>: When studying the effect of applied load on the wear behaviour of the compacts, the sliding speed was always constant and had a value of $6.0287 \times 10^3$ cm/min. A constant value of $3.0144 \times 10^4$ cm of sliding distance was considered between the readings. The applied load was varied in the range of 300 to 3000g.

Experiments on compacts with zinc stearate lubricant to be considered first.

a) <u>Zinc stearate studies</u>: Figures 48-50 show the variation of wear volume with load for the 3 lubricant levels of 0.5, 1.0 and 1.5 wt% zinc stearate for the 3 densities considered. These results come from Tables 26-28. For comparison these same results are plotted in Figures 51-53 for each of the densities: 6.3, 6.5 and 6.8 g/cm$^3$ respectively.

b) <u>Other stearate studies:</u> Figures 54-56 show the variation of wear volume with load at the 3 density levels respectively. These Figures compare each lubricant at the 1 wt% content. The results used are recorded in Tables 29-34. The data from these Tables is plotted again in Figures 57-60, where each lubricant is shown separately and compared with values for the different densities.

c) <u>Wear scars in load studies:</u> Although wear scars were examined for most of these studies, those scars for zinc stearate only are recorded here. These are shown in Figure 61 where the scars under loads of 600, 1200 and 2400g are shown at two magnifications X180 (Figure 61(a)) and X450 (Figure 61(b)).

2. Effect of Speed: In experiments to study the effect of speed on the volume of wear, constant values of running time and applied load were used: these were 2 minutes and 600g respectively.

Compacts with different densities, lubricant types and contents were examined in these experiments.

a) Zinc stearate studies: The 3 lubricant contents studied were 0.5, 1.0 and 1.5 wt%, the results for these trials are given in Figures 62-64 where only the wear volume results for the densities 6.3 and 6.5 g/cm$^3$ are shown against speed.

Because the wear volumes for the high density compacts (6.8 g/cm$^3$) were higher than the results described above (Figures 62-64), these were replotted separately for each of the 3 densities in Figure 64 (6.3 g/cm$^3$), Figure 66 (6.5 g/cm$^3$) and Figure 67 (6.8 g/cm$^3$).

All of these values are recorded in Tables 35 and 36.

b) Other stearate studies: Each of the 4 remaining stearates were studied at 1 wt% content, and for each of the 3 densities. The results of these studies are shown in Figure 68 (calcium stearate), Figure 69 (sodium stearate), Figure 70 (magnesium stearate) and Figure 71 (aluminium stearate). These results are taken from Table 37-40.

Comparison of wear volumes for differing speeds were made from the above results, and these comparisons are shown in Figures 72-74 for each of the 3 densities.

c) Wear scars in speed studies: Wear scars for these trials were examined on the SEM for each run. Typical scars are shown in SEM photographs in Figure 75 for trials with 1 wt% zinc stearate after runs at speeds of 6,029, 15,230 and 30,461 cm/min. Two magnifications are shown, X180 (Figure 75(a)) and X450 (Figure 75(b)).

3. Effect of Sliding Distance: Trials to determine the variation of wear volumes with distance were carried out for one speed of 6029 cm/min under a load of 600g.

Compacts with different densities, lubricant types and contents were examined in these experiments.

a) Zinc stearate studies: Figures 76-78 show the variation of the wear volume with sliding distance for the 3 lubricant contents of 0.5, 1.0 and 1.5 wt% zinc stearate. Each Figure compares the results for the 3 density levels. The full set of results are recorded in Tables 41-43.

Again for comparison purposes, these results are replotted in Figures 79-81 for each of the density levels, so that the effect of lubricant content for a given density can be seen.

b) Other stearate studies: Each of the remaining lubricants were studied at 1 wt% content, and for each of the 3 densities, except for calcium stearate, in which case it was possible to determine results for 4 densities. These results are plotted in Figure 82 (calcium stearate), Figure 83 (aluminium stearate), Figure 84 (magnesium stearate) and Figure 85 (sodium stearate). These results are recorded in Tables 44-47.

Comparisons of wear volumes for differing distances were made from the above results, and these comparisons are shown in Figures 86-88 for each of the 3 densities.

c) Wear scars in distance studies: As before, wear scars were examined on the SEM for these runs. A typical set of wear scars are shown in the SEM photographs in Figure 89 for trials with 1 wt% zinc stearate after runs for the distances of 60,287, 150,718 and 241,149 cm.

## 4. Effect of Hardness:

a) Hardness and Load: Tables 48 and 49 show results of volume of wear variations with hardness and 2 loads: 600 and 1200g. For these studies, results at a constant distance of 30,144 cm, a constant speed of 6029 cm/min and a lubricant content of 1 wt% for each stearate were chosen. These values are plotted in Figure 90 (for 600g load) and Figure 91 (for 1200g load).

b) Hardness and Speed: A similar set of results are gathered in Tables 50 and 51, where the main variation is speed. Two speeds of 6029 and 18,000 cm/min are shown. These values are plotted in Figures 92 and 93 respectively.

c) Hardness and distance: Another set of results are gathered in a similar manner, where the main variation is distance. Two distances were chosen, 30,144 and 150,718 cm. These results are given in Tables 52 and 53, and plotted in Figures 94 and 95, respectively.

5. Effect of Density on Variables: Again because of the complexity and number of variables in this research, the results recorded in Tables 48-53 have been re-examined and plotted in a slightly different way in Figures 96-101. Here the effect of density on the variables: load (Figures 96 and 97); speed (Figures 98 and 99) and distance (Figures 100 and 101), are examined.

6. The Wear Rate: Wear rate can be described as the volume of wear for each unit of the variables. For example if the sliding distance is to be considered, then the measuring unit for distance: cm will be used. In this case the wear rate will be the volume of wear for each cm, i.e:

$$W.R_d = \frac{\text{Volume of wear}}{\text{Sliding distance}} = \frac{\text{mm}^3}{\text{cm}} \qquad (i)$$

The same procedure is followed if the applied load or sliding speed are considered i.e:

$$W.R_L = \frac{\text{Volume of wear}}{\text{Applied load}} = \frac{mm^3}{g} \qquad \text{(ii)}$$

and

$$W.R_S = \frac{\text{Volume of wear}}{\text{Sliding speed}} = \frac{mm^3}{cm/min} \qquad \text{(iii)}$$

Furthermore, the wear rate is in fact the slope of the curve of volume of wear versus sliding distance or applied load or sliding speed. So that the values of the wear rate for every curve of wear studies can be easily obtained.

For accuracy purposes these values of wear rates for all the wear volume curves have been obtained by using the computer. These values have been plotted in tables and graphs and have been drawn from these values.

One value of wear rate has been taken for each curve, some variations in the values of wear rate have been noticed when changing other factors. For example, if we take a compact which has a lubricant content of 1 wt%, and if the values of the load and speed were constant (i.e. if we take the case of volume of wear versus sliding distance as in equation (i)) then the wear rate will have a fixed value; but if the ratio of the lubricant has changed, then the value of the wear rate will be changed also.

The effect of compact density variations and the solid stearate lubricant content variations on the value of the wear rate have been examined and the results have been plotted in the tables and graphs as follows.

a) Effect of density on wear rate: Wear rates have been calculated from zinc stearate trials where the following factors have been varied: load, speed and distance. The results of these calculations are given in Tables 54-56.

Wear Rates from Load Studies are plotted from these Tables in Figure 102.

Wear Rates from Speed Studies are plotted in Figure 103.

Wear Rates from Distance Studies are plotted in Figure 104.

b) Effect of lubricant content on wear rate: From Tables 54-56 it is possible to extract the changes in wear rate with the zinc stearate content change for the 3 densities considered.

Wear Rates from Load Studies are plotted in Figure 105.

Wear Rates from Speed Studies are plotted in Figure 106.

Wear Rates from Distance Studies are plotted in Figure 107.

c) Comparison of wear rates with density for different lubricants: As above in paragraphs (a) and (b), wear rates for each lubricant (at 1 wt% content) have been calculated from the 3 areas of study and are plotted as follows:

Wear Rates from Load Studies: Figure 108

Wear Rates from Speed Studies: Figure 109

Wear Rates from Distance Studies: Figure 110.

# CHAPTER 6

# PRESENTATION OF RESULTS ON FRICTION STUDIES

## 6.1 FRICTION MEASUREMENTS

1. Calibration of "Pin and Disc" Machine
2. Measurement of Friction Force
3. The Coefficient of Friction
   a) Static friction coefficient
   b) Kinetic friction coefficient
4. Effect of Time on Coefficient of Friction
5. Effect of Density on Coefficient of Friction
6. Effect of Hardness on Coefficient of Friction

# CHAPTER 6

# PRESENTATION OF RESULTS ON FRICTION STUDIES

## 6.1 FRICTION MEASUREMENTS

These measurements were carried out on the "Pin and Disc" machine. Compacts were used as before as friction (or wear) pins. The five types of stearate lubricant were examined were pressed with the Hoganas iron powder into compacts of varying density, but with a fixed lubricant content of 1 wt%.

As before the density range was as follows: 6.3, 6.5 and 6.8 g/cm$^3$. One exception was for calcium stearate, where results for 5 densities were measured. These values of density were as follows: 5.5, 5.9, 6.3, 6.5 and 6.8 g/cm$^3$.

1. Calibration of "Pin and Disc" Machine: As explained in Chapter 4, the friction pins (or compacts) were operated in a crossed cylinder mode. The calibration procedure is described in Section 4.3.2 and the calibration graph is shown in Figure 111 and the results tabulated in Table 57. These show the mV output of the strain gauges produced by the applied horizontal force. Each value presented here is the average of six separate determinations.

2. Measurements of Friction Forces: Preliminary investigations showed that the friction force varied with time during a run. For this reason it was decided to carry out a series of friction force measurements over a period of 60 seconds.

Furthermore, because of the large number of possible variables and the exceedingly large number of results possible, it was also decided to keep the following variables constant:

Speed: 6029 cm/min

Distance: 18086 cm

Lubricant content: 1.0 wt%

Only the type of lubricant and the density (at 3 or 5 levels) were varied with applied load.

The results for zinc stearate in compacts with a density of 6.3 g/cm$^3$ are presented in Tables 58-64, where it can be seen that the time intervals chosen for study were: 1, 5, 10, 20, 40, 50 and 60 seconds.

Study of these Tables showed that the most important times were below 15 seconds. This would be within the limits of a normal industrial pressing operation, so that no useful information could be obtained by the study of friction for longer times.

Results for 3 time stages are given in the following Figures, Figure 112 (1 second reading), Figure 113 (5 second reading) and Figure 114 (15 second reading).

For the other 2 density levels, Tables 65-71 give the same type of data for zinc stearate compacts with density 6.5 g/cm$^3$; and Tables 72-78 give corresponding data for compacts of density 6.8 g/cm3. These results were not plotted and are not presented here.

The results for other lubricants were dealt with in exactly the same manner, details are as follows:

| | | | | | |
|---|---|---|---|---|---|
| Aluminium Stearate: | Density | 6.3 | g/cm$^3$ | Tables | 79- 85 |
| | " | 6.5 | " | Tables | 86- 92 |
| | " | 6.8 | " | Tables | 93- 99 |
| Calcium stearate: | Density | 5.5 | g/cm$^3$ | Tables | 100-106 |
| | " | 5.9 | " | Tables | 107-113 |
| | " | 6.3 | " | Tables | 114-120 |
| | " | 6.5 | " | Tables | 121-127 |
| | " | 6.8 | " | Tables | 128-134 |
| Magnesium Stearate: | Density | 6.3 | g/cm$^3$ | Tables | 135-141 |
| | " | 6.5 | " | Tables | 142-148 |
| | " | 6.8 | " | Tables | 149-155 |
| Sodium Stearate: | Density | 6.3 | g/cm$^3$ | Tables | 156-163 |
| | " | 6.5 | " | Tables | 164-169 |
| | " | 6.8 | " | Tables | 170-176 |

Since friction force of itself is not important alone, it is only useful if taken with the applied load to calculate the coefficient of friction $\mu$. Therefore no further graphs were plotted from the friction force data in the Tables 58-176.

3. The Coefficient of Friction: From the information in Tables 58-176 it is possible to calculate the coefficient of friction $\mu$ from details of the applied load and the measurements of the friction force as follows.

$$\mu = \frac{\text{Friction force}}{\text{Applied load}} = \frac{F}{W}$$

Values of $\mu$ have been calculated and are presented in Tables 58-176.

Each set of $\mu$ values for each time period were plotted for each stearate in Figures 115-135. For each of the times: 1, 5, 10, 20, 40, 50 and 60 seconds, there are 3 graphs, one for each of the 3 density levels: 6.3, 6.5, 6.8 g/cm$^3$. Study of these figures show that $\mu$ does appear to vary with time. Hence, in determining the value of $\mu$ for industrial purposes the time of sliding must be considered.

a) Static friction coefficient: In this research, the "static" value of $\mu$ is taken as that value determined after 1 second of sliding. These results for the 5 stearates are presented for each density level in the following Figures: Figure 115 (6.3 g/cm$^3$); Figure 116 (6.5 g/cm$^3$) and Figure 117 (6.8 g/cm$^3$).

b) Kinetic friction coefficient: For periods greater than 1 second, it is considered here that the values of $\mu$ determined are "kinetic" values. These values are presented, as explained in (a) above for each of the 3 densities as follows:

| Sliding period: | | |
|---|---|---|
| | 5 seconds: | Figures 118-120 |
| | 10 seconds: | Figures 121-123 |
| | 20 seconds: | Figures 124-126 |
| | 40 seconds: | Figures 127-129 |

| | |
|---|---|
| 50 seconds: | Figures 130-132 |
| 60 seconds: | Figures 133-135 |

4. <u>Effect of Time on Coefficient of Friction</u>: Because of the large amount of experimental work involved in this research, unfortunately time was not available to carry out a complete study here.

However, it was possible to make a full study for calcium stearate alone at 5 density levels. Values determined in this study are gathered together in Table 177.

From this table, values of μ for each of the 5 densities are plotted against time for periods up to 120 seconds. These plots can be seen in Figures 136-140.

5. <u>Effect of Density on Coefficient of Friction:</u> Again because of limited time only 3 periods, namely 1, 5 and 30 seconds were studied here. Calcium stearate only was examined with the variation of density (or hardness). These results are recorded in Tables 178-180. Values from these Tables are plotted in Figures 141-143, which show the variation of <u>coefficient of friction</u> with <u>density</u>.

6. <u>Effect of Hardness on Coefficient of Friction</u>: From Tables 141-143, it is possible to plot the variation of <u>hardness</u> with the <u>coefficient of friction.</u> These plots are shown in Figures 144-146.

# CHAPTER 7

# DISCUSSION OF RESULTS ON WEAR STUDIES

7.1 MATERIALS CHARACTERISTICS

1. Iron Powder
2. Stearate Lubricants
3. Disc Material

7.2 HARDNESS MEASUREMENTS ON COMPACTS OF IRON POWDER AND ZINC STEARATE

1. Hardness Distribution Axially
2. Hardness Distribution Diametrically
3. Summaries of Hardness Results

7.3 EFFECT OF APPLIED LOAD ON WEAR VOLUME

1. Density Effect for Zinc Stearate
2. Lubricant Content Effect for Zinc Stearate
3. Comparison of Stearates

7.4 EFFECT OF SLIDING SPEED ON WEAR VOLUME

1. Density Effect for Zinc Stearate
2. Lubricant Content Effect for Zinc Stearate
3. Comparison of Stearates

7.5 EFFECT OF SLIDING DISTANCE ON WEAR VOLUME

1. Density Effect for Zinc Stearate
2. Lubricant Content Effect for Zinc Stearate
3. Comparison of Stearates

7.6 EFFECT OF HARDNESS ON WEAR VOLUME

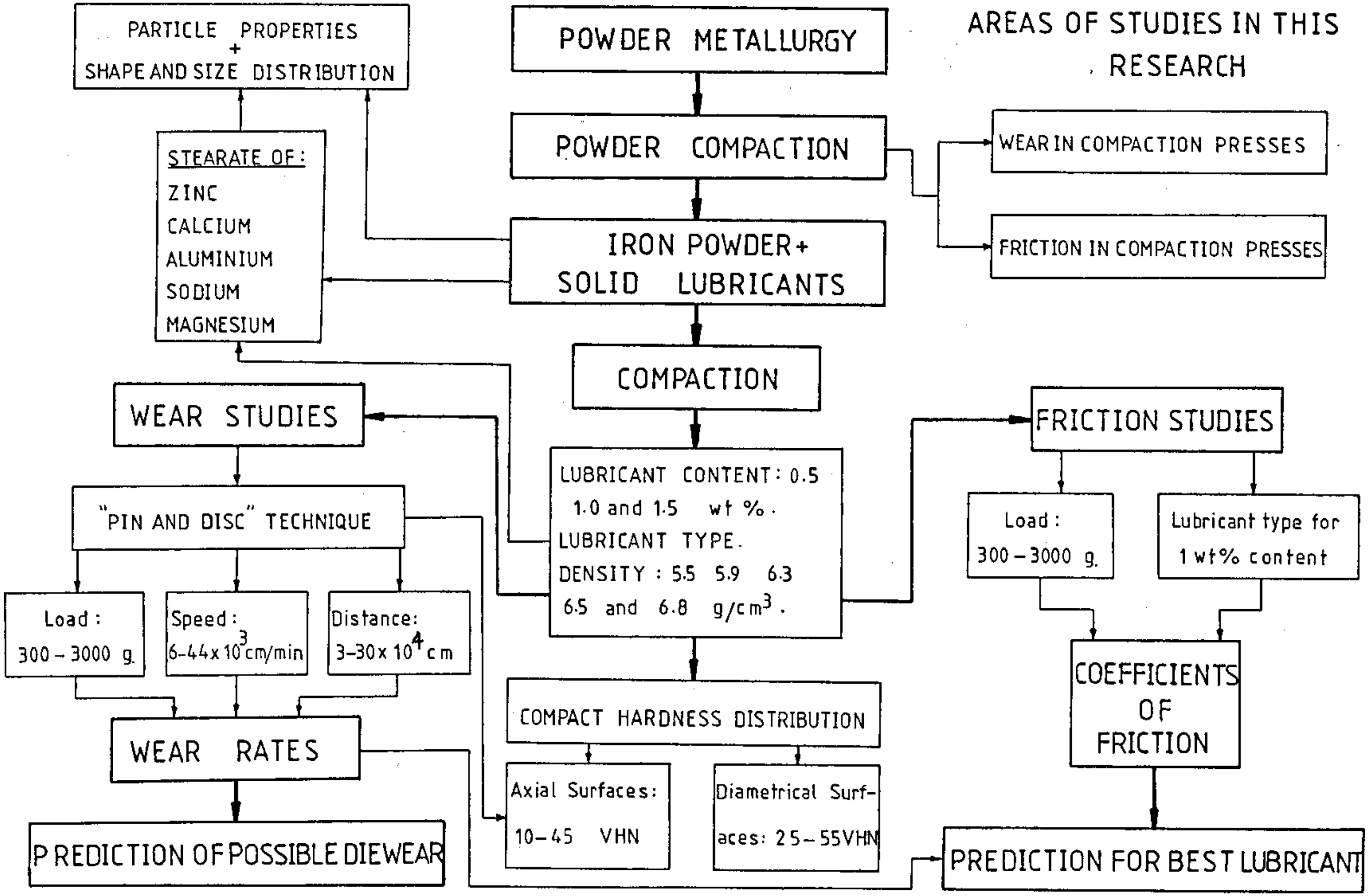
1. Hardness and Load Effects
2. Hardness and Speed Effects
3. Hardness and Distance Effects
4. Density Effects

7.7 WEAR RATE STUDIES

1. Density and Wear Rate
2. Lubricant Level and Wear Rate
3. Comparison of Lubricants and Wear Rates

7.8 CALCULATIONS ON POSSIBLE DIE LIFE FROM WEAR STUDIES

7.9 SUMMARY



AREAS OF STUDIES IN THIS RESEARCH

# CHAPTER 7

# DISCUSSION OF RESULTS ON WEAR STUDIES

## 7.1 MATERIALS CHARACTERISTICS

1. Iron Powder. From previous researches on iron powder[3], the Hoganas ASC 100.29 powder was chosen in preference to other similar powders, see Table 2 for comparisons.

This powder had a high apparent density and a good tapped density, hence it produced more dense compacts than the other powders compared in Table 2. These particular properties are partly due to the powder being produced by the atomisation technique. Examination of the SEM photographs in Figure 21 shows the typical appearance of such an atomised powder.

2. Stearate Lubricants. The range of lubricants used in this research were all from one manufacturer. This was done because it was thought that all the lubricants would then have a standard quality.

a) Density: The density values and other properties of the five stearate lubricants shown in Table 3, indicate that the most dense stearate is zinc stearate and the order of the other lubricants in decreasing density is as follows: zinc, calcium, magnesium, aluminium and sodium.
Zinc stearate is the lubricant most commonly used by the powder metallurgy industries for the compaction of iron

and other powders. As Table 3 shows, this stearate unfortunately also has a high ash content, so that the compacts sintered with this stearate will have a higher retention of lubricant residue than if other lubricants are used.

b) Particle Size: Figure 22 shows that all five lubricants have differing size distributions. The stearate with the finest particle size distribution is calcium and the others increase in the number of coarse particles in the following order:

calcium, magnesium, aluminium, zinc and sodium.

c) Particle Shape: Figures 23 and 24 give some idea of the various shapes of lubricant particles for each stearate. The differences in particle size from each type can be clearly seen and from these photographs the order in average particle size, from fine to coarse particles is in the following order:

calcium, magnesium, aluminium, zinc and sodium stearate.

This confirms the order already given by the particle size measurements shown in Figure 22.

3. Disc Material. The disc material was chosen to be the same as the die and punch material on the press used in this research and in commercial presses.

Figures 25 and 26 show the topography of this surface over which the compacts slide. It can be seen that these surfaces are not smooth but grooved by the polishing or lapping process before wear trials were started. These surfaces can be compared with Figures 61, 75 and 89, which show the surfaces of the compacts after wear against this type of surface. It is assumed that these disc surfaces are similar and comparable with die surfaces on production presses.

## 7.2 HARDNESS MEASUREMENTS ON COMPACTS OF IRON POWDER AND ZINC STEARATE

1. Hardness Distribution Axially. Figures 32-34 show that the compacts with the highest density, at each level of lubricant content, have the highest hardness as would be expected. Furthermore, it can be seen that the compact with the 0.5 wt% lubricant content gives the highest hardness levels, refer to Figures 35-37.

The distribution of hardness in the axial direction alters considerably as the density is increased, see Figure 32. For low levels of lubricant, e.g. 0.5 wt%, there is a distinct dip in the hardness at the centre of the compact. This effect is less distinct as the lubricant content increases. Compare Figures 32-34, and Figures 35-37.

These figures all indicate changes of density within a compact and these changes are to be expected as shown by previous researchers, see references 3, 4.

2. Hardness Distribution Diametrically. Figures 41-43 show a similar trend for these measurements. The lower level of lubricant (0.5 wt% zinc stearate) shows the highest overall hardness. This is due to the fact that the best compaction conditions are for this level of lubricant, see references 3 and 4.

These also show similar results for the effect of lubricant content on the hardness and its link with density. That is, for the three density levels, the compacts with the lowest lubricant content gave the highest hardness.

Examination of Figures 38-40 show these effects in a slightly different way.

Comparison of results in both axial and diametric directions for these compacts (see Figures 32-27 and compare with Figures 38-43) show that in general:

| | | |
|---|---|---|
| Axial direction, | range of hardness: | 20-45 VHN |
| Diametrical direction, | range of hardness: | 28-55 VHN |

Also examination of Figures 38-43, show that the variation of hardness for a given compact over that for the diameter to be similar to that for the axial direction, with minimum values in the centre of the compact. This effect is due to uneven compaction in the press[3,4].

For wear and friction studies only the results for the hardness in the axial direction are used. For these researches, an average hardness value was determined for each compact (or pin).

3. Summaries of Hardness Results. Using the averaged values of hardness, Figures 44 and 45 show the link between hardness, lubricant content and density in the axial directions.

Similarly, values for the diametrical direction are summarised in Figures 46 and 47. These results are used in the calculations involving wear and friction.

## 7.3 EFFECT OF APPLIED LOAD ON WEAR VOLUME

1. Density Effect for Zinc Stearate. Examination of Figures 48-50, show that the pins (or compacts) with the highest density (6.8 g/cm$^3$) give the highest wear volume over the range of loads (0-3 kg) studied. This is unexpected, as current wear theories would indicate that materials with a high hardness should give less wear. Furthermore, those compacts with a high level of lubricant, e.g. 1.5 wt%, have lower wear volume (see below). However, increasing the load in general, increases the wear volume.

2. Lubricant Content Effect for Zinc Stearate. Figures 51-53 illustrate this behaviour. There appears to be a critical load value, around 2 kg, above which the wear volume increases considerably. Figure 53 shows that those compacts with 1.5 wt% zinc stearate have a low wear volume. This effect is not shown for compacts under the same conditions which have lower densities.

For the densities of 6.3 and 6.5 g/cm$^3$ the results can be confusing for loads over 2 kg.

3. Comparison of Stearates. This was done using compacts with 1.0 wt lubricant content (or ratio) only. Figures 49 and 54-56 give these comparisons, which show that zinc and calcium stearates give the lowest wear volumes. In general, the highest wear volumes are seen with magnesium stearate.

Considering density, most of the lubricants give increased wear volume as the density of the compacts increases, as has already been indicated for zinc stearate (see above 7.31). This effect can be seen more clearly in Figures 57-60, where individual lubricants are assessed with their density levels.

This effect can be explained from the porosity (related to density) of the compacts, see Figure 29(a) and (b). Low density compacts will have more pores at the surface of the compact (or pin) in contact with the wear disc. This increase in pores at the surface allows more lubricant to be contained within them, hence low density (high porosity) compacts give lower wear volumes since the rubbing surfaces are more lubricated. The reverse is true for high density (low porosity) compacts.

However, for densities below 6.3 g/cm$^3$ (see Figures 29 and 57) it would appear that because of the low compaction pressure needed to form compacts at densities of 5.5 g/cm$^3$, the bonding of the particles is much weaker. Since these compacts are not sintered, the bonding relies only on the deformation of the particle mass on compaction. It would appear that in this case greater wear occurs due to the lower bonding within the compacts (or wear pins).

Sometimes the wear debris for low density compacts can be retained within the pores and therefore take no further part in the process. Whereas, for high density compacts, the wear debris can abrade further surfaces or be thrown clear, hence affecting the overall wear volume. Examination of Figures 61(a) and (b) show that for low loads the rubbing surfaces are free of debris. At high loads of around 2.4 kg, wear debris can be retained on the surface of the rubbing components. See Figure 61(a), which shows that for 2400g, the surface is very rough, possibly due to a torn surface or build-up of wear debris which is cold-welded to the compact surface have loosely compacted particles which can easily be broken.

## 7.4 EFFECT OF SLIDING SPEED ON WEAR VOLUME

1. Density Effect. This had a considerable influence on the wear volume for these speed studies. Figures 62-64 show that for levels of zinc stearate at or above 1.0 wt%, the higher density compacts had the greatest wear. For compacts of density 6.8 g/cm$^3$, the wear volumes were very high so that not all the determinations could be drawn on the same scale. Reference to Figure 67 shows this more clearly. Figures 63 and 64 indicate that above a speed of around 25,000 cm/min, the wear volume stabilises to a near constant value. This could be explained by the build up and maintenance of a lubricant/wear debris layer between the two sliding surfaces.

Furthermore, during the determinations at high speed, an oxide film (presumably $FeO/Fe_2O_3$) was seen within the wear scars.

Unfortunately, because compacts broke up at speeds over 30,000 cm/min, no further determinations could be made to elucidate this behaviour.

2. Lubricant Content Effect for Zinc Stearate. All three Figures 65-67 show that, below 15,000 cm/min, all the wear volumes are similar irrespective of density or lubricant content. However above this speed, particularly for the high density compacts (6.8 $g/cm^3$), the wear volumes increase considerably.

It would appear that the 6.8 $g/cm^3$ compacts are very susceptible to wear at speeds greater than 12,000 cm/min. It is suggested that for this latter situation, the build up of lubricant/ wear debris/oxide film (see Section 7.41) can occur at this density at high speed. Therefore continuous wear is seen, since fresh surfaces are being exposed throughout the run. At lower densities, this behaviour is masked by the higher porosity at the rubbing surface of the lower density compacts (or pins) as far as these few results show, see Figure 29.

3. Comparison of Stearates. The Figures 72 and 73 show that for densities below 6.8 $g/cm^3$, zinc stearate has the lowest wear rates at speeds below 20,000 cm/min for levels of 1.0 wt%. At higher speeds, magnesium stearate again has the highest wear volume.

For densities of 6.8 g/cm$^3$, Figure 74, zinc stearate shows unusual wear volumes at all speeds. No explanation for this is known at present, it could be that this set of compacts was unusual in some way; this point will have to be studied later in another project. However, neglecting the anomalous zinc stearate values, magnesium stearate again has the highest wear volume.

Figures 63 and 68-71 illustrate individual stearates and again show that the higher density give higher wear volumes than lower density ones.

In general, the overall conclusion for these results is that wear volumes increased with speed, as might be expected.

## 7.5 EFFECT OF SLIDING DISTANCE ON WEAR VOLUME

1. Density Effect for Zinc Stearate. The compacts with the highest density (6.8 g/cm$^3$) showed the highest wear volume, compare Figures 76-78. Again the lower density compacts, 6.3 and 6.5 g/cm$^3$ give very similar wear behaviour, that is low wear volumes which vary linearly with distance. This effect can be seen differently in Figures 79 and 80, whereas Figure 81 shows the dramatic change in behaviour for the high density compact.

2. Lubricant Content Effect for Zinc Stearate. Furthermore, the effect of change in lubricant content in Figures 79 and 80, are as would be expected, the increase in content from 0.5 to 1.5 wt%

gives an increase in wear volume. It is assumed that this might be due to the known decrease in compaction behaviour for materials pressed at lubricant levels beyond the optimum value of 0.5 wt%. The increase in lubricant content above this value causes a weakening effect in the compact due to reduced compaction.

Examination of Figures 29(a) and (b), demonstrates how the density of a compact controls the surface. There are considerable differences in surface topography between compacts with a density of 5.5 and 6.8 g/cm$^3$. It is noticeable also, that the surface of the compact with the highest density is very different from all the others, see Figures 29(a) and (b). It is this difference in surface character which appears to have such an effect on the wear measurements, as already reported in past sections (see Sections 7.31 and 7.32). This difference in surface would also explain the results of Figure 81, where the variation of results is difficult to interpret. Presumably, there is an inter-relation between lubricant content and density that cannot easily be understood from these results.

The effect of density on wear volumes for each of the other lubricants can be seen in Figures 82-85. All these lubricants show the anomalous effects for the high density (6.8 g/cm$^3$) compacts, as well as a linear relationship for all compacts below this density.

3. Comparison of Stearates. Direct comparisons are shown in Figures 86-88 for each density level. These show that for densities of 6.3-6.5 g/cm$^3$, zinc stearate exhibits the lowest wear

volume; with the others giving higher wear volumes, in particular sodium stearate shows high wear volumes.

The wear scars shown in Figure 89, give some idea of the effect of sliding distance on the surfaces of wearing compacts. These show some retention of wear debris on the surfaces, as well as within the pores. For comparison of Figure 89 with Figure 30 shows how the surfaces of the compacts have changed. It is assumed that similar wear scars are obtained for the other lubricants, these cannot be presented here because of the large number of photographs that would be required.

An overall conclusion for this section, would be that wear volume increases linearly with sliding distance for specimens of density below 6.5 g/cm$^3$. This would agree with Archards equation of wear.

## 7.6 EFFECT OF HARDNESS ON WEAR VOLUME

1. Hardness and Load Effects. For a constant speed, increasing the load, increases the wear volumes. Figures 90 and 91 show this effect, where it is noticeable that for a range axially surface hardness from 10-40 VHN (also means change in density) there is minimum wear volume for compacts with surface hardness around 30 VHN. This corresponds to the densities: 6.3-6.5 g/cm$^{-3}$, already discussed. At high loads, the results separate clearly, so that it can be seen that again zinc and calcium stearates give low wear volumes to the compacts containing them. Also, magnesium and sodium stearates give the highest wear volumes under the same conditions.

2. Hardness and Speed Effects. Under constant load conditions, an increase in speed in general increases the wear volumes, compare Figures 92 and 93. Zinc stearate again gives low wear volumes (Figure 93) for compacts having axial surface hardnesses below 33 VHN. Here magnesium stearate gives the highest wear volumes. Again the wear volumes accelerate for compacts with a high hardness (or high density around 6.8 g/cm$^3$).

3. Hardness and Sliding Distance. If the axial surface hardness is above 33 VHN, i.e. the density is above 6.5 g/cm$^3$, wear volumes increase rapidly with sliding distance. Differentiation between stearates is again difficult here.

In all three cases above, the Archard wear equation could be applied easily; but above the critical hardness (or density) the wear behaviour appears to change.

4. Density Effects. Since Density and Hardness are related, similar conclusions can be drawn from Density versus Wear Volumes with varying conditions of load, speed and sliding distance. Figures 96-101 are included here to complete the survey of results (see Section 7.2).

## 7.7 WEAR RATE STUDIES

Although values of wear volume are useful in examining wear behaviour, some benefit can be obtained in trying to estimate Wear Rates. These rates were obtained from previous results by computer analysis, so that only one rate was obtained for each set of results considered.

1. Density and Wear Rate. Figure 102 shows that in the Load Studies, the wear rates increase with density for lubricant levels below 1.5 wt%. The values for 1.5 wt% can be considered to be either slightly decreasing with density, or more probably they are static within experimental error.

For Speed Studies, Figure 103, the wear rates also increase with density.

Similarly in Figure 104, the wear rates in the Distance Studies show a similar trend.

2. Lubricant Level and Wear Rate. Figures 105-107 illustrate the above results in a different and perhaps clear manner. The results for the high density, 6.8 g/cm$^3$, compacts behave differently to the lower density compacts. The former all have high wear rates in all the studies with load, speed and distance variations. Also, the compacts containing 1.5 wt% of lubricant all had lower wear rates for this density. In general the other compacts tended to have a progressively increasing wear rate irrespective of the increase in lubricant content.

Comparison of Figures 102-107, show that load has the greater effect on increasing wear rates, with speed and distance having lesser effects respectively.

3. Comparison of Lubricants and Wear Rates. At 1 wt% level of lubricant content, a comparison of wear rates is possible by examination of Figures 108-110. Here again the wear rates are most effected by variations in load and speed, rather than distance. Compare these Figures 108-110 with Figures 105-107.

Furthermore, each set of results in Figures 106-108 show that zinc stearate gives the lowest wear rates and that magnesium stearate gives the highest wear rates.

For varying load conditions (see Figure 108), calcium stearate appears to have similar lubricating properties to zinc stearate. However, this is not so for variations in speed and distance (see Figures 109 and 110).

## 7.8 CALCULATIONS ON POSSIBLE DIE LIFE FROM WEAR STUDIES

From the results obtained from the studies of the effect of applied load, speed, sliding distance, density and hardness on the wear behaviour of compacts, it has been shown that the volume of wear for the compacts is directly proportional to the applied load, speed, and sliding distance in most cases.

But when the hardness is concerned, two situations were observed. The first is for the compacts with density value of less than 6.5 g/cm$^3$, it was shown that the volume of wear is inversely proportional to the hardness of the compact. For this case an agreement with Archard's equation can be seen.

For the compacts which have a value of density higher than 6.5 g/cm$^3$, it was shown that the volume of wear is not inversely proportional to the hardness of the compacts but directly proportional to hardness; i.e. the volume of wear was increased when the hardness of the compact was increased.

Before carrying out any calculation of the possible tool life, the value of wear coefficient in Archard's equation must be calculated.

1. Calculating the value of Z: The Archard's equation 2 can be written in the following form:

$$Z = \frac{V.H}{w.x} \tag{38}$$

where: $V$ = volume of wear; $H$ = hardness of compact;

$w$ = applied load; $x$ = sliding distance.

The values of these factors have been determined before, as shown by the results obtained in Chapter 5. For the accuracy of the calculation, two cases will be considered:

a) Compact density 6.3 g/cm$^3$ and zinc stearate content of 1.0 wt%.

i) $w = 0.6$ kg

$x = 0.3014 \times 10^6$ mm

$V = 0.1734$ mm$^3$

$H = 26$ kg/mm$^2$

by substituting these values in equation 38 the value of Z is:

$$Z_i = 2.49 \times 10^{-5}$$

ii) $w = 1.2$ kg

$x = 0.3014 \times 10^6$ mm

$V = 0.2171$ mm$^3$

$H = 26$ kg/mm$^2$

From equation 37:

$$Z_{ii} = 1.56 \times 10^{-5}$$

iii) $w = 2.4$ kg

$x = 0.3014 \times 10^6$ mm

$V = 0.708$ mm$^3$

$H = 26$ kg/mm$^2$

$$\therefore \quad Z_{iii} = 3.2 \times 10^{-5}$$

An average value of Z is:

$$Z = 2.41 \times 10^{-5} \tag{39}$$

b) Compact density <u>6.5 g/cm$^3$</u> and zinc stearate content of 1.0 wt%.

i) $w = 0.6$ kg

$x = 0.3014 \times 10^6$ mm

$V = 0.164$ mm$^3$

$H = 33$ kg/mm$^2$

Then:

$$Z_i = 2.99 \times 10^{-5}$$

ii) $w = 1.2$ kg

$x = 0.3014 \times 10^6$ mm

$V = 0.38925$ mm$^3$

$H = 33$ kg/mm$^2$

Then:

$$Z_{ii} = 3.55 \times 10^{-5}$$

iii) $w = 2.4$ kg

$x = 0.3014 \times 10^6$ mm

$V = 1.536$ mm$^3$

$H = 33$ kg/mm$^2$

Then:

$$Z_{iii} = 7.0 \times 10^{-5}$$

The average value of Z is:

$$Z = 3.277 \times 10^{-5} \qquad (40)$$

From (40) and (39) the range of the values of Z can be derived:

$$Z = (2.41 - 3.3) \times 10^{-5} \qquad (41)$$

The values of Z for compacts of other lubricants have been obtained by the same way and they are shown in the following table:

| Lubricant Content 1.0 wt% | Stearate Type | | | | |
|---|---|---|---|---|---|
| | Zinc | Calcium | Sodium | Aluminium | Magnesium |
| The range of "Z" values x $10^{-5}$ | 2.4-3.3 | 0.5-1.7 | 2.3-4.3 | 3.2-6.6 | 3.6-10.6 |

2. <u>Calculation of Possible Tool Life</u>: An equation to calculate the thickness of the worn area on the die was derived by Mallender and Coleman[1] as follows:

$$y_{die} = \frac{H_{compact}}{H_{die}} \left[\frac{Z}{F} (\ell.\sigma_c + L\sigma_E)\right] \qquad (42)$$

where: $y_{die}$ = thickness of worn area on the die; $H_{compact}$ = hardness of compact; $H_{die}$ = hardness of the die; F = flow pressure of the softer material[159]; $\ell$ = final compaction movement; $\sigma_c$ = compaction pressure; L = compact length for our case L = 10 mm; $\sigma_E$ = ejection stress.

Mallender and Coleman derived this equation by using the Archard's equation (2) and by assuming the applicability of the statement which indicates that the amount of wear occurring between two sliding materials are inversely proportional to their hardness.

Equation (41) has been derived by assuming that Archard's equation can be applied for all densities. Our results suggested that this equation cannot be applied for compacts which have densities higher than 6.5 g/cm$^3$; i.e. for the first case when the volume of wear is directly proportional to the load, distance and inversely to the compact hardness.

By accepting the applicability of equation (41) for the densities less than the value of 6.5 g/cm$^3$, the die worn area thickness can be determined. If the allowance on the die diameters was assumed, then the die life can easily be determined before it is worn out.

For the cases of 6.3 and 6.5 g/cm$^3$ compact densities and lubricant content of 1.0 wt%, and by assuming the value of $L = 1.0$ mm and $F = 1500$ N/mm$^2$, and referring to the following Table for the stress values[4], the values of $y_{die}$ can be determined.

| Stearate Content 1.0 wt% | Radial Stress MN/m$^2$ | | Ejection Stress MN/m$^2$ | |
|---|---|---|---|---|
| | Compact Density: | | Compact Density: | |
| | 6.3 g/cm$^3$ | 6.5 g/cm$^3$ | 6.3 g/cm$^3$ | 6.5 g/cm$^3$ |
| Zinc | 150 | 215 | 4.5 | 6.1 |
| Calcium | 151 | 213 | 5.2 | 6.8 |
| Sodium | 176 | 248 | 4.5 | 6.1 |
| Aluminium | 175 | 242 | 5.9 | 8.0 |
| Magnesium | 174 | 242 | 5.8 | 7.8 |

The values of $H_{die}$ was measured and found to be: <u>856 kg/mm$^2$</u> and the hardness values of the different stearate compacts are as in the following table:

| | HARDNESS OF COMPACTS: $H_{compact}$ kg/mm$^2$ | | | | |
|---|---|---|---|---|---|
| Stearate / Density | Zinc | Calcium | Sodium | Aluminium | Magnesium |
| 6.3 g/cm$^3$ | 26.0 | 24.3 | 24.35 | 26.25 | 25.39 |
| 6.5 g/cm$^3$ | 33.0 | 30.11 | 31.26 | 32.45 | 32.11 |

Assuming the value of the clearance for the diameter is $5 \times 10^{-3}$ mm, then the table below gives the life values for the die used on iron powder with different stearates.

The die life was calculated for the two limits of Z values range.

| Stearate Content 1.0 wt% | Density | Stearate Lubricant | | | | |
|---|---|---|---|---|---|---|
| | | Zinc | Calcium | Sodium | Aluminium | Magnesium |
| Die life by compact number | 6.3 | 52,910 | 17,353 | 51,860 | 32,662 | 30,275 |
| | 6.5 | 21,360 | 44,635 | 15,457 | 9,310 | 5,895 |

Here again Zinc and Calcium Stearates give good lubrication and hence longer life to powder metallurgy dies.

## 2.9 SUMMARY OF WEAR STUDIES

Examination of the areas of study in this research (see diagram at beginning of this chapter), shows that there are many variables that are involved, either directly, or indirectly in these wear experiments.

As has been seen in this discussion chapter, some of the relationships between the variables are complex or difficult to understand or interpret.

For this reason, many of the results have been plotted in a number of different ways, in an attempt to reach some conclusions about each factor. Some of these Figures have helped in this discussion of results. It is now possible to make some overall summary of the main points discovered in this research, these are listed as follows:

Load Studies: The effect of hardness has been difficult to assess, because the exact value of hardness varies within a wear pin (or compact) as the studies on axial and diametrical hardness distributions showed (Section 7.2). Therefore the use of an average hardness value could be suspect in any wear calculations. The range of hardness was from 20-55 VHN. It is also obvious that density and hardness are directly linked, and both of these are affected by the microstructure of the porous materials used in this research.

The wear behaviour in these Load Studies was dependent on the level of density. Below 6.5 g/cm$^3$ one type of wear behaviour was seen; whereas above this value, a different behaviour was observed. In general, wear volume increased with load in a non-linear manner. Furthermore, high density materials showed high wear volumes.

When considering the effects of the presence of stearate lubricants, the effect of the content of stearate was difficult to assess since it was masked by the microstructure and density effects mentioned above. The effect of lubricant type appears to be clear in most cases examined the materials containing zinc stearate showed the lowest wear volumes. In some cases calcium stearate also showed low wear volumes. On the other hand, materials containing magnesium stearate nearly always showed the highest wear volumes.

Speed Studies: As would be expected these experiments showed that with the increase in sliding speed there was in general an increase in wear volume. If the speeds were excessive, i.e. about 20,000 cm/min, the materials would tend to break up at the sliding interface. This effect was seen for very low densities e.g. 5.5, and for very high densities, e.g. 6.8 g/cm$^3$. With respect to the presence of stearate lubricants in the wearing surfaces; those materials containing zinc stearate showed the lowest wear volumes. Magnesium stearate was still the worst lubricant.

Distance Studies: Many of the plots of wear volume against sliding distance showed linear relationships. This was particularly true for those materials containing zinc stearate, which again showed the lowest wear volumes. The linear relationship between wear volume and distance, for materials containing other types of metallic stearates studied in this research, was also seen.

Wear Rates: These increased with load and increase of density. The wear rates for the Speed Studies and the Distance Studies showed similar relationships.

As would be expected from the above summaries, the wear rates for zinc stearate (and in some cases for calcium stearate) were the lowest when compared with the other stearates. Furthermore, magnesium stearate had the highest wear rates.

Die Wear Estimations: Results presented in Section 7.8.2, which were calculated using some of the measurements and observations gathered in this research, reinforce the conclusions summarised above. That is, zinc stearate would give the lowest die wear and the other stearates in decreasing usefulness would be: calcium, sodium, aluminium and magnesium. These results are for densities around 6.5 g/cm$^3$, unfortunately because of the anomalous results for materials with a density greater than this value (6.8 g/cm$^3$), the Archard type equation does not hold and so the estimations of die wear for densities in the region of 7.0 g/cm$^3$ cannot be easily calculated without further study. This would involve the development of another wear equation for this system.

# CHAPTER 8

# DISCUSSION OF RESULTS OF FRICTION STUDIES

8.1 FRICTION FORCE VARIATION WITH LOAD AND TIME

1. Calibration of Friction Force
2. Friction Force and Load Variation with Time

8.2 FRICTION COEFFICIENT VARIATION WITH LOAD

1. Static Friction Values
2. Kinetic Friction Values
3. Kinetic Friction Values after 1 minute

8.3 FRICTION COEFFICIENT VARIATION WITH TIME

8.4 FRICTION COEFFICIENT VARIATION WITH DENSITY.

8.5 FRICTION COEFFICIENT VARIATION WITH HARDNESS

8.6 SUMMARY

# CHAPTER 8

# DISCUSSION OF RESULTS OF FRICTION STUDIES

Only a limited study was possible on the friction behaviour of these powder metal and lubricant systems. These results on friction studies have been separated from the wear studies (reported in Chapter 7) for clarity. However, the discussion and ideas discussed in the previous chapter must also be considered here.

## 8.1 FRICTION FORCE VARIATION WITH LOAD AND TIME

1. Calibration of Friction Force. The calibration graph for horizontal force and mV output for this wear apparatus is shown in Figure 111. This explains that all mV output readings of the apparatus are linearly proportional to the friction forces measured in these studies.

2. Friction Force and Load Variation with Time. Figure 112 gives the 1 second values which are closest to "static friction force" values. It can be seen that for all the lubricants a similar set of results were obtained. That is, the friction forces in all cases increased with increased loads up to around 2 kg.

Although it is difficult to differentiate between lubricants at this stage, zinc stearate appears to give a low friction force value, particularly at high loads around 2 kg. It can be seen also that the slope of the zinc stearate line is the lowest amongst a group of lines which have small slopes anyway.

Force studies after 5 and 15 seconds, Figures 113 and 114, show that these slopes increase considerably with time.

It will be shown later, in Section 8.3, that because of the large variation in friction force with time after periods greater than 15 seconds, further interpretation of results becomes very difficult. Hence no further results are included here after 60 seconds.

## 8.2 FRICTION COEFFICIENT VARIATION WITH LOAD

1. Static Friction Values. Examination of Figures 115-117 show that the coefficient of friction at the start of a test decreases with the applied load. Comparison of these Figures shows that the density of the compacts does not affect the results in this case.

The values of $\mu$ for each stearate are very similar to each other, and no differentiation is possible between one stearate and another.

2. Kinetic Friction Values. It has been assumed here that after 5 seconds of sliding that a kinetic state has been reached. From Figures 118-120, a near constant value of $\mu = 0.2$ appears to have been reached. Again the effect of differing densities does not change these values appreciably. Distinction between each stearate is again impossible, since the variations in the graphs is probably within experimental error.

After sliding for 10 seconds, the results are slightly different (see Figures 121-123). The value of μ appears to increase slightly above 0.2 for each stearate and the effect of increasing load is becoming more apparent. Furthermore, the separation between the μ values of each stearate are becoming more distinct. Again the effect of different densities does not appear to affect these results.

Similar results were obtained for values at 15 seconds, but these are not reported here.

Results for 20 seconds of sliding are shown in Figures 124-126. Here again there is a slight increase in μ values as the load is changed, but no apparent difference is seen between compacts with different densities.

Figures 127-129 show that after 40 seconds of sliding, the values of μ are between 0.3 and 0.4 for loads over 1 kg. Some differences are now seen due to the differing densities.

Results for 50 seconds sliding, see Figures 130-132, begin to show differences due to the differing densities. The compacts with the highest density of 6.8 g/cm$^3$ (and some of the highest wear) give the lowest value of μ, see Figure 132. Presumably, this is because the lubricants and wear debris help the sliding surfaces, giving values of μ between 0.1 and 0.2. This means that the shear forces contributing to the friction force are low due to this "film" between the surfaces.

For sliding times for 60 seconds and longer, this "film" effect is more pronounced. Figure 135 shows that as the load is increased above 1 kg the value of $\mu$ is between 0.1 and 0.2, which is typical of a "lubricated" system.

Figures 133-135 demonstrate how the density, and presumably the surface topography, of the compacts affects the coefficient of friction values. It is difficult to distinguish one stearate from another, but zinc stearate still appears to give some of the lowest values of $\mu$ (see Figure 133). Results from these Figures are assumed to be those for a "stable" sliding system and that any increase in time would not affect the results drastically.

## 8.3 FRICTION COEFFICIENT VARIATION WITH TIME

A full set of results for all the stearates was not possible. However, a study was possible with calcium stearate over a range of 5 densities, varying from 5.5 - 6.8 g/cm$^3$. These results are seen in Figures 136-140. These all demonstrate that "stable" sliding conditions are only achieved after 60 seconds. Fluctuations in $\mu$ occur at higher times, but these are within certain limits. For example, for the highest wearing system with density of 6.8 g/cm$^3$ (Figure 140), a fairly constant value of $\mu$ between 0.24 and 0.28 is achieved for long sliding times.

Except for results of compacts with density of 5.5 g/cm$^3$ (Figure 136), there is a gradual decrease in $\mu$ for all the compacts with increasing density. Again, it is suggested that this is due to the development of a "wear film" between the sliding surfaces. This would assume that high density compacts are approaching a "lubricated" system.

## 8.4 FRICTION COEFFICIENT VARIATION WITH DENSITY

The results from the previous Section (8.3) can be re-examined in a slightly different way to see if there is any effect due to density. Because of the large number of variables already discussed, interpretation of Figures 141-142 is difficult. However, it can be seen that the overall conclusion is that the average coefficient of friction increases with time as already shown and that some stabilisation at times greater than 60 seconds ~~if sliding~~ can occur.

## 8.5 FRICTION COEFFICIENT VARIATION WITH HARDNESS

Figures 144-146 are really a duplication of results discussed briefly in Section 8.4 above, since density and hardness for these studies are directly related. However they are included for completeness although their interpretation is difficult.

## 8.6 SUMMARY

Results in this section are limited because there was not sufficient time to carry out a complete survey as with the Wear Studies. Again the complexity of the sliding system is apparent, which often made interpretation of the results difficult. However, some general points can be summarised as follows:

Friction Force, Load and Time: It was found that the friction force varied considerably with sliding time between 1 and 60 seconds. For low times, this force increased linearly with load. As the time increased, the slope of this linear relationship tended to increase. For compaction press studies, only times less than 15 seconds are useful, since this is the maximum duration of most industrial pressing cycles. Therefore, more emphasis was placed on results determined in times less than 15 seconds.

*Coefficient of Friction*: The value of μ is obviously related to the friction force and load results mentioned above. Values of μ for short times (1 second) for all the stearate lubricants *decrease with load*. Such values have been considered to be close to "static" coefficient of friction values.

For higher sliding times, μ for all stearate lubricants again decreases with load, although this decrease is now *not* so severe. Presumably this is due to the load spreading out a film of lubricant and wear debris between the sliding surfaces, so that the higher the load, the greater area of this film is present between the sliding surfaces.

For longer periods of sliding (over 15 seconds) similar conclusions have been drawn. That is, μ decreases with increasing load for longer periods of sliding.

Finally, for studies with calcium stearate at *constant load*, the *friction coefficient increases* with time. Presumably because the lubricant film becomes "flooded" with wear debris and the resultant film between the sliding surfaces loses its lubricating properties. Typical increases in μ are from 0.20 to 0.30 over a period of 60 seconds.

# CHAPTER 9

# CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

9.1 CONCLUSIONS

1. Wear Studies
   - a) Effect of load variation on wear studies
   - b) Effect of speed variation on wear studies
   - c) Effect of distance variation on wear studies
   - d) Wear rate
   - e) Die wear calculations
2. Friction Studies

9.2 SUGGESTIONS FOR FUTURE WORK

# CHAPTER 9

# CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

## 9.1 CONCLUSIONS

Due to the wide range of variables and the complexity of some of the relationships, definite conclusions are not always possible for this research. Those conclusions that can be drawn from the study of the determinations, observations and calculations are listed as follows.

1. The density of the iron powder/stearate compacts controls the overall wear behaviour. This factor also controls the microstructure and therefore has an effect on the sliding surfaces.
2. The hardness of the powder compacts varies within the compact in all three directions, this makes it difficult to assess an exact hardness value for a metal powder component unlike a fully dense metal. The hardness distribution is controlled by the compaction process, the nature of the metal powder particles and the type and content of the lubricant (or stearate) addition.
3. There is a direct relationship between density and hardness for powder metal components. Both of these are related to the lubricant (or stearate) content.

## 1. Wear Studies:

### a) Effect of Load Variation on Wear Studies:

4. Wear studies with variation in load show that in general the wear volume increased with applied load. This wear behaviour was dependent on density, one type of wear was observed for compacts with densities below 6.5 g/cm$^3$, where the wear decreased with increasing density (or hardness) as predicted by wear equations. For compacts with densities greater than this value, increased wear was observed which is the reverse of predictions given by standard wear theory.

5. Comparison of stearates as admixed lubricants in these iron powder/lubricant systems were shown in these wear studies to behave differently. Compacts with zinc stearate showed the lowest wear volumes. In some cases calcium stearate also showed low wear volumes, but magnesium stearate in the compacts produced high wear volumes.

### b) Effect of Speed on Wear Studies:

6. In general, increasing the sliding speed increased the wear volume.

7. If speeds greater than 20,000 cm/min were involved, compact surfaces tended to break up.

8. In these studies, again zinc stearate showed the lowest wear volume and magnesium stearate showed the highest wear volume.

c) Effect of Distance on Wear Studies:

9. Many of the plots of wear volume against sliding distance showed a linear relationship.

10. Zinc stearate again showed the lowest wear volume.

d) Wear Rates:

11. These were related to density and load, the wear rates all increased with increase in these factors.

12. Wear rates in speed and distance studies also showed a similar set of relationships.

13. The lowest wear rate was observed for compacts containing zinc stearate, and the highest wear rates were again seen for compacts containing magnesium stearate.

e) Die Wear Calculations:

14. Using the data gathered in this research, it is possible to estimate a die life for a tool steel, as used in industrial presses.

15. Calculations indicate, as would be expected from the foregoing conclusions, that the order of lubricants that would reduce die wear is as follows:

Best lubricant: Zinc stearate
Calcium stearate
Sodium stearate
Aluminium stearate

Worst lubricant: Magnesium stearate

16. Calculations on die wear were only possible for compacts of density up to the level of 6.5 g/cm$^3$, because the wear behaviour of compacts with greater density gave anomalous results (see conclusion 4).

2. Friction Studies:

17. Sliding time affected the variation of friction force with load for periods up to 60 seconds of sliding.

18. For sliding times of less than 15 seconds the friction force increased linearly with load. This period of time is the most important one for industrial press studies, since most compaction processes take less than this time period.

19. The coefficient of friction ($\mu$)is obviously related to friction force and load, and for short times of sliding (around 1 second) this coefficient decreases with load for all the stearates examined. These values decreased in the order of: $\mu = 0.3$ to 0.1. These values are considered to be close to the "static" friction coefficient values for these iron powder/stearate/tool steel sliding systems.

20. For higher sliding times (greater than 1 second) the coefficient of friction for all the stearates decreased with load in a less severe manner, for example $\mu = 0.3$ to 0.2.

21. For constant load, the value of the friction coefficient increases with time. Results with calcium stearate only, show that $\mu$ changes from 0.20 to 0.38 in 60 seconds.

## 9.2 SUGGESTIONS FOR FUTURE WORK

Only a limited amount of study was possible on the friction behaviour of powder metal/stearate/tool steel systems, therefore it is suggested that the following areas might be studied:

1. Investigation of friction between other powder/lubricant systems and die/tool steels.
2. Examination of friction for other tool materials, e.g. carbides, nitride materials.
3. Investigation of the effects of the following factors on friction behaviour,

    lubricant structure
    temperature
    speed
    and distance

4. An examination of friction under very high loads, similar to those experienced in industrial production presses.
5. In the wear behaviour area, some consideration might be given to the study of wear volume or wear rates for high density compacts with densities above 6.8 $g/cm^3$.

# CHAPTER 10

# REFERENCES AND APPENDICES

# CHAPTER 10

## 10.1 REFERENCES

1. Mallender, R F and Coleman, D S.
Fourth European Powder Metallurgy Conference, Paper 3-11-1, May 1975, Grenoble, France.

2. Archard, J F and Hirst, W.
Proc. Roy. Soc., Vol. 238A, 515-527, August 1956.

3. Mallender, R F and Coleman, D S.
Reports and PhD Thesis, "Interfacial Coefficients in Powder Metal Compaction", Department of Materials Engineering and Design, University of Technology, Loughborough, 1974.

4. Rajab, M and Coleman, D S.
Reports and PhD Thesis, "A Study of the Production Problems in Pressing Complex Shapes from Metal Powders", Department of Materials Engineering and Design, University of Technology, Loughborough, 1982.

5. Dowson, D.
MSc Tribology Course, Leeds University, 1978-79.

6. Kragelski, I V.
"Friction and Wear", Butterworths, London, 1965.

7. Halling, J.
"Introduction to Tribology", Wykeham Publications (London) Ltd. London and Winchester, 1976.

8. Halling, J.
Wear, Vol. 4, 239-249, 1975.

9. Bowden, F P and Tabor, D.
"Friction and Lubrication of Solids", Part I, Oxford Press, 1950.

10. Holm, R.
"Electrical Contact", Almquist and Wiksells, Uppsala, 1946.

11. Tabor, D.
Proc. Roy. Soc., Vol. 192A, 247, 1948.

12. Rabinowicz, E.
"Friction and Wear of Metals", J Wiley and Sons Inc,
New York, 1965.

13. Hertz, H J.
Reine Angeur.Math., Vol. 92, 156, 1886.

14. Bowden, F P and Tabor, D.
Proc. Roy. Soc., Vol. 169A, 391, 1939.

15. Archard, J F.
J. Appl. Phys., Vol. 24, 8, August 1953.

16. Archard, J F.
J. Appl. Phys., Vol. 32, No. 8, 1420, August 1956.

17. Archard, J F.
Proc. Roy. Soc., Vol. 243A, 190-205, 1957.

18. Amontons.
Histoire de L'Academie Royale Sciences avec les Memoires
de Mathematique et de Physique, 206, 1699.

19. Makfarlane, J S and Tabor, D.
Proc. Roy. Soc., Vol. 202A, 244, 1950.

20. Shaw, P and Leavy, E.
Phil. Mag., 809, 1930.

21. Machin, E S and Yankee, J.
J.Appl. Phys., Vol.25, 576, 1954.

22. Coffin, L F.
Lubrication Engg., Vol. 12, 50, 1956.

23. Burwell, J F and Strang, C D.
Proc. Roy. Soc., Vol. 212A, 470, 1956.

24. Rabinowicz, E and Tabor, D.
Proc. Roy. Soc., Vol. 208A, 455, 1951.

25. Suh, N P.
Wear, Vol. 25, 111-124, 1973.

26. Jahanmir, S, Suh, N P and Abrahamson, E P.
Wear, Vol. 28, 235-249, 1973.

27. Jahanmir, S, Suh, N P and Abrahamson, E P.
Wear, Vol. 32, 33, 1975.

28. Tabor, D.
J. Lubr. Tech., 385, October 1977.

29. Burwell, J T and Strang, C D.
J. Appl. Phys., Vol. 23, No. 1, January 1952.

30. Burwell, J T.
Wear, Vol. 1, 119-141, 1957/58.

31. Euler.
Histoire de L'Academie Royale des Sciences et Belles Lettres, 122, 1748, Berlin, 1750.

32. Barwell, F T.
Wear, Vol. 1, 418, 1957/58.

33. Bowden, F P and Tabor, D.
"Friction and Lubrication of Solids", Part II, Oxford Press, 1964.

34. Quinn, T F J.
Brit. J. Appl. Phys., Vol. 13, 33, 1962.

35. Lancaster, J K.
Proc. Roy. Soc., Vol. 273A, 466, 1963.

36. Kerridge, M and Lancaster, J K.
Proc. Roy. Soc., Vol. 236A, 250, 1956.

37. Kerridge, M.
Proc. Phys. Soc., Vol. 68B, 400-407, 1955.

38. Yamada, K, Takada, N, Kagami, J and Naoi, T.
Wear, Vol. 54, 217-233, 1979.

39. Richardson, R C D .
Wear, Vol. 10, 291-309, 1967.

40. Sarkar, A D.
"Wear of Metals", Pergamon International LIbrary, 1976.

41. Hirst, W.
Proc. Inst. Mech. Engrs., Vol. 182, Pt. 3A, 281, 1967/68.

42. Tonn, W.
Z. Metallk., Vol. 29, 196, 1937.

43. Khrushchov, M M and Babichev, M A.
"Friction and Wear in Mechanics", 1, Izd. Akad. Nauk, USSR, 69, 1941.

44. Khrushchov, M M.
Wear, Vol. 28, 69, 1974.

45. Rabinowicz, E.
ASME Wear of Metals Conference, 197-201, New York, 1981.

46. Egawa, K.
J. Jpn. Soc. Lubr. Engg., Vol. 19, 897, 1974.

47. Hagmark, S, Vingsbo, O and Fridstrom, S.
Wear, Vol. 31, 39, 1975.

48. Suh, N P.
Wear, Vol. 44, 1, 1977.

49. Eyre, T S.
Tribology International, 91-96, April 1978.

50. Oberle, T L.
J. Metals, Vol. 3, 438, 1951.

51. Spurr, R T and Newcomb, T P.
Proc. Conf. on Lubrication and Wear, Institution of Mechanical Engineers, 269-275, London, 1957.

52. Lancaster, J K.
Friction and Wear, 1016-1043, 1969.

53. Sin, H, Saka, N and Suh, N P.
Wear, Vol. 55, 163-190, 1979.

54. El-Sherbiny, M G and Salem, F B.
Wear, Vol. 54, 391-400, 1979.

55. Summersmith, D.
An Introduction to Tribology, The Machinery Publication Company, 1969.

56. Abrahamson, E P, Jahanmir, S, Suh, N P and Turner, P L.
J. Lubrication Technology, 1973.

57. Hirth, J P and Rigney, D A.
Wear, Vol. 39, 133, 1976.

58. Godfrey, D.
Lubrication Engg., 37, Jan-Feb, 1956.

59. Rowe, G W.
Research, Vol. 14, 137, 1960.

60. Stolarski, T A.
Tribology International, 169-179, August 1979.

61. Coulomb, C A.
Memoires de Mathematique et de Physique de L'Academie Royale de Sciences, 161, 1785.

62. Ewing, A.
Notes of Proc. Roy. Instn., Vol. 13, 387, 1892.

63. Hirn, G A.
Bull. Soc. Indust. Mulhouse, Vol. 26, 188, 1854.

64. Morin, A J.
See MSc Tribology Course Notes, Leeds University, 1978-79.

65. Rennie, G.
Phil. Trans., Vol. 34, 143, 1829.

66. Hardy, W B.
"Collected Works", Cambridge University Press, 1936.

67. Tomlinson, G A.
Phil. Mag., Vol. 7, 905, 1929.

68. Archard, J F.
See MSc Tribology Course Notes, Leeds University, 1978-79.

69. Newcomb, T P.
See MSc Tribology Course Notes, Leeds University, 1978-79.

70. Bowden, F P and Tabor, D.
Nature, No. 3798, August 15th, 1942.

71. Bowden, F P and Tabor, R.
"Friction and Lubrication", Methuens Co Ltd., London, 1956.

72. Bowden, F P and Tabor, D.
"Friction", Heineman Press, 1973.

73. Forrester, P G.
Proc. Roy. Soc., Vol. 187A, 439, 1946.

74. Mokhtar, M O A, Zaki, M and Shawki, G S A.
    Tribology International, 261-264, December 1979.

75. Taylor, C.
    See MSc Tribology Course Notes, Leeds University, 1978-79.

76. Barwell, F T.
    Proc. Roy. Soc., Vol. 212A, 508, 1952.

77. Langmuir, J.
    J. Franklin Inst., Vol. 218, 143, 1934.

78. Bragg, W.
    Nature, Vol. 115, 266, Feb. 24th, 1940.

79. Hardy, W B and Doubleday, I.
    Proc. Roy. Soc., Vol. 100A, 550, 1921-22.

80. Bowden, F P, Gregory, J N and Tabor, D.
    Nature, No. 3952, 97, July 28th, 1945.

81. Deryaguin, B V, Karassev, V V, Zakhavaeva, N N and Lazarev, V P,
    Wear, Vol. 1, 277-290, 1957-58.

82. Cameron, A.
    ASLE Trans., Vol. 180, 195, 1959.

83. Tabor, D.
    Proc. Inst. Mech. Engrs., Vol. 182, Pt. 3A, 262, 1967-68.

84. Tabor, D.
    Proc. Roy. Soc., Vol. 212A, 498, 1952.

85. Hardy, W B and Bircumshaw, I.
    Proc. Roy. Soc., Vol. 108A, 1, 1925.

86. Tabor, D.
    Nature, Vol. 195, 308, Feb. 24th, 1940.

87. Lancaster, P R and Rowe, G R.
Wear, Vol. 2, 428-437, 1955-59.

88. Karmakar, A.
First World Conference in Industrial Tribology, Paper F11, New Delhi, India, 1972.

89. Clayton, D.
Brit. J. Appl. Phys., 2nd Suppl., Vol. 1, 25, 1951.

90. Pugh, P.
"Friction and Wear", London, Newnes-Butterworths, 1973.

91. Cowley, C W, Ultee, G J and West, G W.
ASLE Trans., 281, 1956.

92. Hirst, W, Kerridge, M and Lancaster, J K.
Proc. Roy. Soc., Vol. 212A, 516, 1952.

93. Bowden, F P and Moore, A C.
Research Correspondence, Vol. 2, 585, 1949.

94. Braithwaite, E R.
"Solid Lubricants and Surfaces", Pergamon Press, 1964.

95. Kingsbury, E P.
J. Appl. Phys., Vol. 29, 6, 888, 1958.

96. Kingsbury, E P.
ASLE Trans., Vol. 180, 30, 1959.

97. Lunn, B.
Wear, Vol. 1, 25, 1957-58.

98. Jones, D.
See MSc Tribology Course Notes, Leeds University, 1978-79.

99. Smith, E A.
J. Inst. Petroleum, Vol. 42, 322-329, 1956.

100. Clauss, F J.
"Solid Lubricants and Self-Lubricating Solids", Academic Press, New York and London, 1972.

101. Robertson, W M.
Wear, Vol. 68, 97-107, 1981.

102. Campbell, W E.
Lubrication Engg., 195, August 1953.

103. Rowe, G W.
Lubrication Engg., 325, 1955.

104. Shooter, K V and Thomas, P H.
Research, Vol. 2, 533, 1949.

105. Shooter, K V.
Proc. Roy. Soc., Vol. 212A, 488, 1952.

106. Bowden, F P and Hughes, T P.
Proc. Roy. Soc., Vol. 172A, 263, 1939.

107. Bowden, F P and Young, J E.
Proc. Roy. Soc., Vol. 208A, 311, 1951.

108. Whitehead, R.
Proc. Roy. Soc., Vol. 201A, 109, 1950.

109. Savage, R H.
J. Appl. Phys., Vol. 19, 1, 1948.

110. Ramadanoff, D and Glass, S W.
Trans. AIEE, Vol. 63, 825, 1944.

111. Elsey, H M.
Trans. AIEE, Vol. 64, 576, 1945.

112. Campbell, W E and Kozek, R.
Trans. ASME, Vol. 70, 491, 1948.

113. Crump, W J J.
"Solid Lubricants", See MSc Tribology Course Notes, Leeds University, Leeds, 1978-79.

114. Sugishita, J and Fujiyoshi, S.
Wear, Vol. 66, 209-221, 1981.

115. Sugishita, J and Fujiyoshi, S.
Wear, Vol. 68, 7-20, 1981.

116. Tamaka, K and Vchiyama, Y.
Wear of Metals Conference, ASME, 637-643, New York, 1981.

117. Milne, A A.
Wear, Vol. 1, 92-103, 1957-58.

118. Scott, D.
Wear, Vol. 21, 155, 1972.

119. Casstevens, J M.
Wear, Vol. 49, 169-178, 1978.

120. Da-Yue, H, Ting-Hong, G, Hang, Chau, L and Rui-Zhong, Q.
Wear of Metals, Conference ASME, 644-647, New York, 1981.

121. Stjermberg, K G, Fischer, U and Hugoson, N I.
Powder Metallurgy, Vol. 18, No. 35, 89, 1975.

122. Dufek, V and Jemcek, L.
Powder Metallurgy, Vol. 13, No. 25, 56, 1970.

123. Greenwood, H W.
Metallurgia, Vol. 37, 283, 1948.

124. Kamm, R, Steinberg, M and Wulff, J.
AIME Tech. Publ., 2133, 1947.

125. Seeling, R P and Wulff, J.
AIME Tech. Publ., 2044, 1946.

126. Hausner, H H and Sheinyartz, I.
Proc. 10th Annual Meeting MPA, Vol. 6, 1954.

127. Hausner, H H and Sheinhartz, I.
Proc. 10th Annual Meeting MPA, Vol. 6, 1954.

128. Leopold, P M and Nelson, R C.
Int. J. Powder Metallurgy, Vol. 1, 3, 1975.

129. Dangerfield, C J and Coleman, D S.
J. Powder and Bulk Solids Tech., 36, 1976.

130. Sajdak, R J, McNally, R P, Nasta, M D and Becklow, J K.
Inter. J. Powder Metallurgy, Vol. 6(2), 13, 1970.

131. Sheinhartz, I, McCullough, H M and Zambrow, J L.
J. Metals, Vol. 6, 515, May 1954.

132. Train, D and Hesey, J A.
Powder Metallurgy, Vol. 6, 20, 1960.

133. Duwez, P and Zwell, L J.
Metals, Vol. 1 (2), 137-144, 1949.

134. Eyre, T S.
Tribology International, Vol. 9, No. 5, 203,October 1976.

135. Heckel, R W.
Prog. Powder Metals, Vol. 17, 66, 1961.

136. Donachie, M J and Burr, M F.
J. Metals, Vol. 15, 849, November 1963.

137. Shapiro, I and Koltholf, I M.
J. Phys. and Colloid Chem., Vol. 51, 983, 1947.

138. Torre, C.
Beig-Huttenmann, Monatsh, Montan Hochschule Leoben, Vol. 93, 62, 1948.

139. Kawakila, K and Helmut Ludde, K.
Powder Tech., Vol. 4, 61-68, 1970-71.

140. James, P J.
Powder Metallurgy International, Vol. 4, No. 2, 82-85, 1972.

141. James, P J.
Powder Metallurgy International, Vol. 4, No. 3, 145-149, 1972.

142. James, P J.
Powder Metallurgy International, Vol. 4, No. 4, 194-198, 1972.

143. Bockstiegel, G and Svensson, O.
Modern Developments in Powder Metallurgy, Vol. 4, "Processes", Plenum Press, New York, 87, 1971.

144. Geijer, E and Jamison, R S.
(P/M) Ed. W Leszynski, Interscience, New York and London, 585, 1961.

145. Ljungberg, I and Arbstedt, P G.
Proc. 12th Annual Meeting of MPA, 78, 1956.

146. Halling, J.
"Introduction to Tribology", London, Butterworths, 1965.

147. Goodhew, P J.
"Electron Microscopy and Analysis", Wukeham Science Series, No. 33.

148. Scott, D and Mills, G H.
Proc. Workshop on Failure Analysis - SEM, Illinois Inst. of Tech. Res. Inst., Chicago, IL60616, USA.

149. Glauert, A M.
"Practical Methods in Electron Microscopy", Vol. I,
North-Holland, 1972.

150. Nelson, H R.
Conf. on Friction and Surface Finish, MIT, 217, 1940.

151. Moore, J W.
Proc. Roy. Soc., Vol. 195A, 231, 1948-1949.

152. Eyre, T S.
Wear Workshop, Brunel University, 23rd April 1981, UK.

153. Abbott, E J and Freestone, F A.
Mech. Engng., Vol. 55, 569, 1933.

154. Reason, R E, Hopkins, M R and Garrod, R I.
Report on Measurement of Surface Finish by Stylus Method
Taylor-Hobson, Leicester, England, 1944.

155. Halliday, J S.
Proc. Inst. Int. Conf. on Lubrication and Wear, Paper 40,
I Mech. Engg., London, 1957.

156. Rabinowicz, E.
Proc. Phys. Soc., Vol. 64A, 939, 1951.

157. Bochstiegel, G and Svensson, O.
Powder Metallurgy, Vol. 12, No. 24, 316, 1959.

158. Leopold, P M and Nelson, R C.
Inst. J. Powder Metallurgy, Vol. 1, 4, 1965.

159. Archard, J F and Hirst, W.
Proc. Roy. Soc., Vol. 236A, 397-409, 1956.

160. Smith, A B.
Private communication, University of Technology, Loughborough,
England, 1983.

161. Halling, J.
Wear, Vol. 4, 22-31, 1961.

162. Da Vince, L.
(1452-1519), Notebooks, Jonathan Cape, London, 1938.

## 10.2 APPENDIX

### Derivation of the Wear Volume Equation:

The following equation has been used in calculating the value of the volume of wear in this work:

$$V = \frac{\pi a^4}{64r}\sqrt{\frac{R}{r}} \tag{A}$$

where: a = small diameter of the worn area; r = compact radius; and R = disc radius see Figure 147.

This is the well known equation for the case of cross-cylinders case[161,160].

In deriving this equation the following procedure was followed:

When two cross-cylinders are in contact and sliding against each other, then wear will take place at the area of contact. This area of contact, which is in fact rectangular, will be given by the following formula:

$$A = X.Y \tag{B}$$

where: X, Y are the diameters of this area on X-Y plane, see Figures 148 and 149.

The volume of this element will be given by an integration form as follows:

$$V = \int_{o}^{\delta} X.Y\, dz \qquad \text{(C)}$$

This integration cannot be carried out in this form, so it has to be converted to an acceptable form. From Figure 147 the following formula can be derived:

$$R^2 = (\frac{y}{2})^2 + (R-d)^2 \qquad \text{(D)}$$

where: $y$ = length of the trace on the disc; $R$ = radius of the disc, and $d$ = depth of the worn area on the disc.

Equation D can be re-written in the following form:

$$\frac{y^2}{4} = 2Rd-d^2 \qquad \text{(E)}$$

Then, by ignoring the terms of the second order equation E takes the following form:

$$\frac{y^2}{4} = 2Rd$$

or:

$$d = \frac{y^2}{8R} \qquad \text{(F)}$$

If the same procedure was followed on the disc, a very similar equation can be obtained as follows:

$$\delta = \frac{b^2}{8R} \qquad \text{(G)}$$

From equations F and G:

$$Z = \delta - d = \frac{b^2}{8R} - \frac{y^2}{8R}$$

i.e. $$y = \sqrt{b^2 - 8RZ} \qquad \text{(H)}$$

From Figure 149, a similar equation to E can be written:

$$\frac{X^2}{4} = (2r-Z)Z$$

i.e. $$X = \sqrt{8.rZ} \qquad \text{(I)}$$

where: r = radius of the compact; Z = depth of the worn area,
and X = length of the worn area as shown in Figure 149.

By the same procedure, an equation similar to G can be written:

$$\delta = \frac{a^2}{8r} \qquad \text{(J)}$$

Substituting equations H and I in equation C, it takes the following form:

$$V = \int_0^{\delta} \sqrt{8rZ} \, . \, \sqrt{b^2 - 8RZ} \, dz \qquad \text{(K)}$$

Equation K is not easy to integrate, however since the values of r, b and R are constant, it can be assumed that the following is true:

$$8RZ = b^2 \cos^2\theta \qquad \text{(L)}$$

By differentiating both sides:

$$8R.dz = -2\ b^2.\ \sin\theta.\cos\theta.d\theta$$

i.e. $$dz = -\frac{b^2.\sin\theta.\cos\theta.}{4R}\ d\theta \qquad (M)$$

By substituting equations L and M into equation K, the following form can be obtained:

$$V = -\int_0^\delta \sqrt{\frac{r}{R}}\ .b.\cos\theta.b\ \sqrt{1-\cos^2\theta}.\ \frac{b^2}{4R}\ \sin\theta.\cos\theta\ d\theta$$

i.e. $$V = \frac{-b^4\ \sqrt{r}}{4\ \sqrt{R^3}} \int_0^\delta \cos^2\theta.\ \sin^2\theta.\ d\theta \qquad (N)$$

But:

$$\cos\theta.\sin\theta = \frac{\sin 2\theta}{2}$$

hence $$\cos^2\theta \cdot \sin^2\theta = \frac{\sin^2 2\theta}{4} \qquad (O)$$

Also:

$$2\sin^2 2\theta = 1 - \cos 4\theta$$

so that equation O becomes:

$$\cos^2\theta.\sin^2\theta = \frac{1}{8}\ (1 - \cos 4\theta) \qquad (P)$$

Substituting these in equation N:

$$V = - \frac{b^4 \sqrt{r}}{4 \sqrt{R^3}} \int_{o}^{\delta} \frac{1}{8} (1 - \cos 4\theta).d\theta$$

i.e. $$V = - \frac{b^4 \sqrt{r}}{64 \sqrt{R^3}} \int_{o}^{\delta} (1 - \cos 4\theta)\ d\theta \qquad (Q)$$

The limits of this integration must be changed to suit the value of $\theta$.

Equation L can be re-written in the following form:

$$\cos\theta = \sqrt{\frac{8RZ}{b^2}}$$

i.e. $$\theta = \cos^{-1} \sqrt{\frac{8RZ}{b^2}} \qquad (R)$$

when: $Z = 0 \rightarrow \theta = \frac{\pi}{2}$ (lower term)

$Z = \delta = \frac{b^2}{8R} \rightarrow \theta = 0$ (upper term)

Substituting in the integration of equation Q we get:

$$V = - \frac{b^4 \sqrt{r}}{64 \sqrt{R^3}} \int_{\pi/2}^{0} (1 - \cos 4\theta).d\theta$$

$$\therefore \quad V = - \frac{b^4 \sqrt{r}}{64 \sqrt{R^3}} \left[\theta - \frac{\sin 4\theta}{4}\right]_{\pi/2}^{o}$$

$$\therefore \quad V = \frac{\pi b^4 \sqrt{r}}{64 \sqrt{R^3}} \qquad (S)$$

where: b is the larger diameter of the worn area.

Alternatively equation S can be written in another form, in respect to the small diameter of the worn area (a) as follows:

$$\delta = \frac{b^2}{8r} = \frac{a^2}{8r}$$

Hence:

$$b^2 = \frac{8R.a^2}{8r}$$

i.e. $$b^4 = \frac{R^4.a^4}{r^2} \qquad (T)$$

Substituting equation T into equation S, the following equation can be obtained:

$$V = \frac{\pi \; a^4 \sqrt{R}}{64 \; \sqrt{r^3}} \qquad (U)$$

In this research work, equation U was used in evaluating the volume of wear.

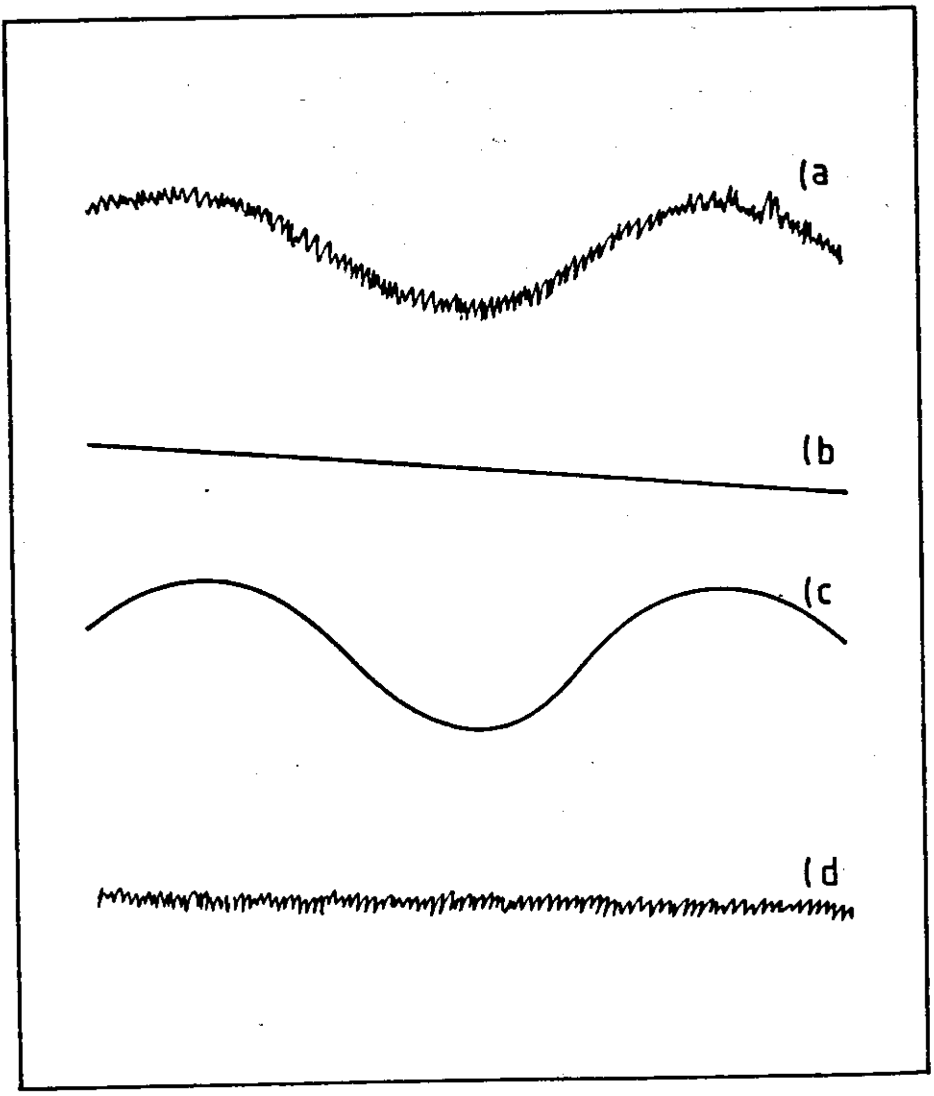


Fig. 1

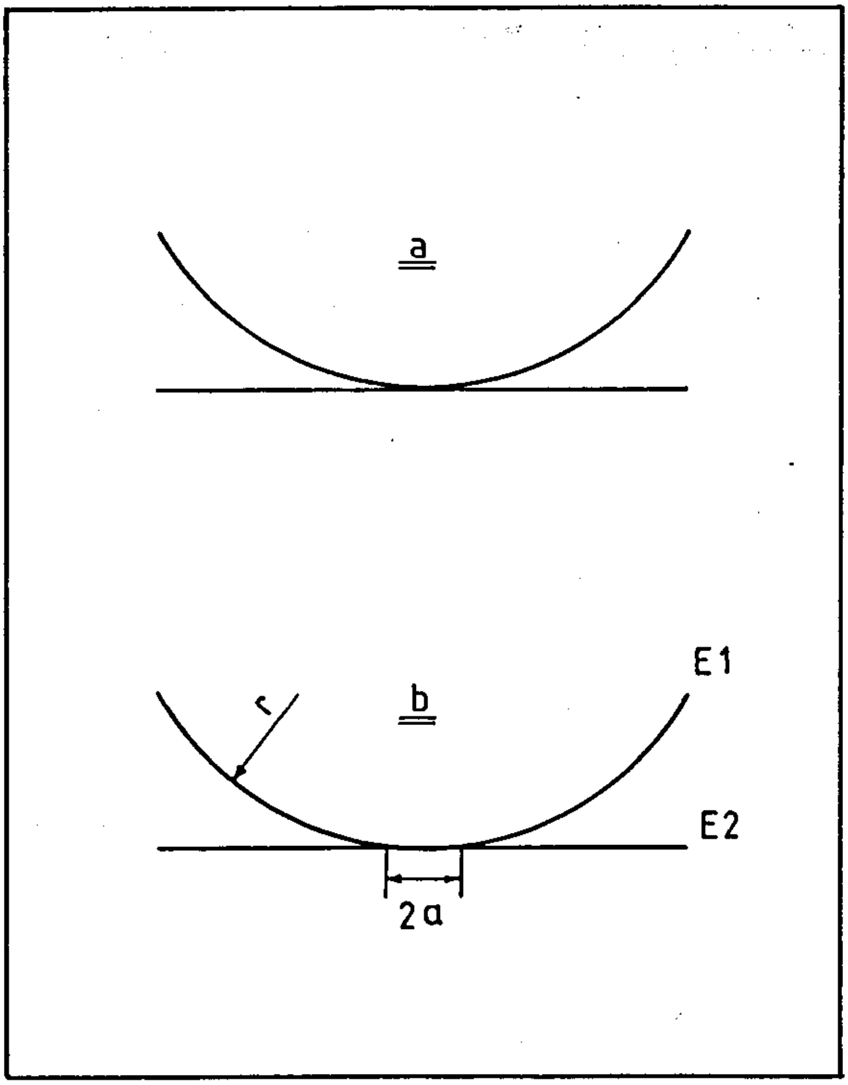


Fig. 2

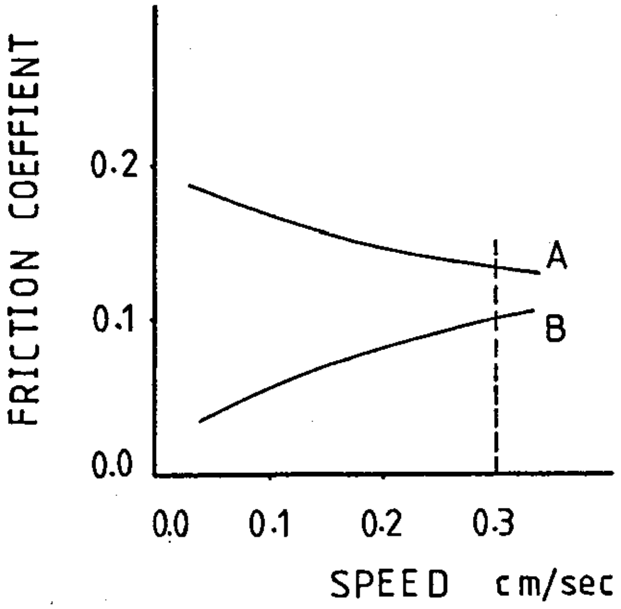

FRICTION COEFFIENT
0.2
0.1
0.0
A
B
0.0
0.1
0.2
0.3
SPEED cm/sec

Fig. 3

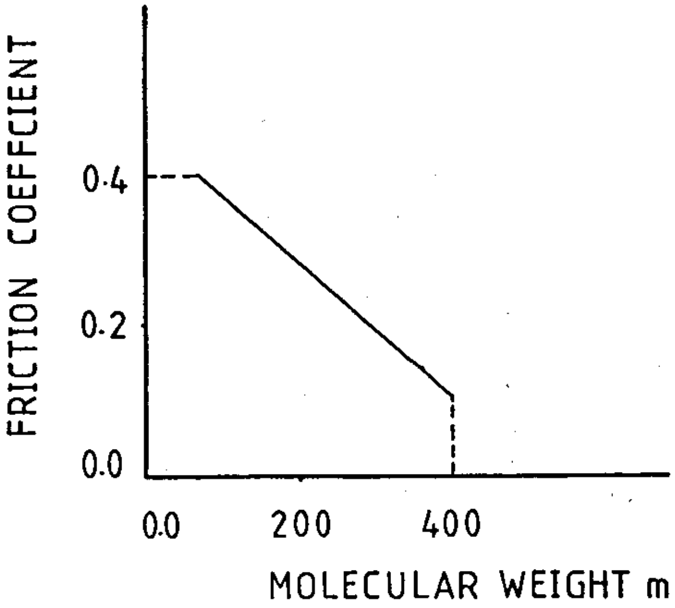

FRICTION COEFFCIENT
0.4
0.2
0.0
0.0
200
400
MOLECULAR WEIGHT m

Fig. 4

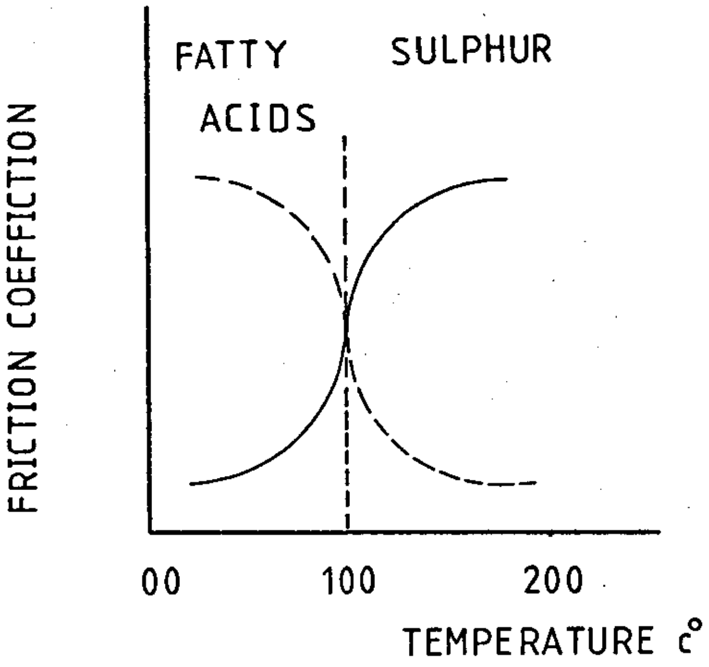

FATTY
ACIDS
SULPHUR
FRICTION COEFFICTION
00
100
200
TEMPERATURE c°

Fig. 5

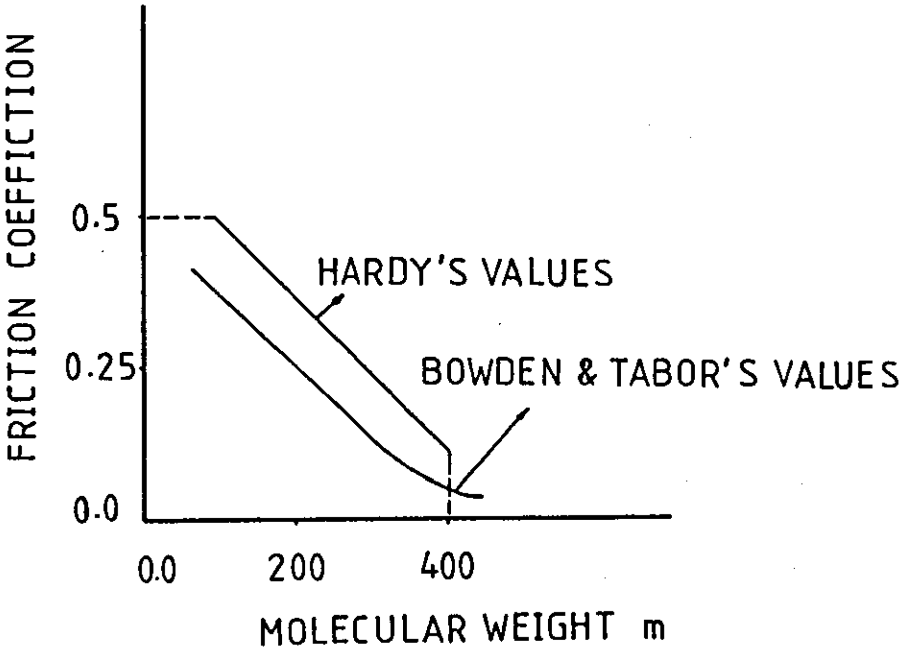

FRICTION COEFFICTION
0.5
0.25
0.0
HARDY'S VALUES
BOWDEN & TABOR'S VALUES
0.0
200
400
MOLECULAR WEIGHT m

Fig. 6

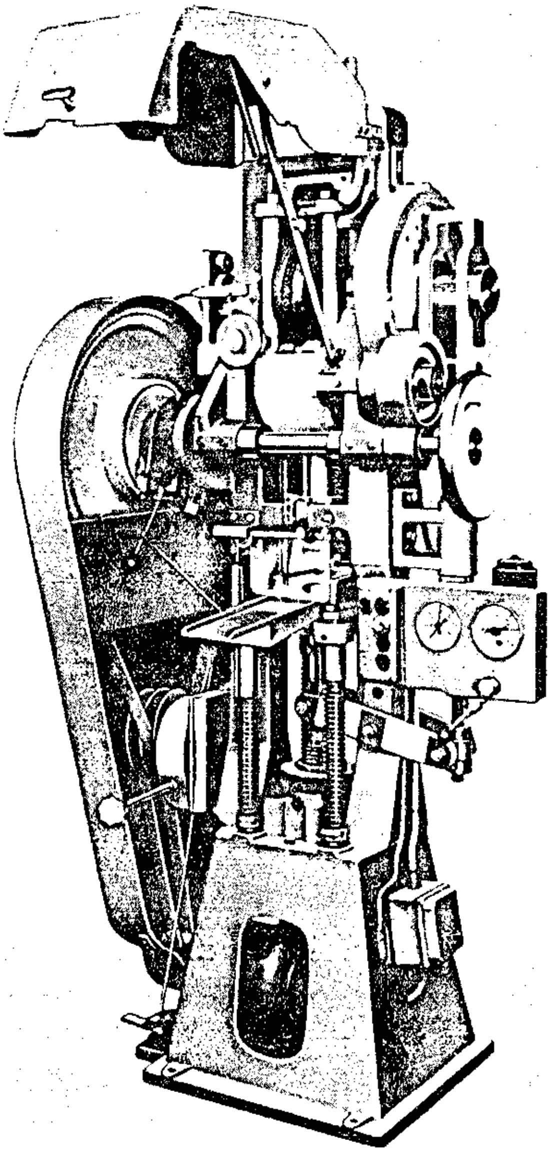


Fig.7 General View of the Press

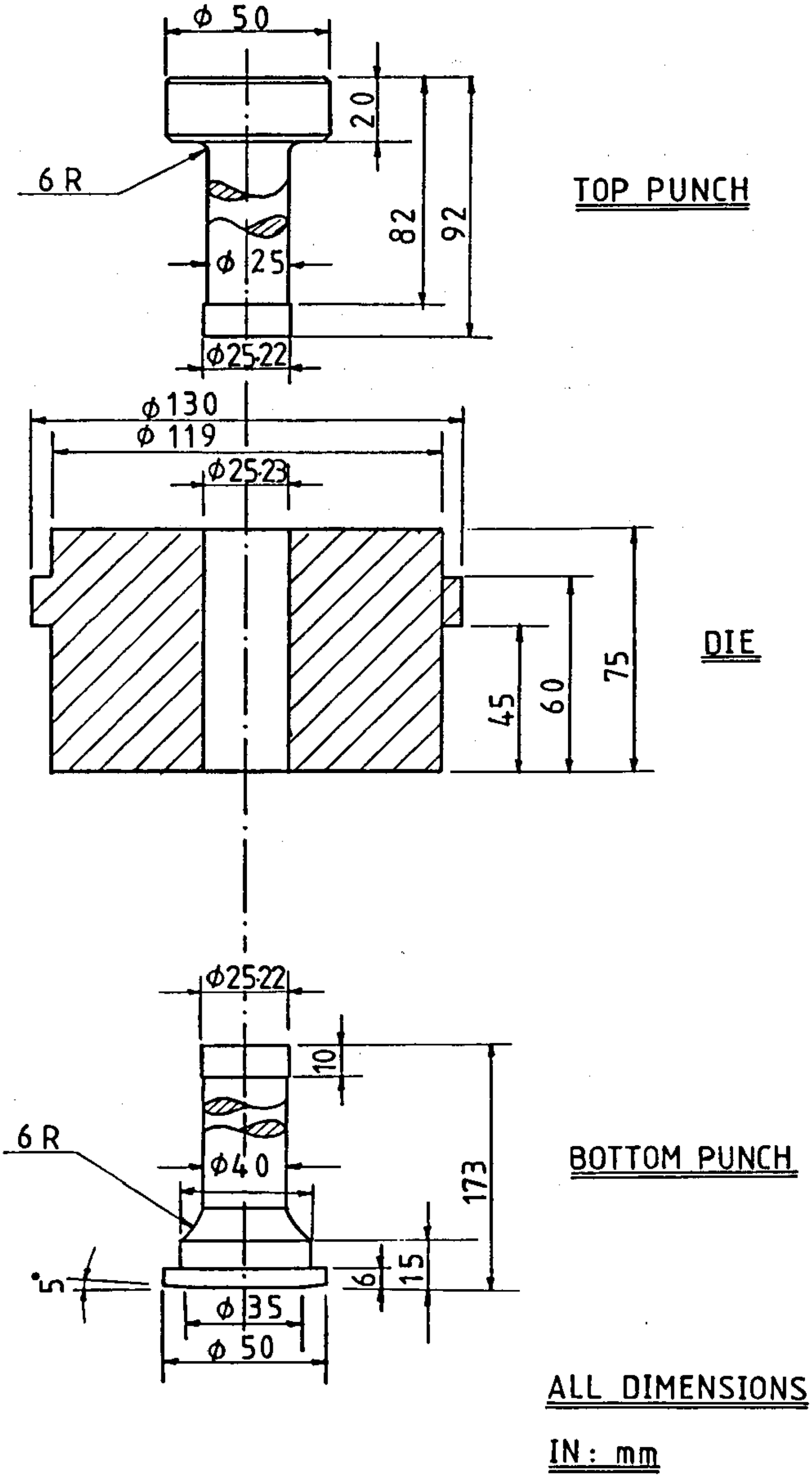

ϕ 50
20
82
92
6 R
ϕ 25
ϕ25·22
TOP PUNCH
ϕ130
ϕ 119
ϕ25·23
75
60
45
DIE
ϕ25·22
10
173
6 R
ϕ40
BOTTOM PUNCH
5°
6
15
ϕ 35
ϕ 50
ALL DIMENSIONS
IN: mm

Fig. 8

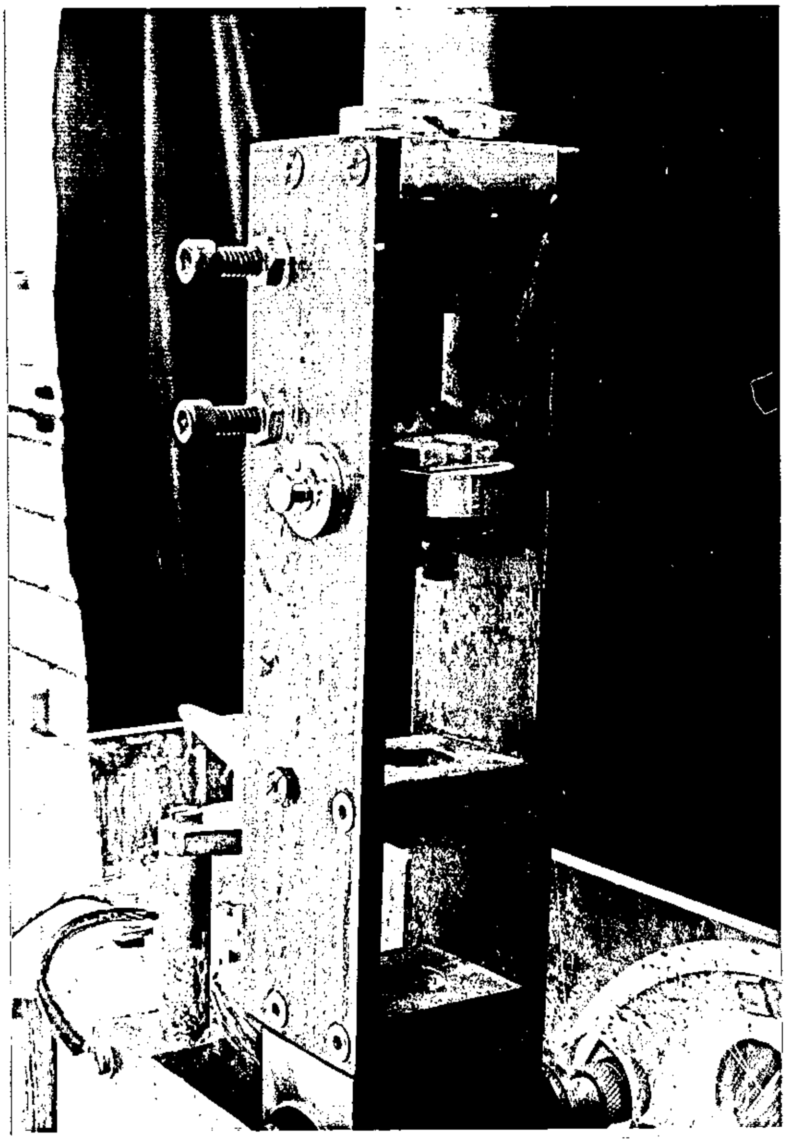


Fig. 9 Specimen Holder of Pin and Disc Machine

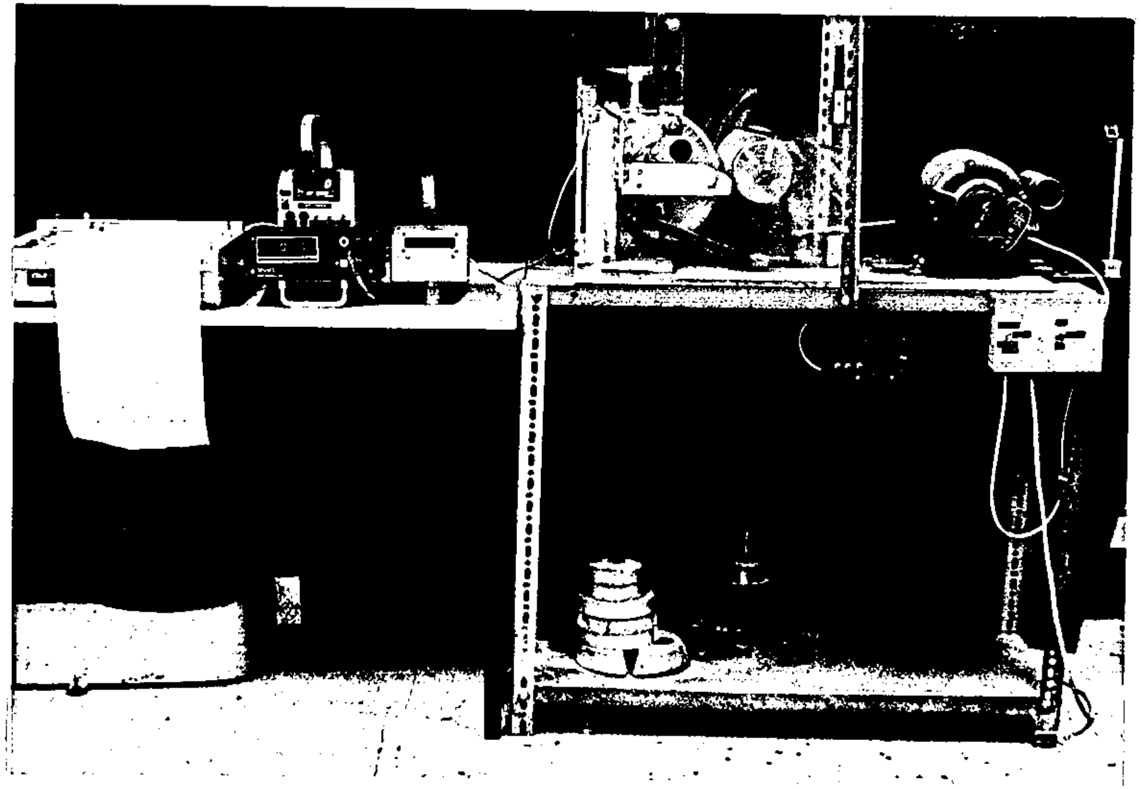


Fig. 10 The Pin and Disc Machine

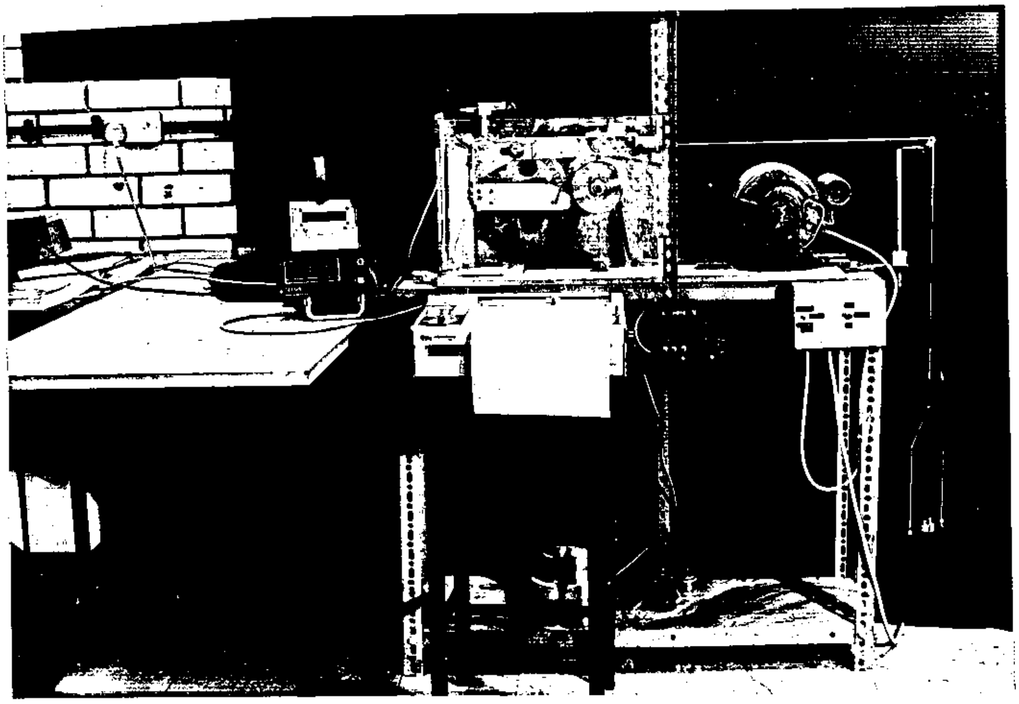


Fig.11 The Pin and Disc Machine during the Calibration

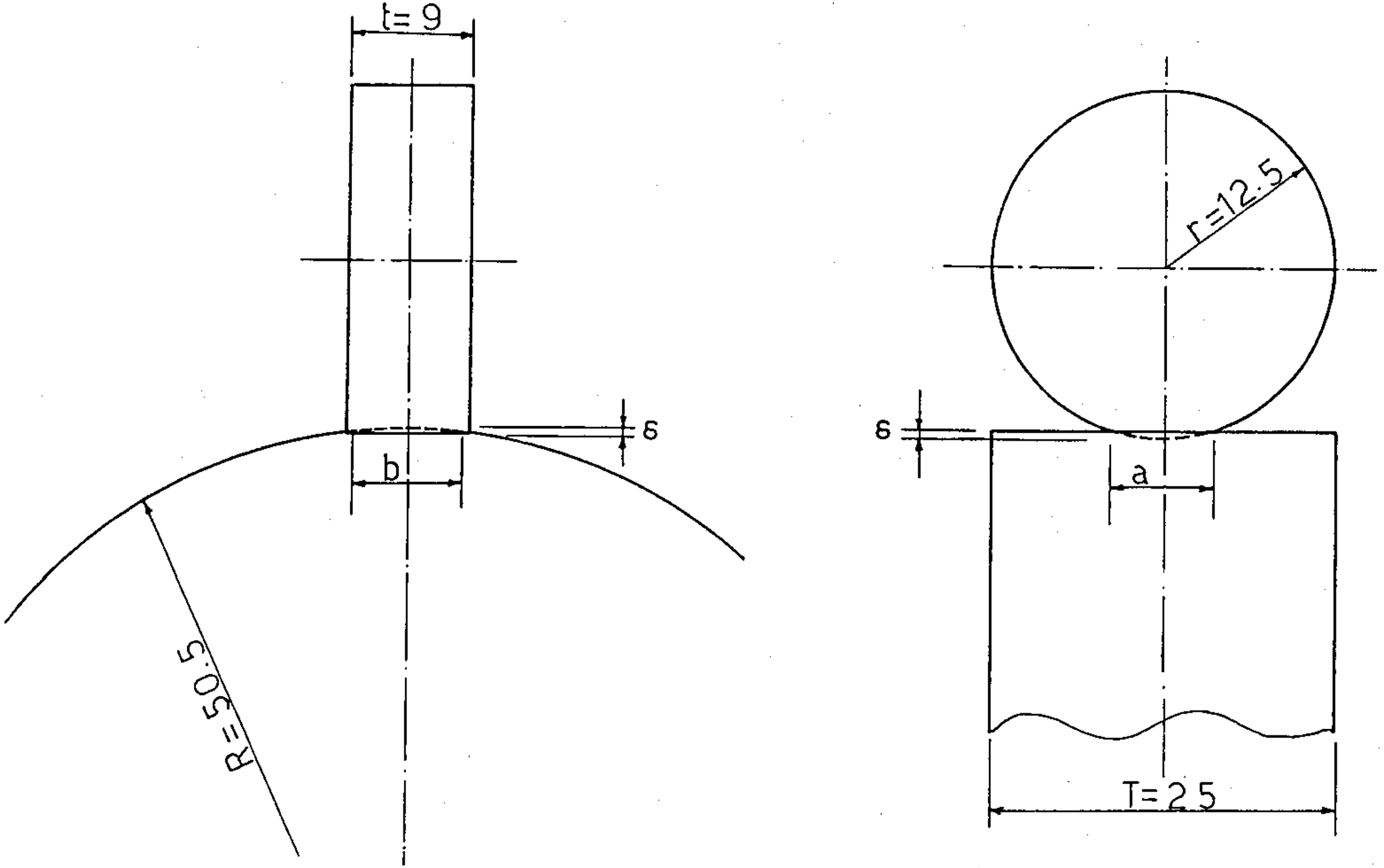


Fig. 12

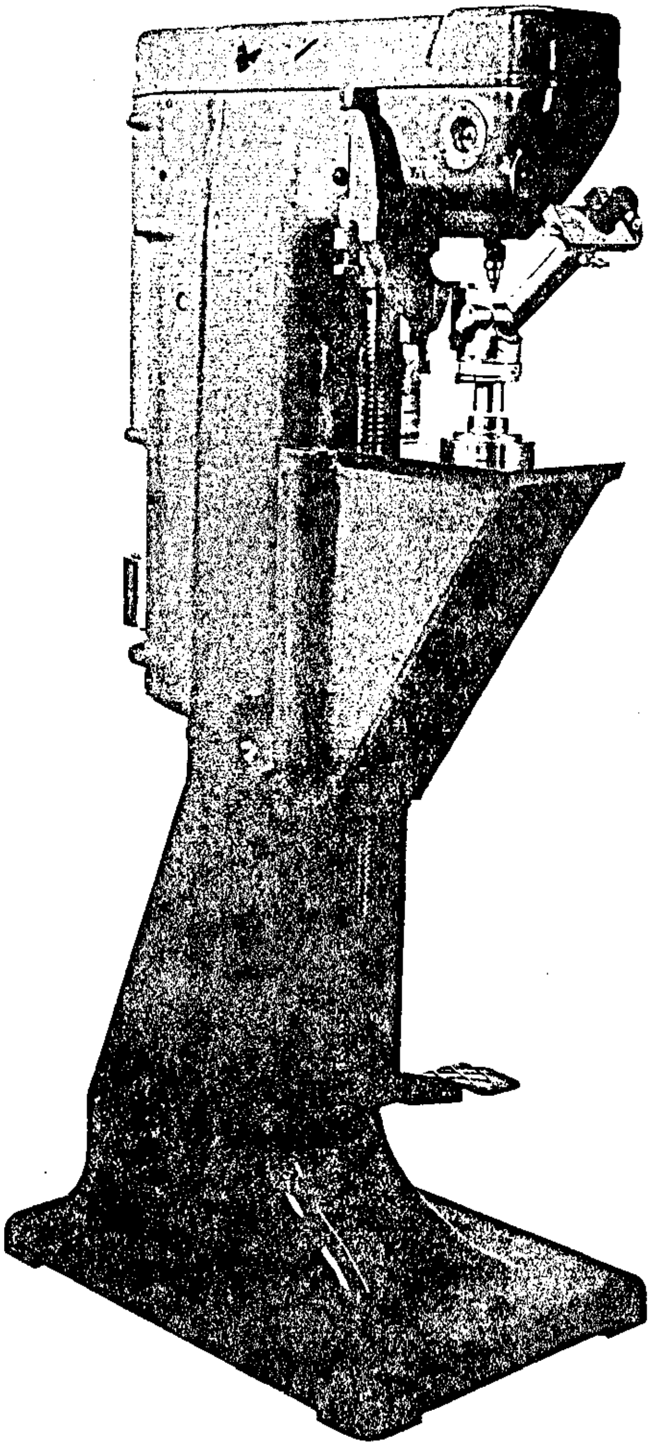


Fig. 13 Vickers Pyramid Hardness Testing Machine

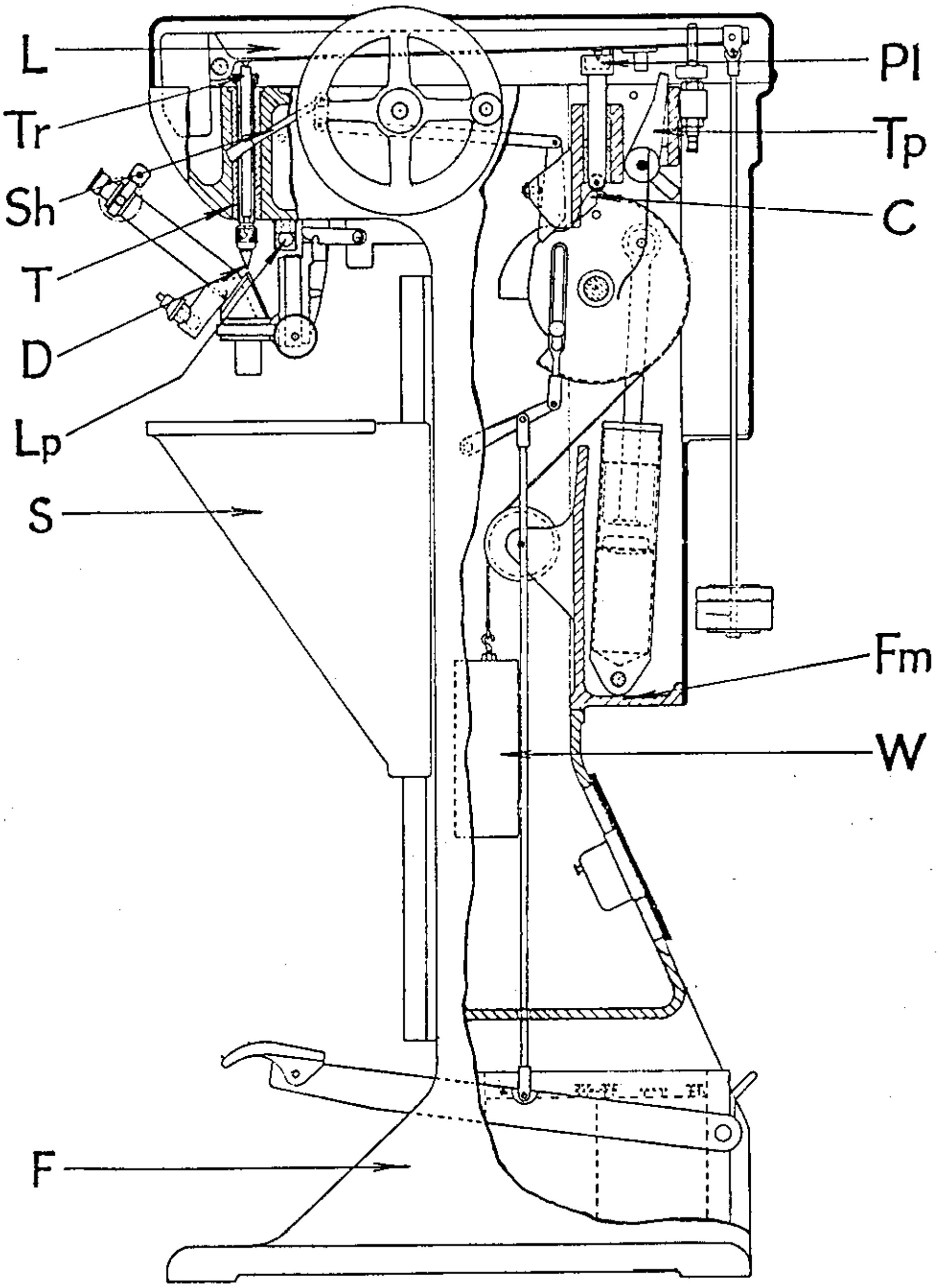


Fig. 14 Vickers Pyramid Hardness Testing Machine
General Arrangement Diagram

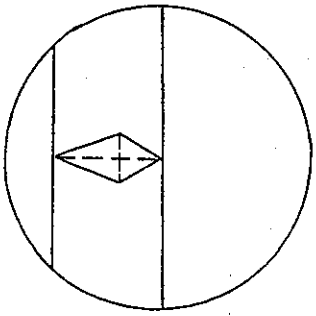


Fig. 15 The impression

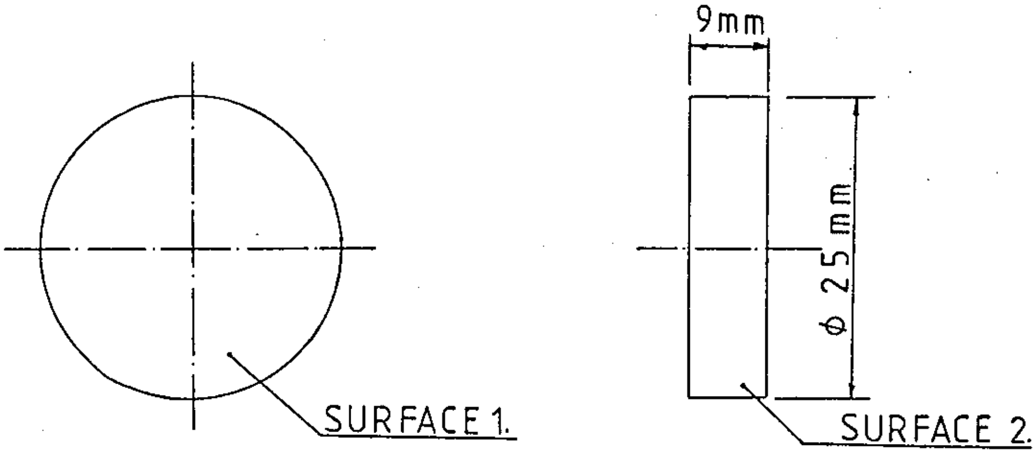


Fig. 16 The examined surfaces

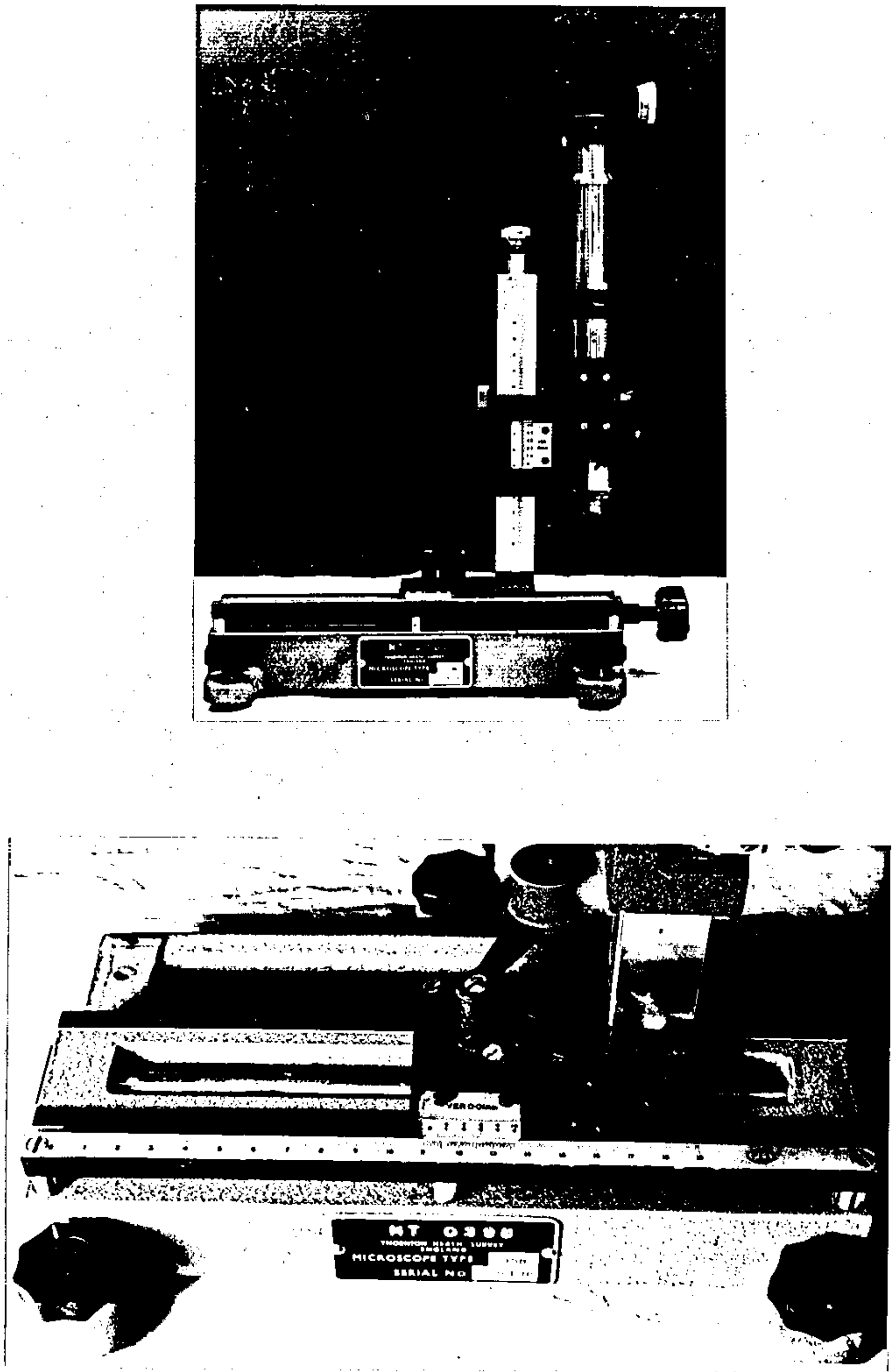


Fig. 17 Travelling Microscope

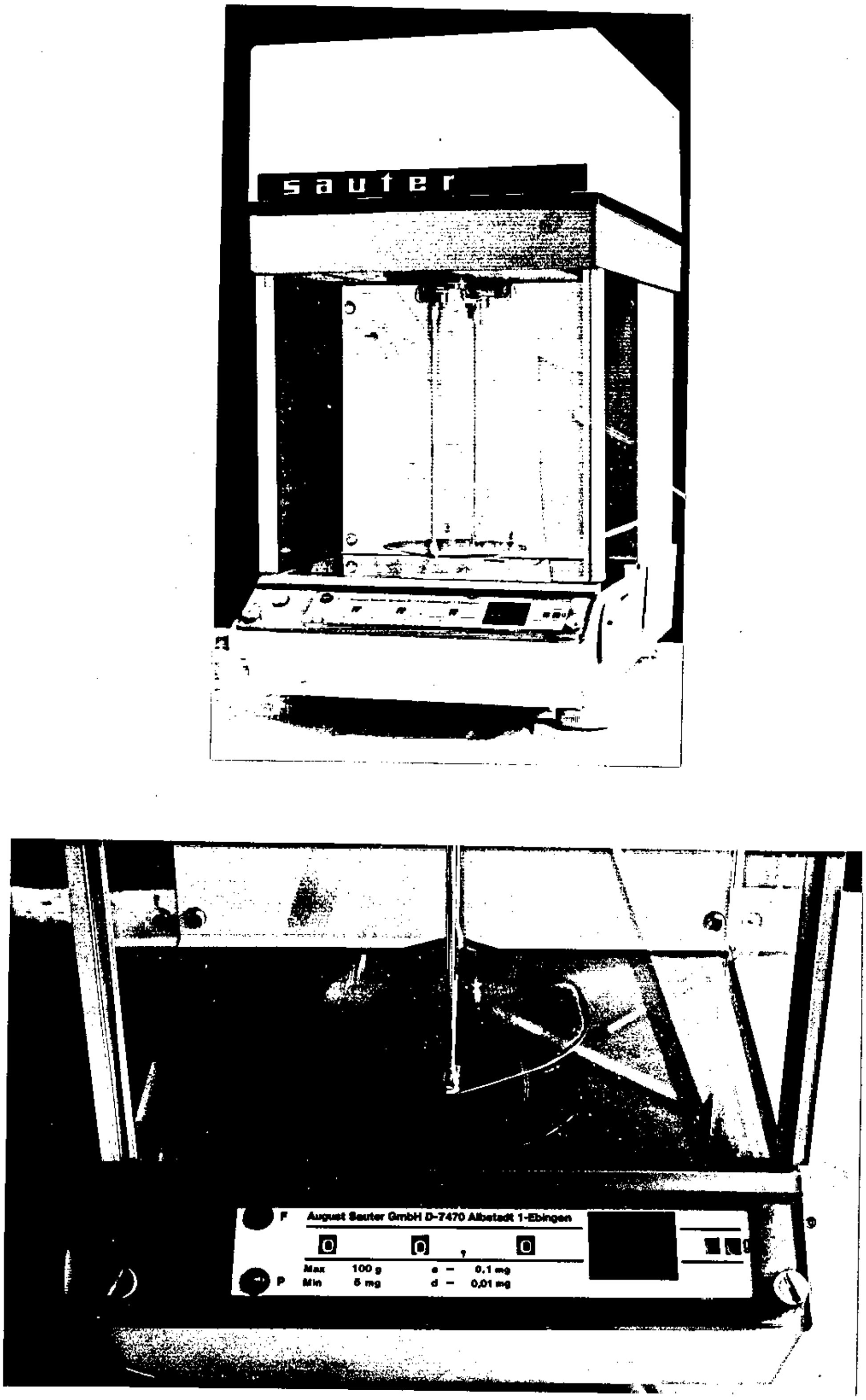


Fig. 18 General View of the Balance

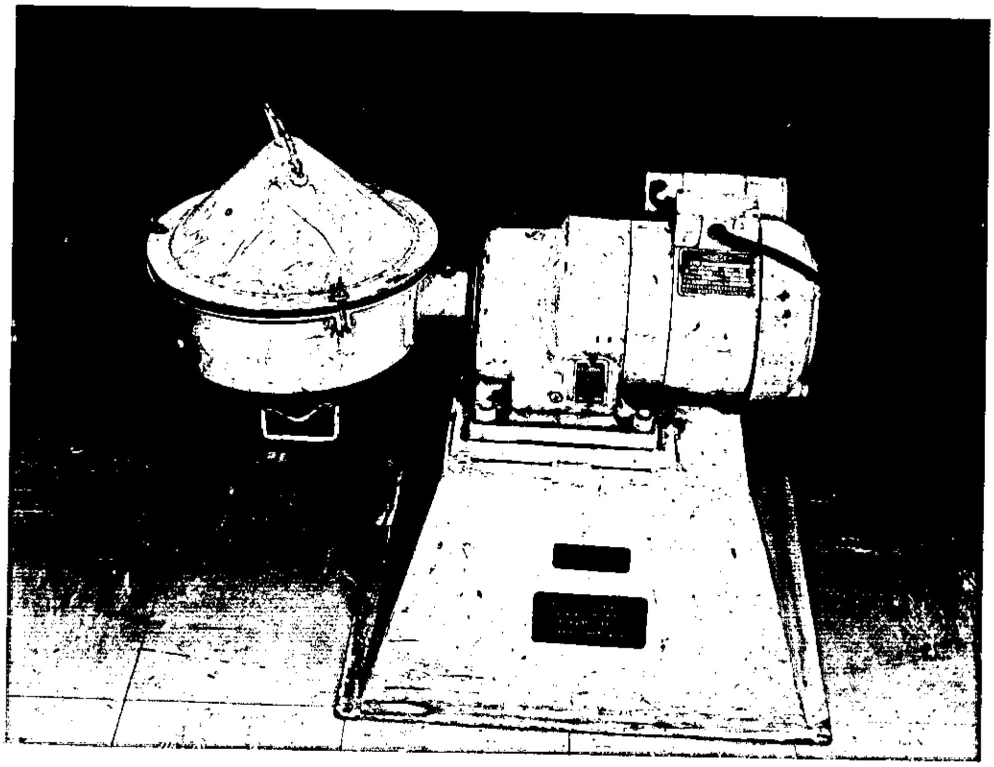


Fig. 19 General View of the Powder Mixer

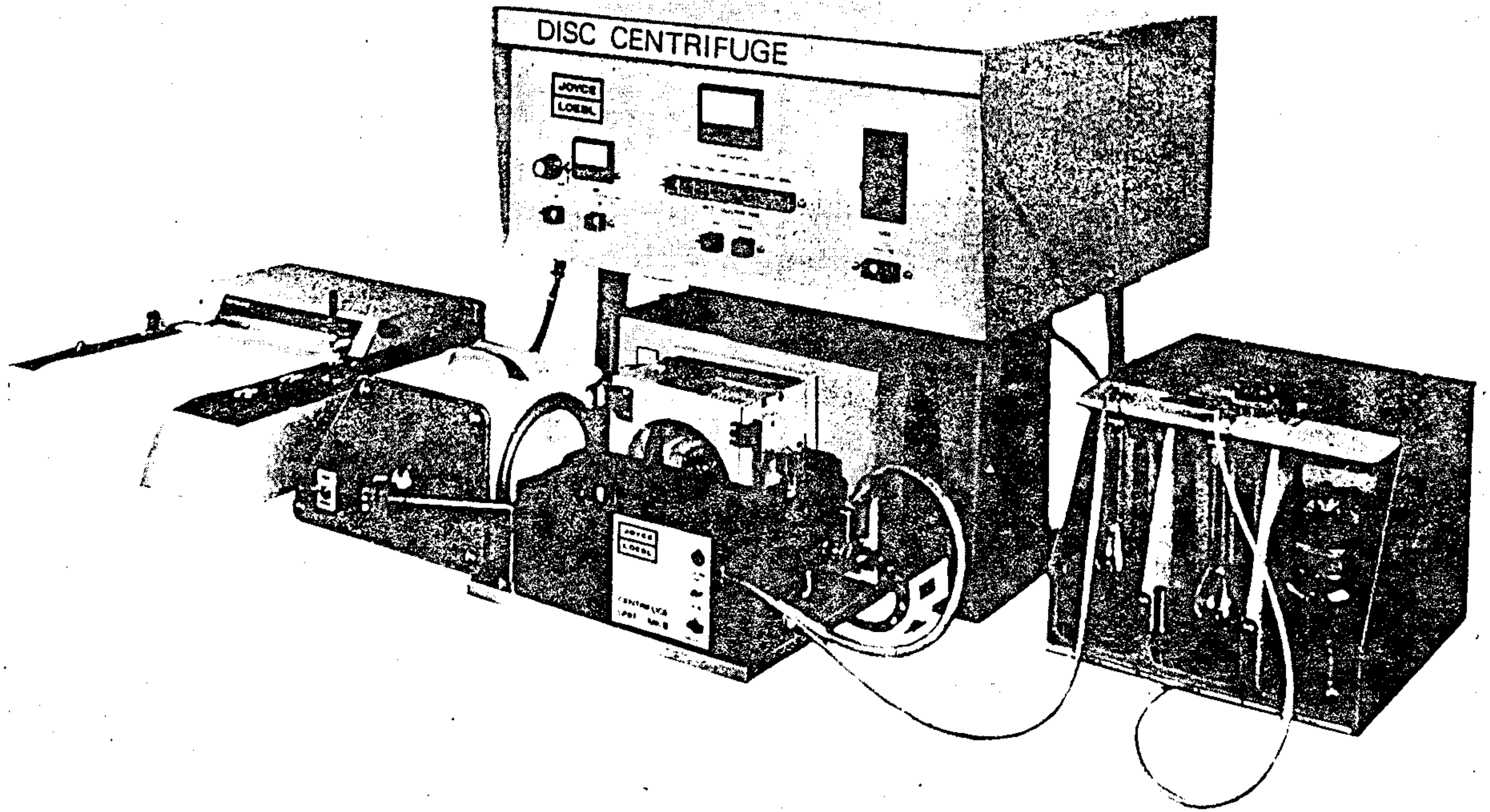


Fig. 20 Disc Centrifuge with Photosedimentometer

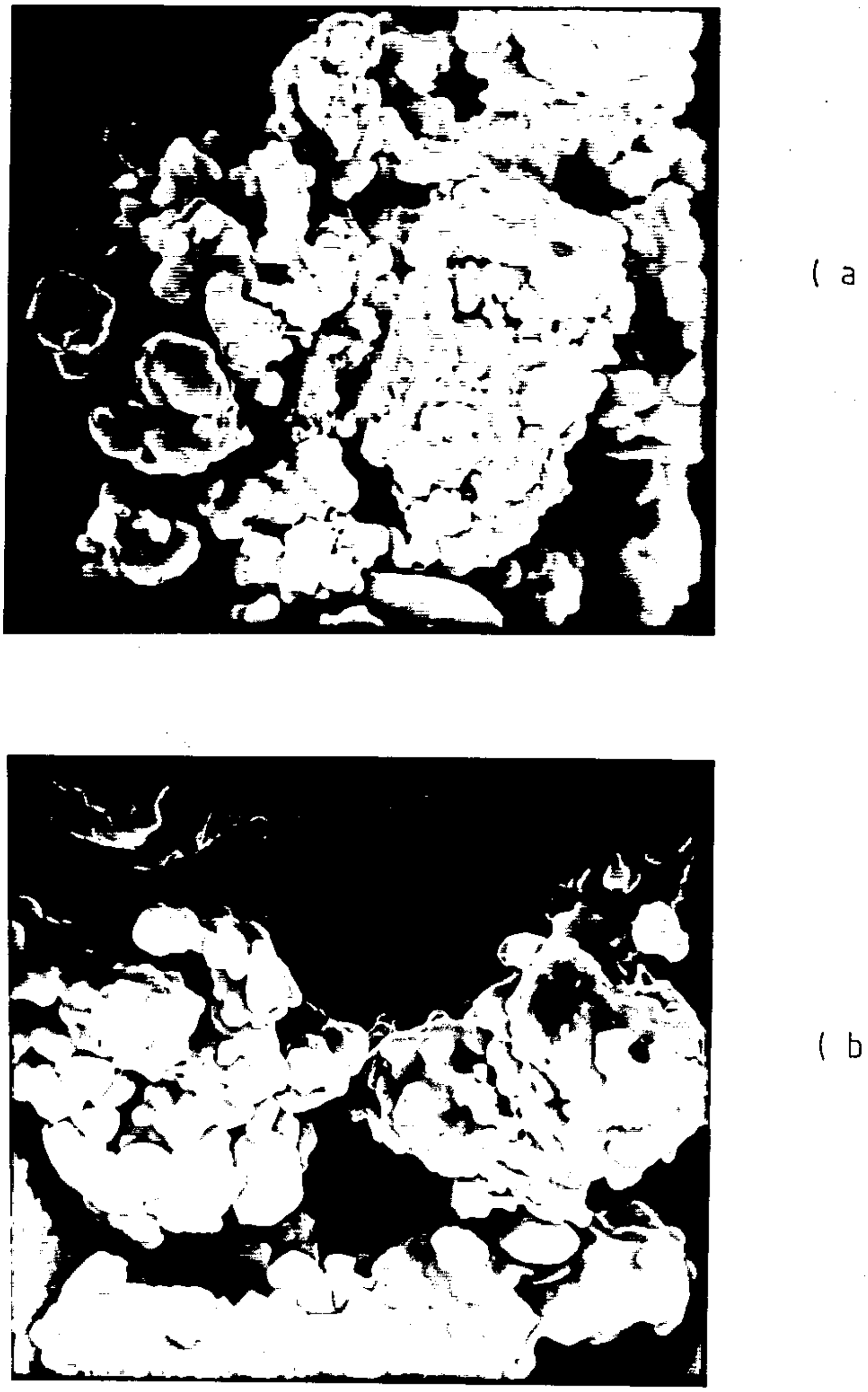


Fig. 21 S.E.M Photographs for Iron Powder_a)X300 ; b)X500

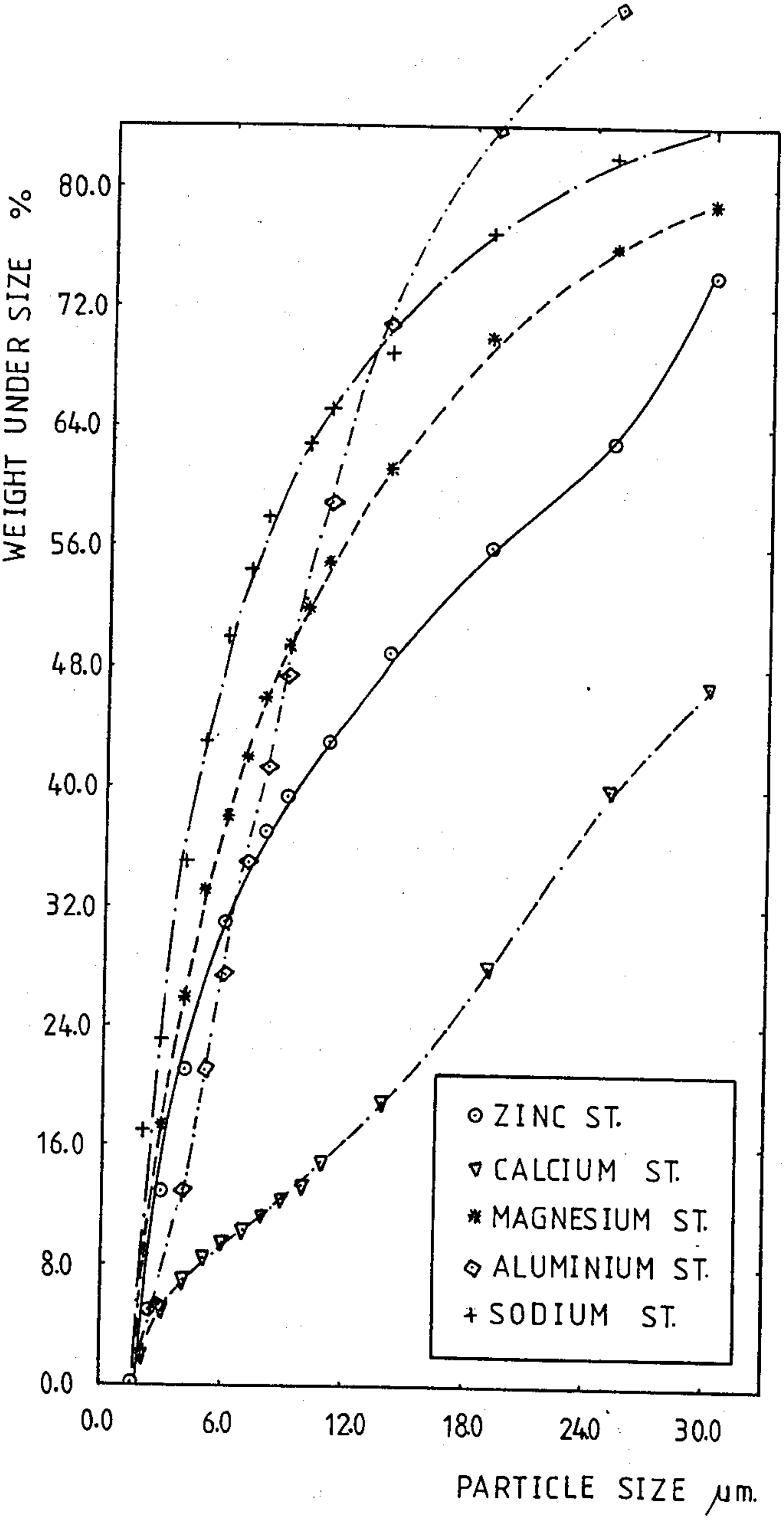
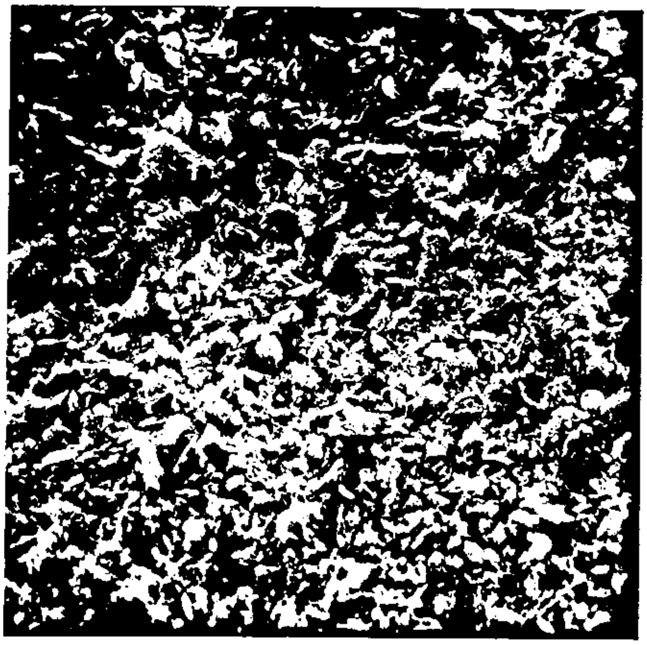

WEIGHT UNDER SIZE %
80.0
72.0
64.0
56.0
48.0
40.0
32.0
24.0
16.0
8.0
0.0
0.0
6.0
12.0
18.0
24.0
30.0
PARTICLE SIZE μm.
⊙ ZINC ST.
▽ CALCIUM ST.
* MAGNESIUM ST.
◇ ALUMINIUM ST.
+ SODIUM ST.

Fig. 22

( 1

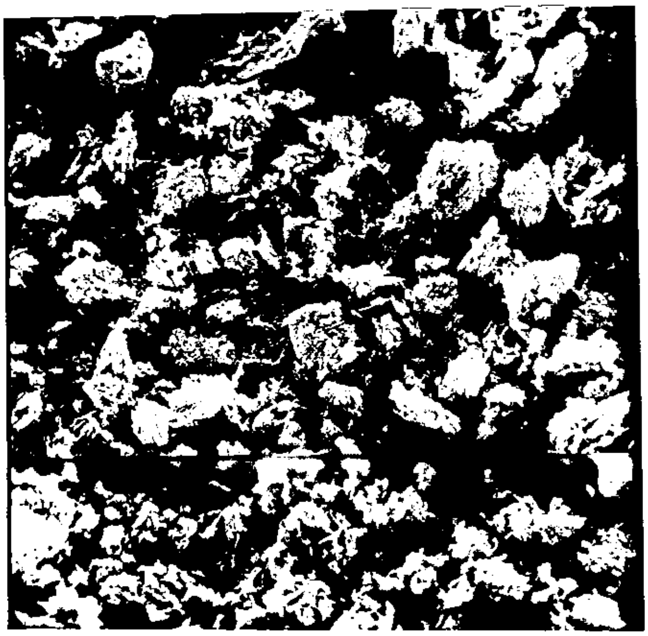


( 2

Fig. 23 S.E.M Photographs for Lubricants
1 ) Zinc ; 2 ) Calcium ; 3 ) Sodium
4 ) Aluminium ; 5 ) Magnesium
All Photographs at X 450

( 3

( 4



( 5

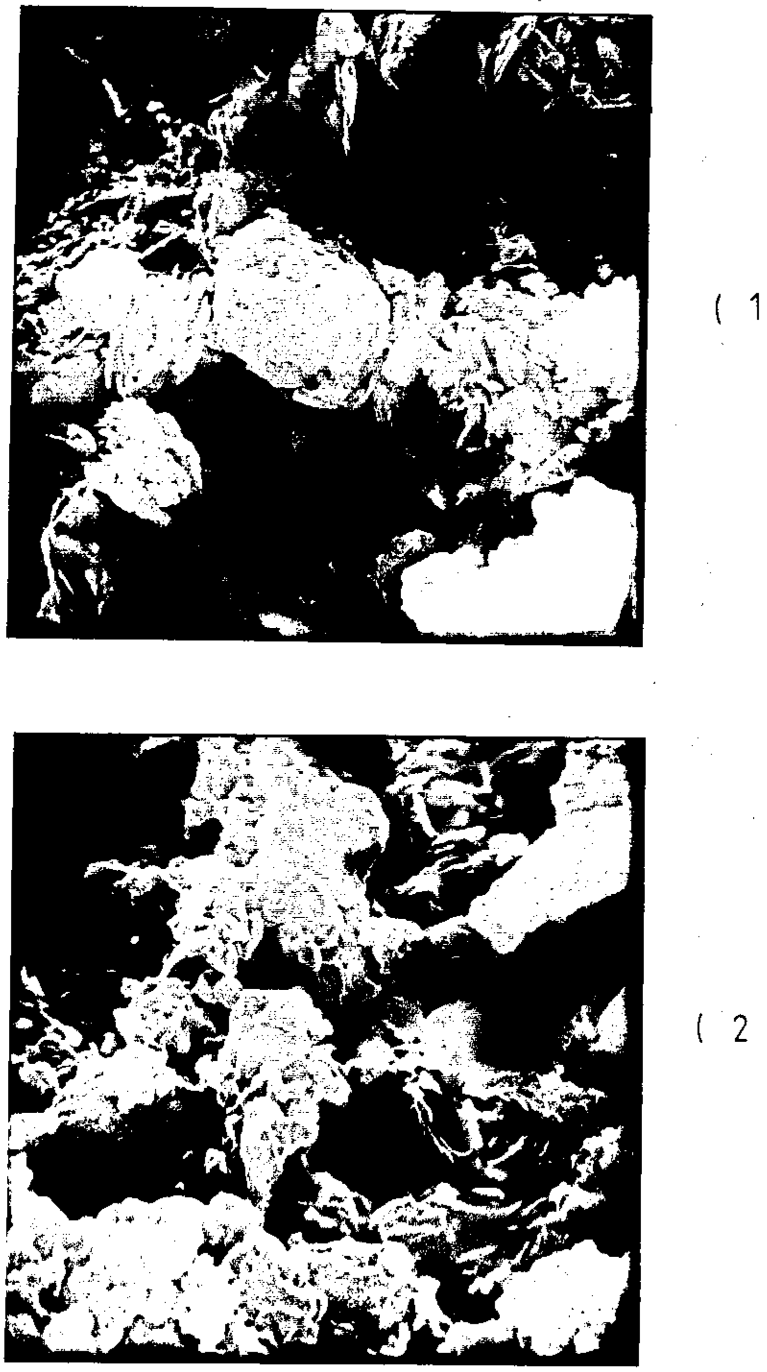
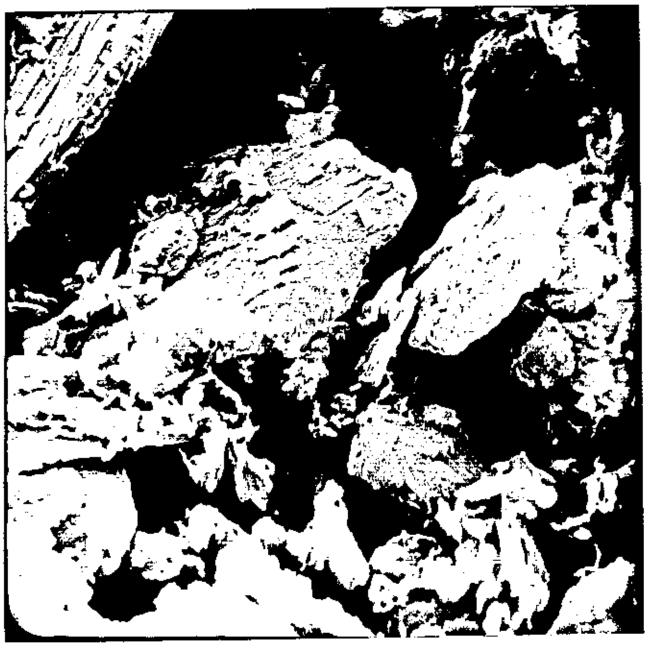


Fig. 24 S.E.M Photographs for Lubricants
1) Zinc ; 2) Calcium ; 3) Sodium
4) Aluminium ; 5) Magnesium.
All Photographs at X 1800



( 3

( 4

( 5

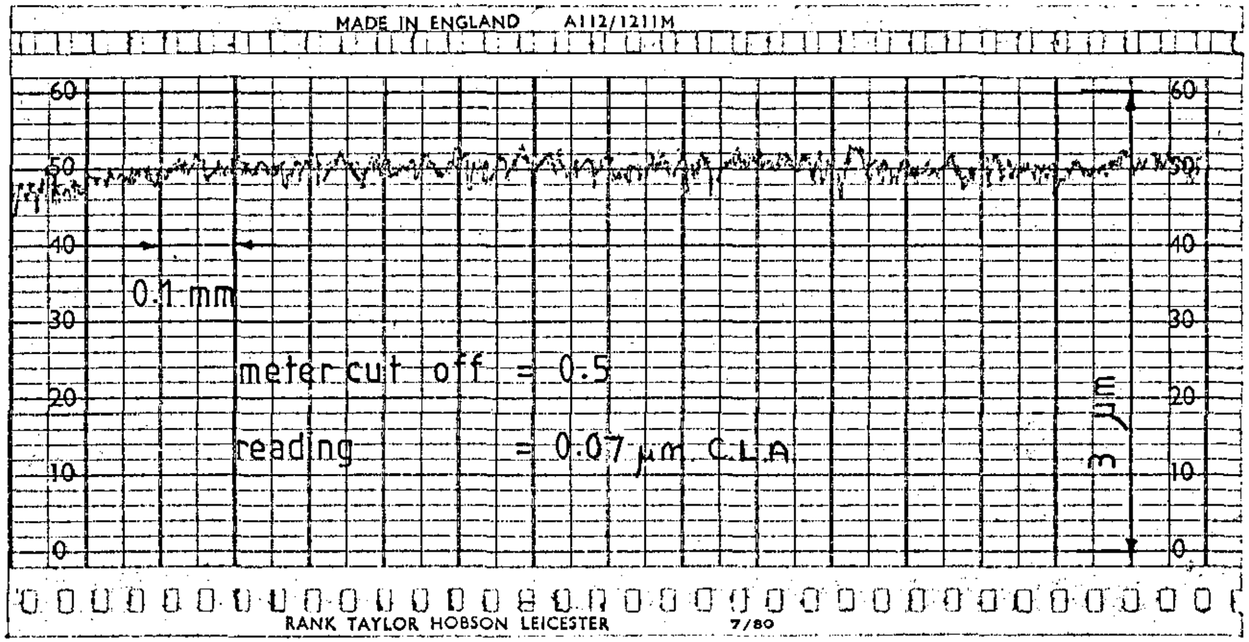


Fig. 25 Talysurf trace for disc surface before run

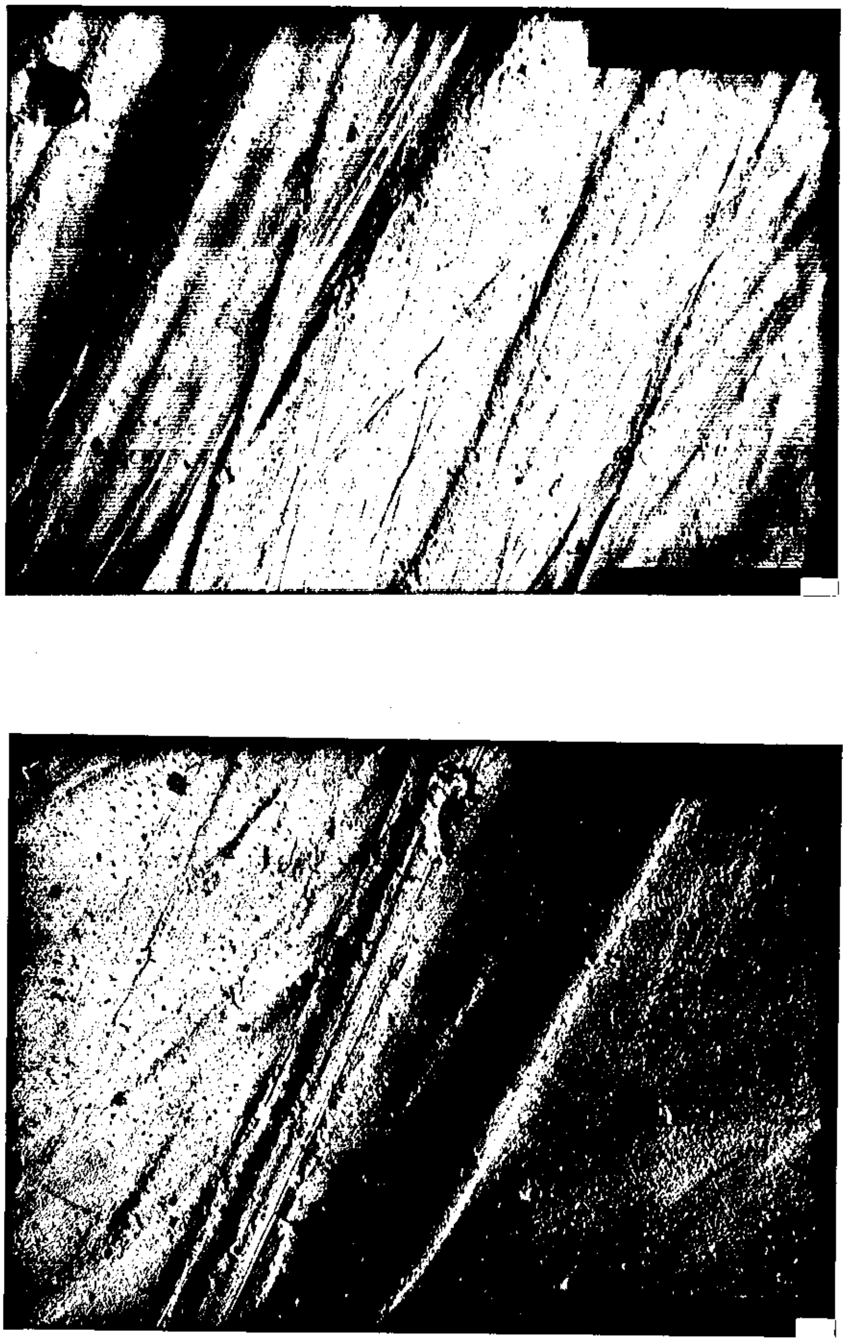


Fig. 26 T.E.M. Photographs for the disc surface before run taken by replica.
All photogrphs at : X 6200

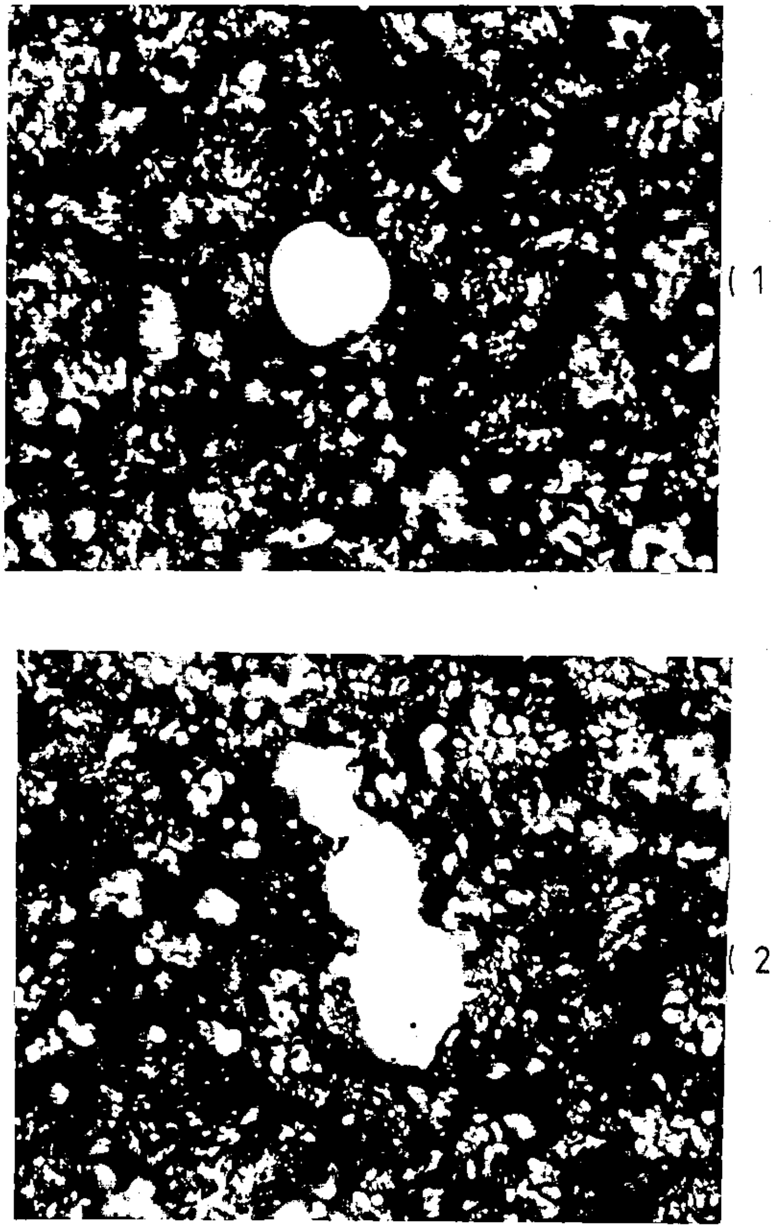
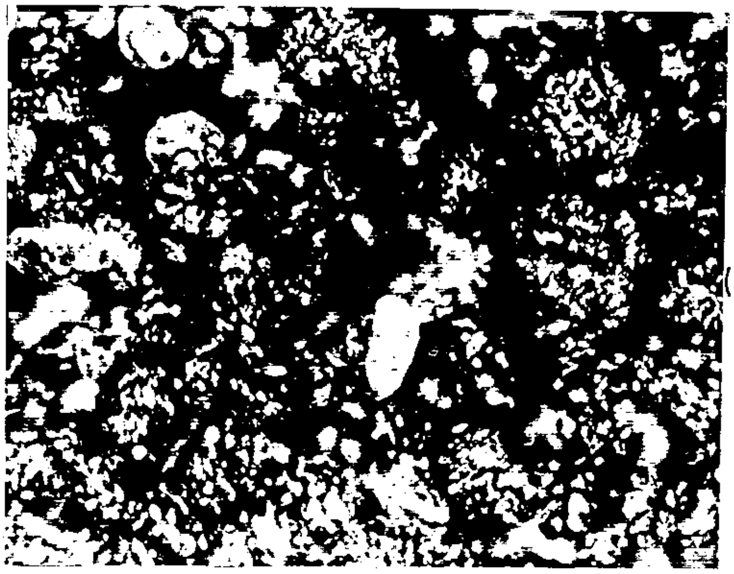
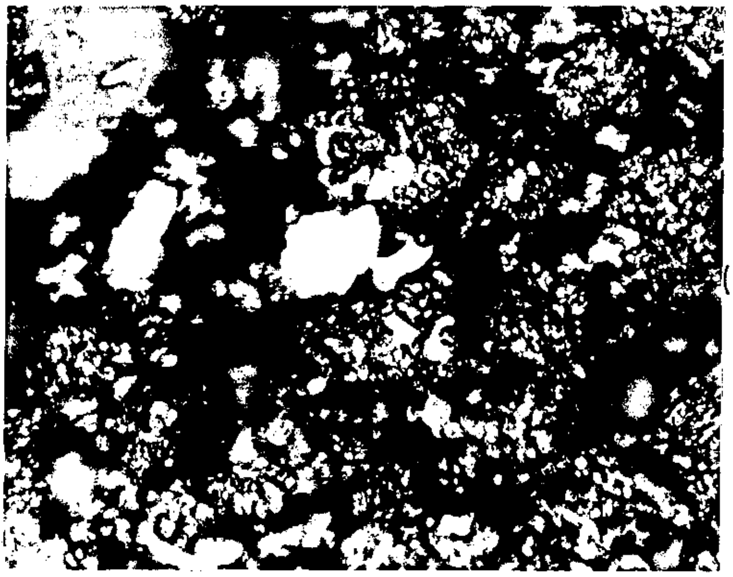


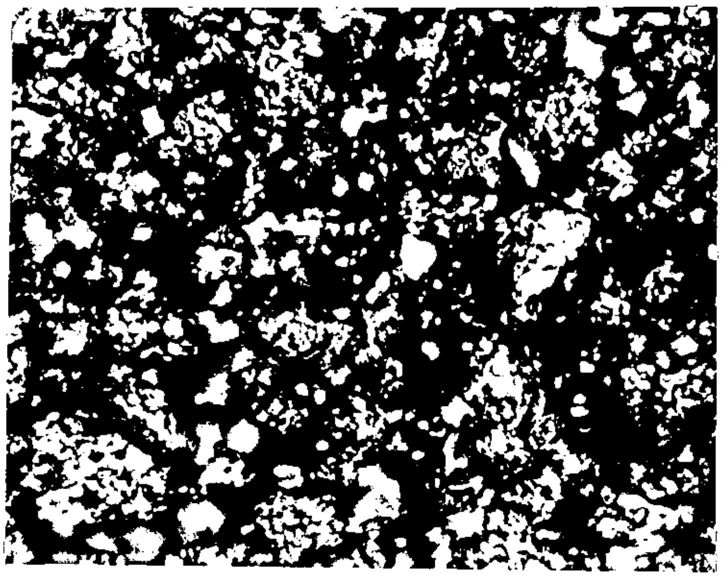
Fig. 27 O.M. Photographs for Iron and different Stearates Mixtures.
1) Zinc, 2) Calcium, 3) Sodium, 4) Aluminium, 5) Magnesium and Iron Powder. All Photographs at X 150.



( 3



( 4



( 5

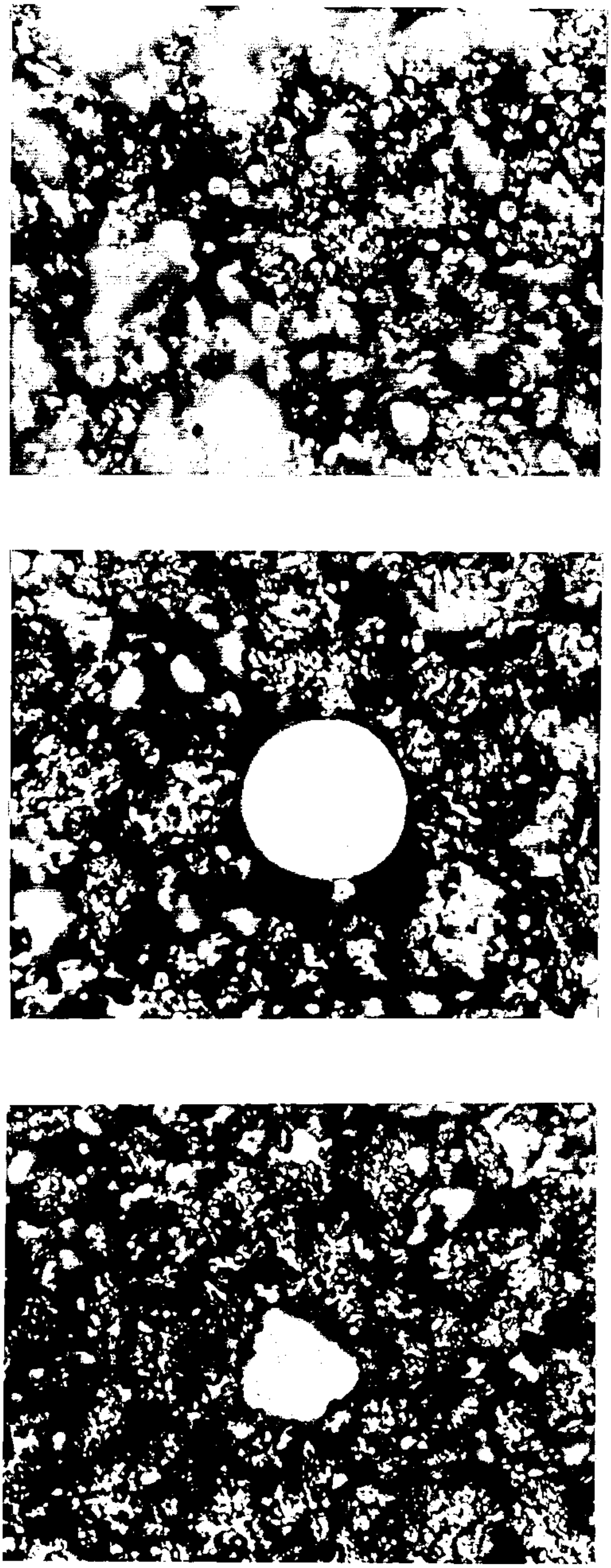


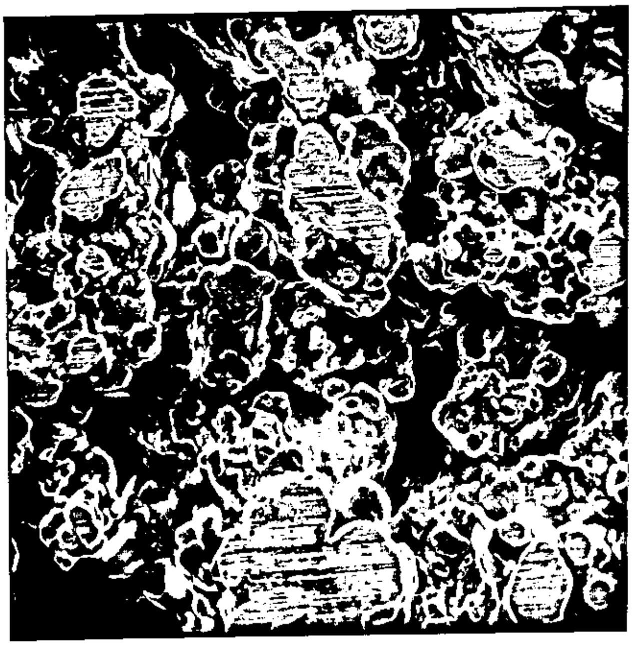
Fig. 28

O.M. Photographs for Iron and Zinc Stearate Powders Mixture.

Lubricant contents:

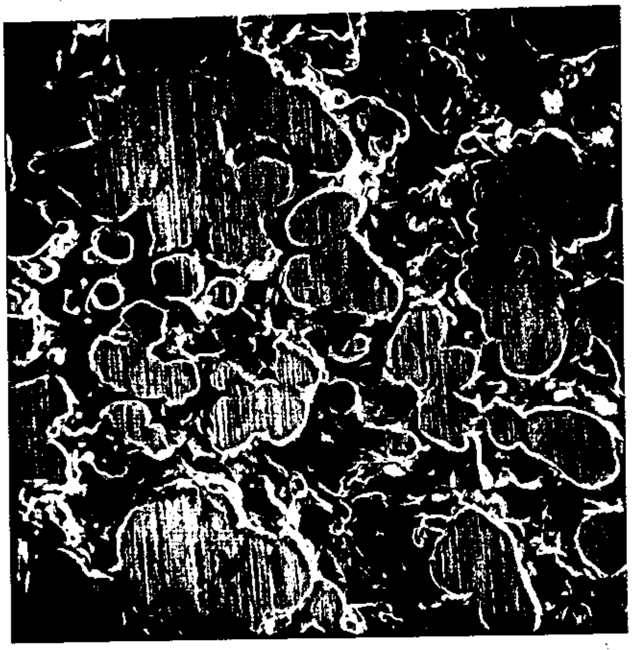
1) 0.5 ; 2) 1.0 ; 3) 1.5 wt%.

All Photographs at: X150.

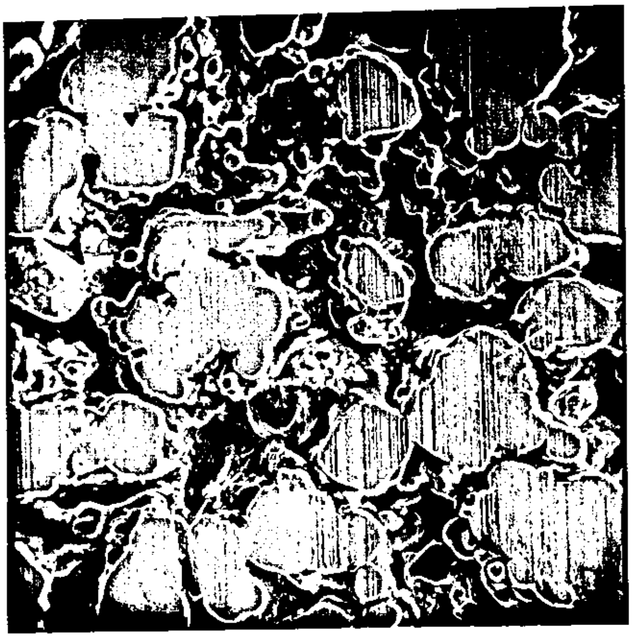

( 1


( 2

Fig. 29a S.E.M Photographs for Surfaces of Calcium Stearate Specimens Densities: 1) 5.55 ; 2) 5.93 ; 3) 6.3 ; 4) 6.5 ; 5) 6.8 g/cm$^3$. All Photographs at X450

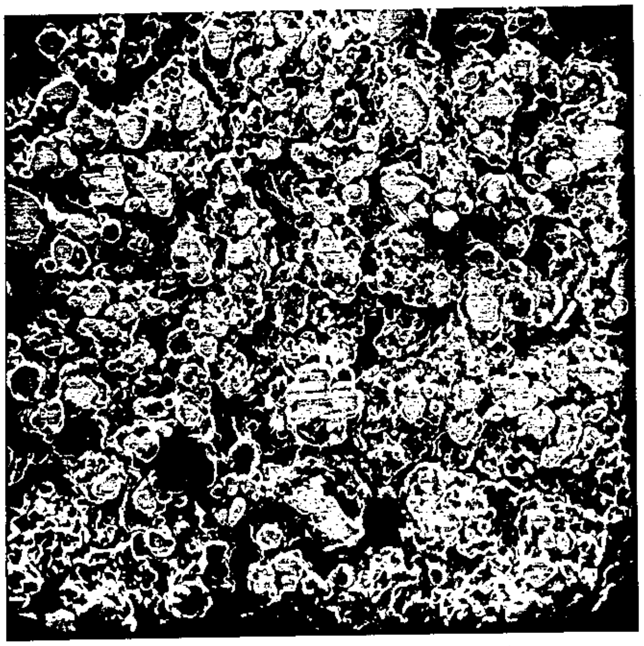


( 3

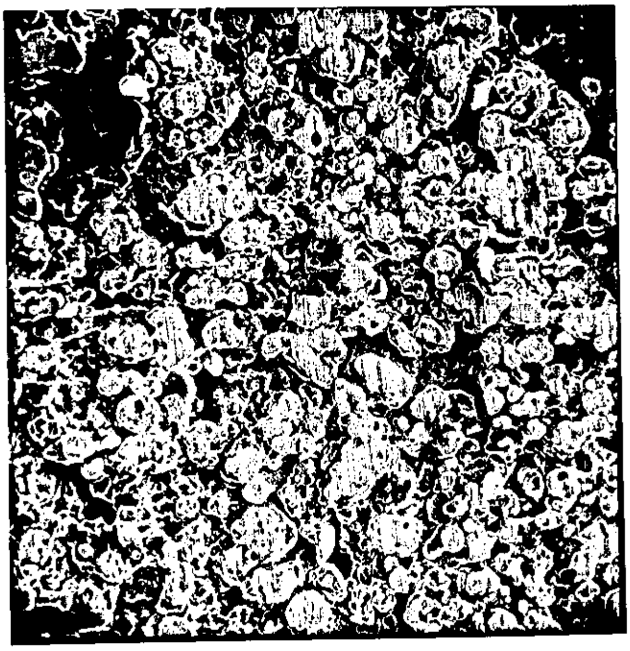


( 4

( 5

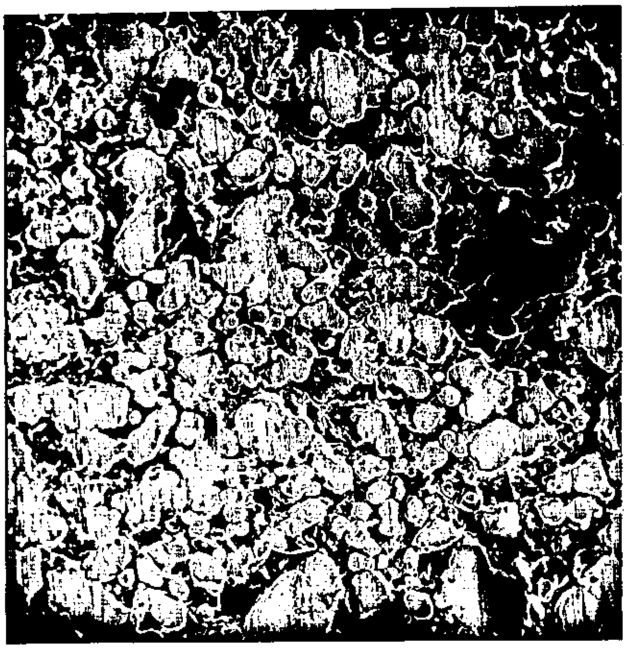


( 1

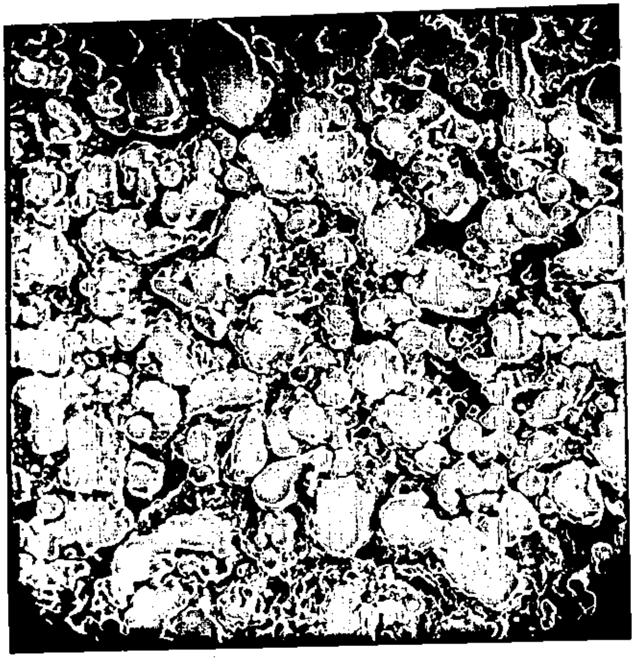


( 2

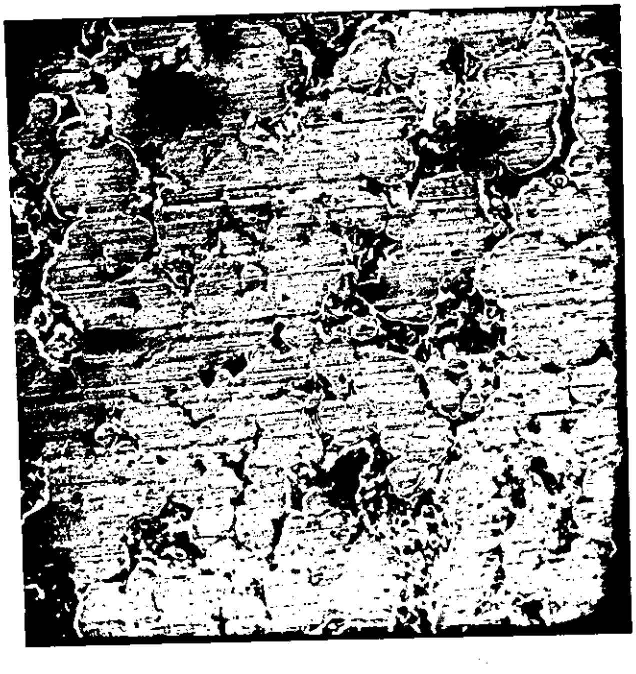
Fig. 29b S.E.M Photographs for Surfaces of Calcium Stearate Specimens Densities: 1) 5.5 ; 2) 5.9 ; 3) 6.3; 4) 6.5 ; 5) 6.8 g/cm$^3$.
All Photographs at X 180



( 3



( 4



( 5

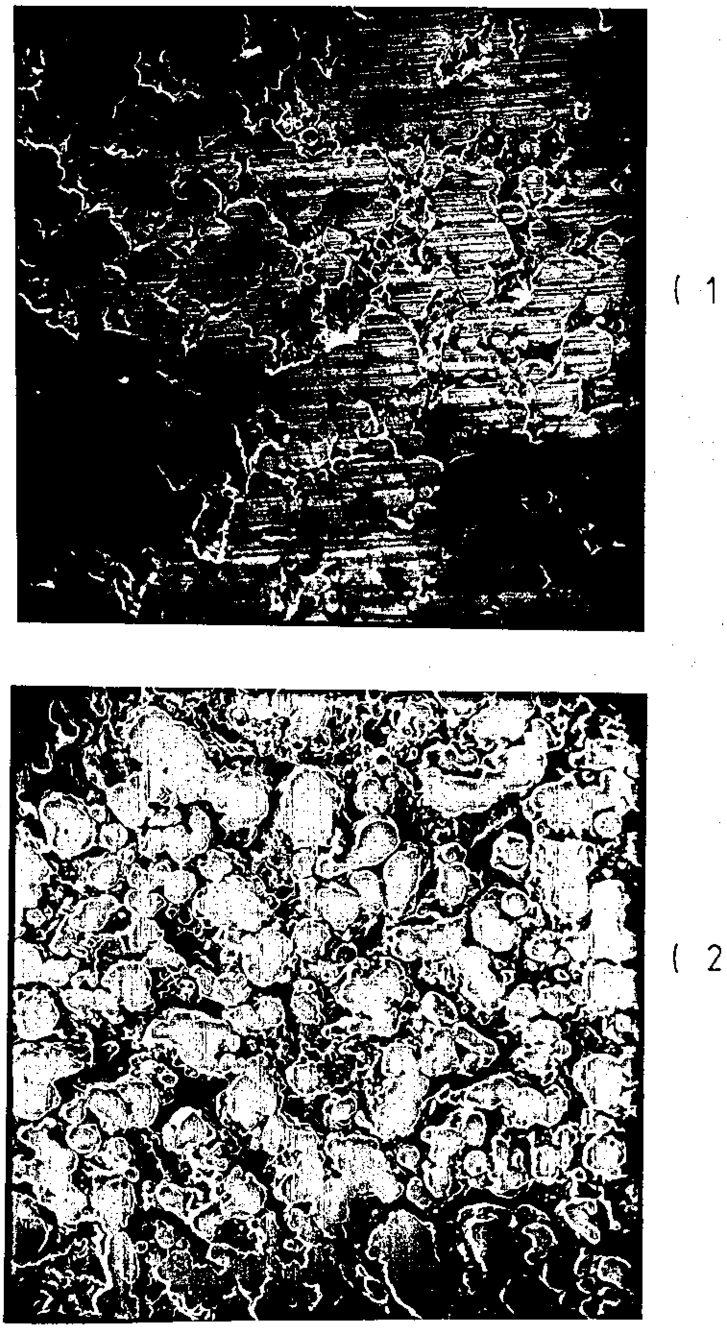
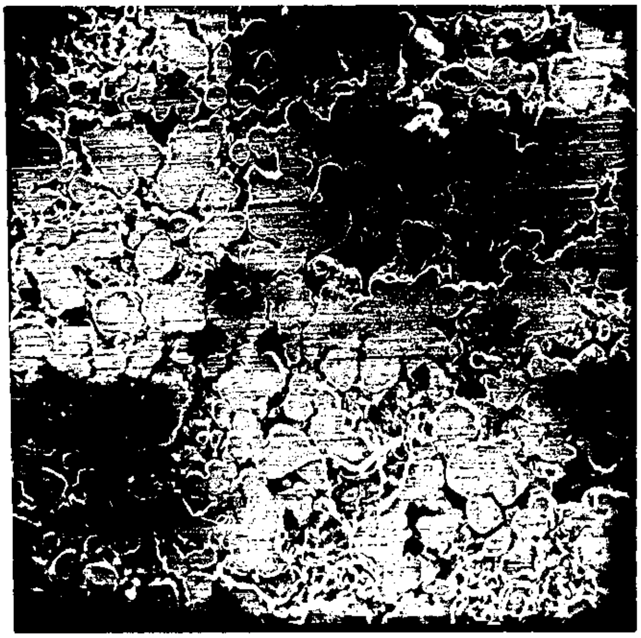
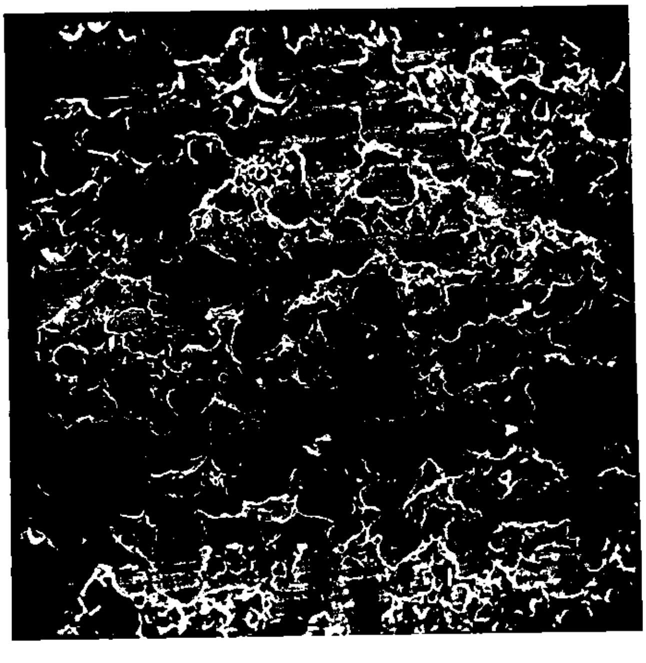


Fig. 30a S.E.M Photographs for Surfaces of
Specimens with different Stearate
1 ) Zinc ; 2 ) Calcium ; 3 ) Sodium
4 ) Aluminium ; 5 ) Magnesium
All Photographs at X180



( 3

( 4



( 5

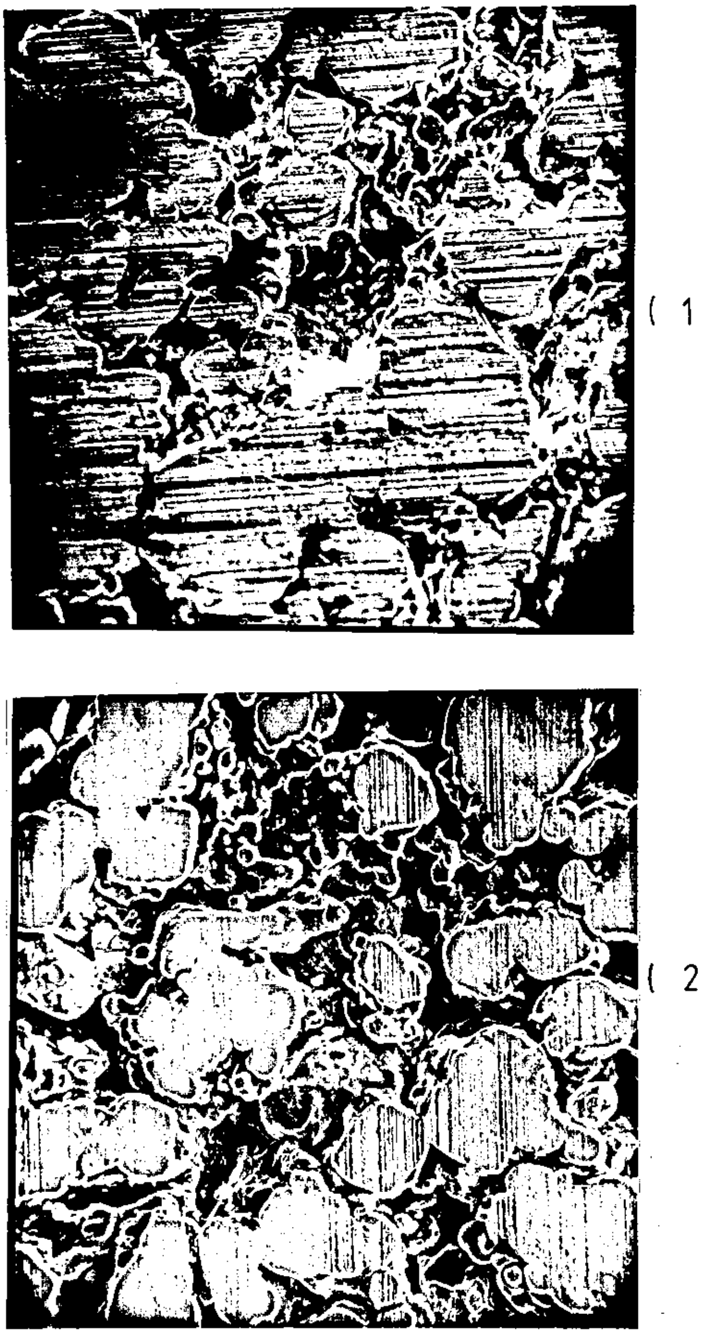
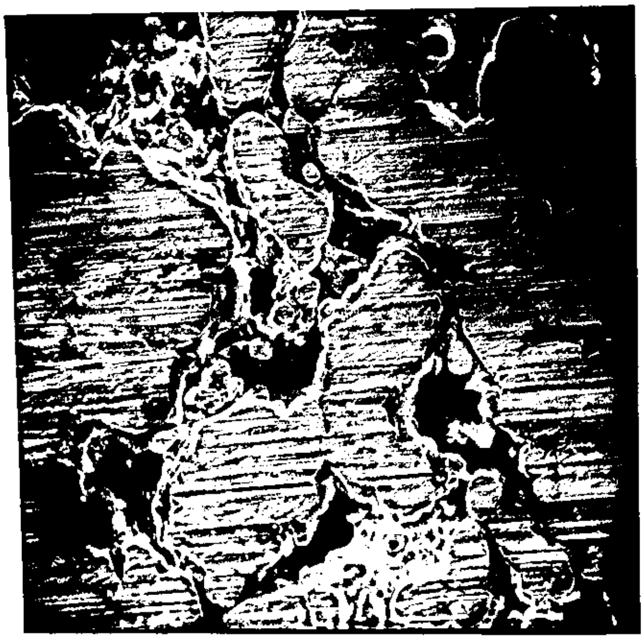


Fig. 30b S.E.M Photographs for Surfaces of Specimens with different Stearate
1 ) Zinc ; 2 ) Calcium , 3 ) Sodium
4 ) Aluminium ; 5 ) Magnesium
All Photographs at X 450

( 3



( 4

( 5

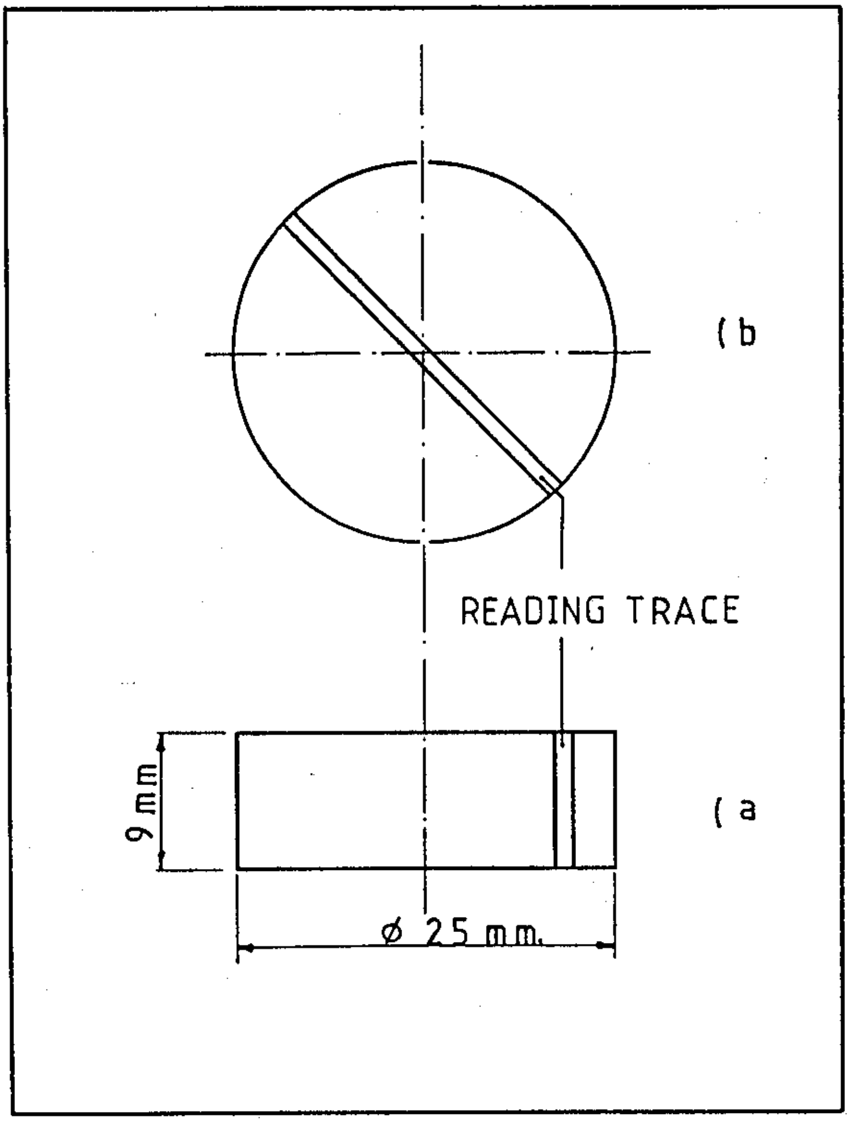


Fig. 31

a) Axial Surface ; b) Diametrical Surface

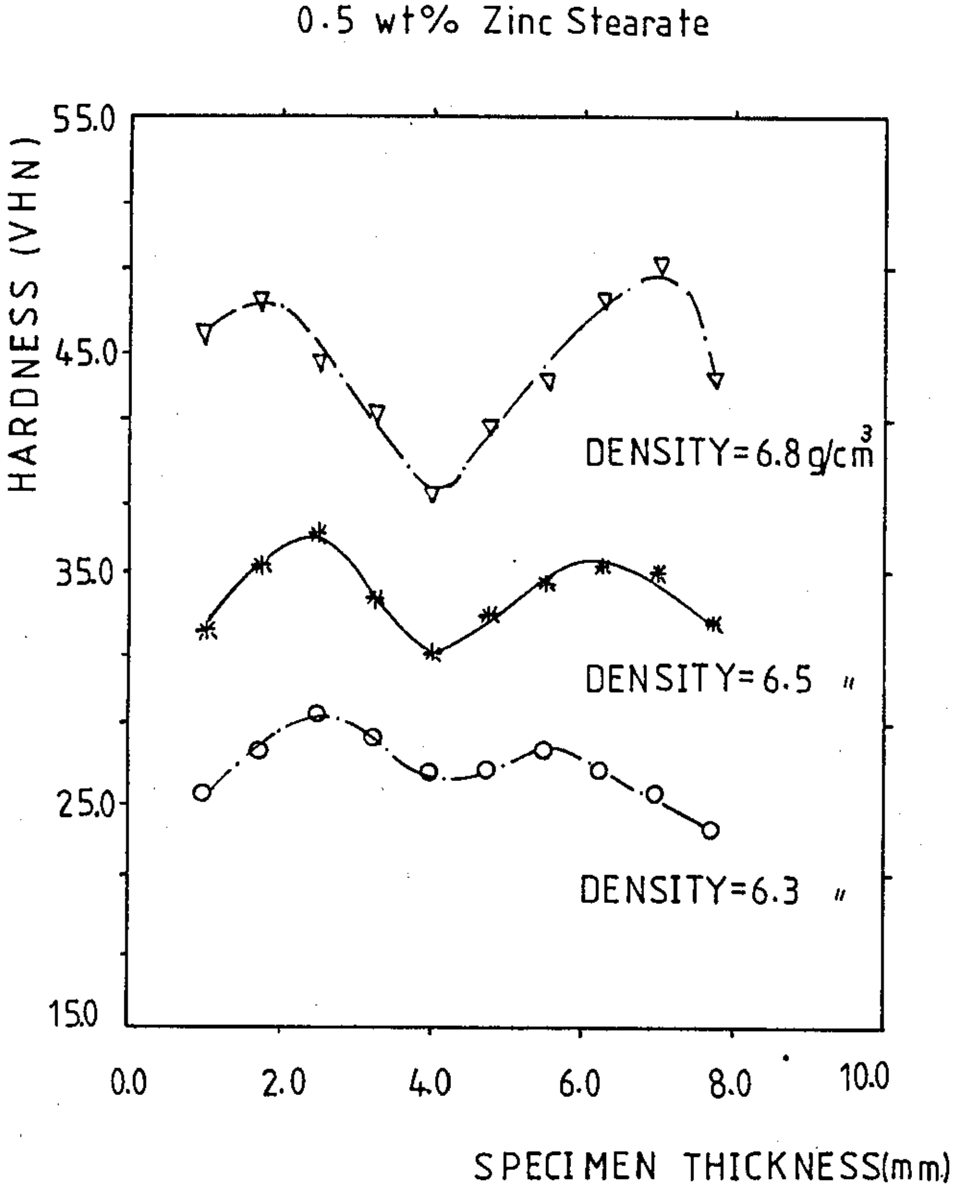

0.5 wt% Zinc Stearate
HARDNESS (VHN)
55.0
45.0
35.0
25.0
15.0
0.0
2.0
4.0
6.0
8.0
10.0
SPECIMEN THICKNESS(mm)
DENSITY=6.8 g/cm³
DENSITY=6.5 "
DENSITY=6.3 "

Fig. 32

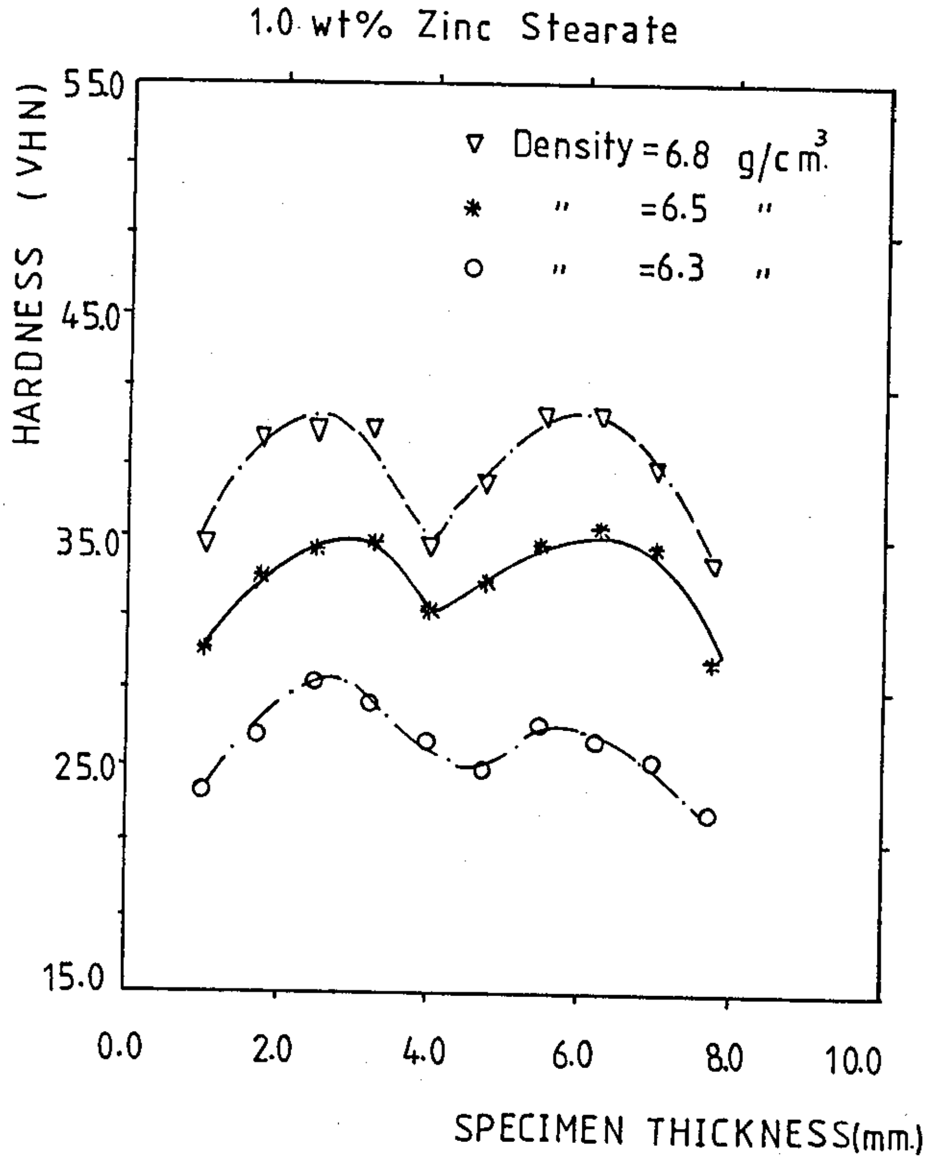

1.0 wt% Zinc Stearate
HARDNESS (VHN)
55.0
45.0
35.0
25.0
15.0
0.0
2.0
4.0
6.0
8.0
10.0
SPECIMEN THICKNESS(mm.)
▽ Density = 6.8 g/cm³
* " = 6.5 "
○ " = 6.3 "

Fig. 33

1.5 wt% Zinc Stearate

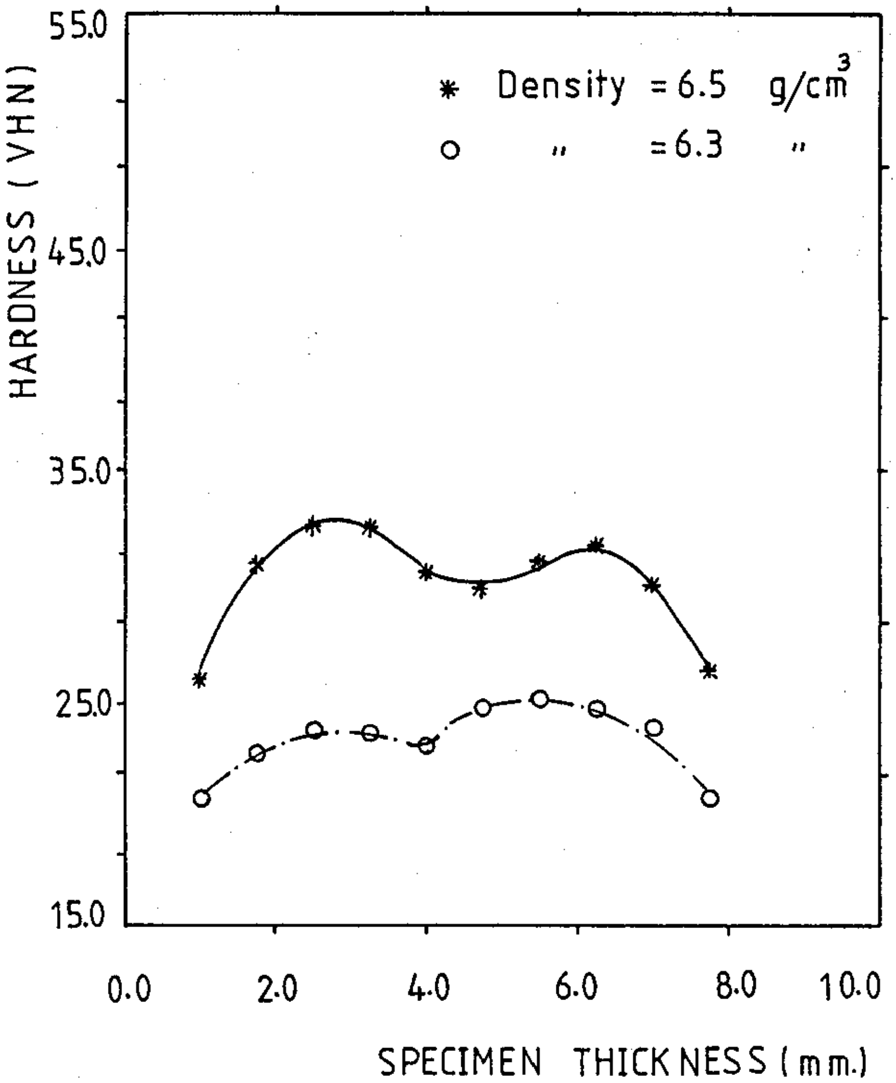


Fig. 34

Density 6.3 g/cm$^3$

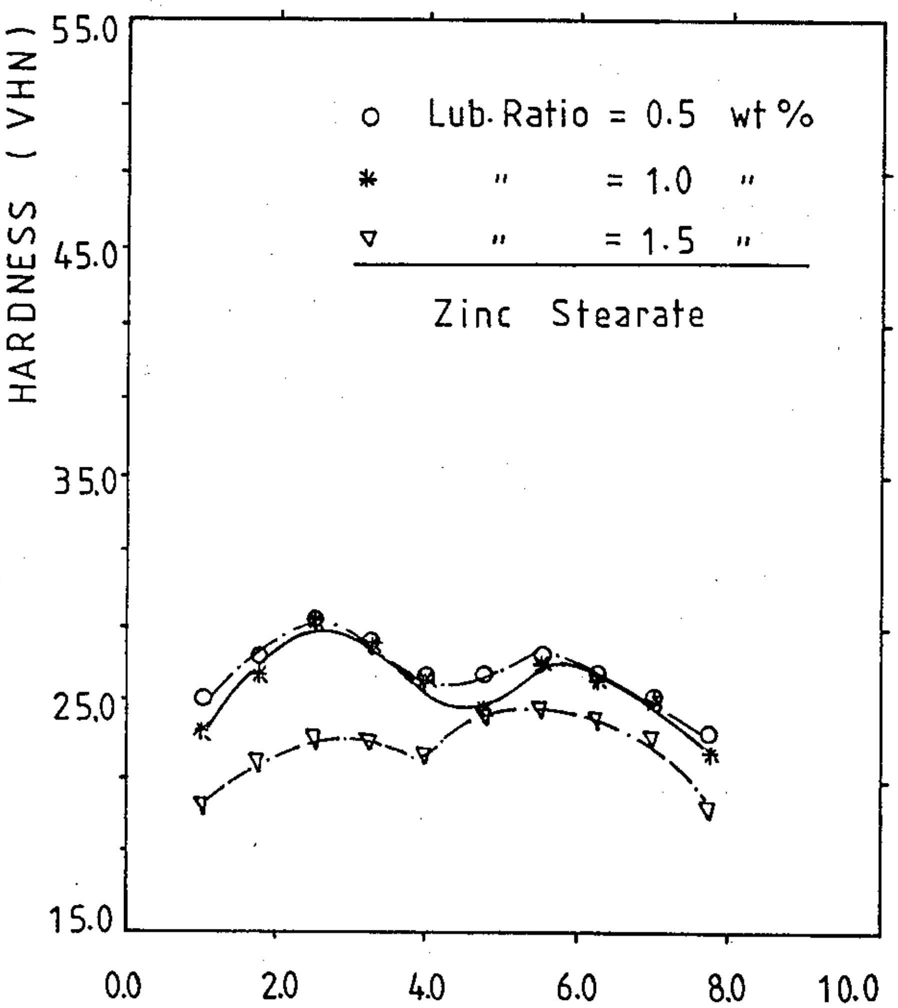


Fig. 35

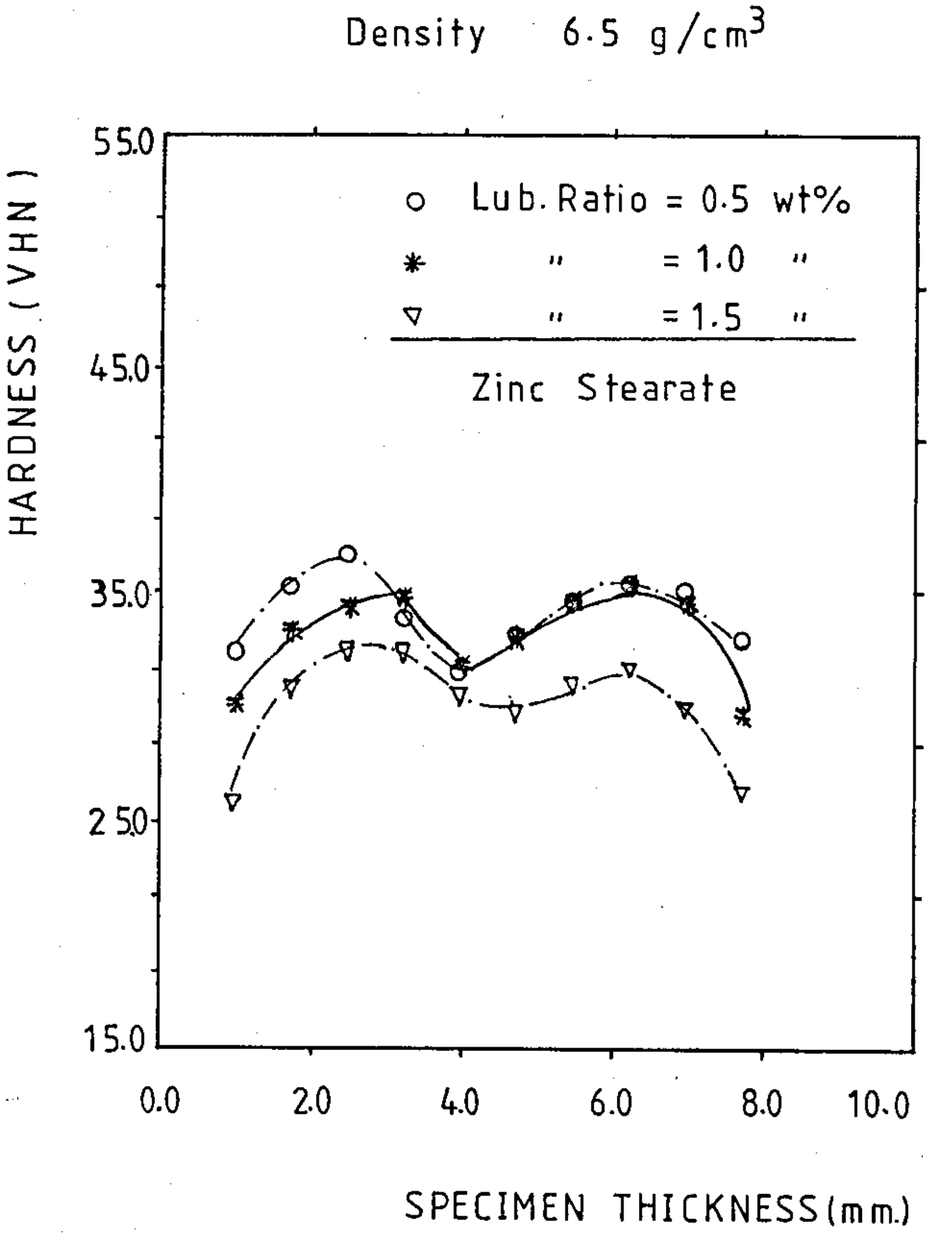

Density 6.5 g/cm$^3$
HARDNESS (VHN)
55.0
45.0
35.0
25.0
15.0
0.0
2.0
4.0
6.0
8.0
10.0
SPECIMEN THICKNESS(mm.)
○ Lub. Ratio = 0.5 wt%
✱ " = 1.0 "
▽ " = 1.5 "
Zinc Stearate

Fig. 36

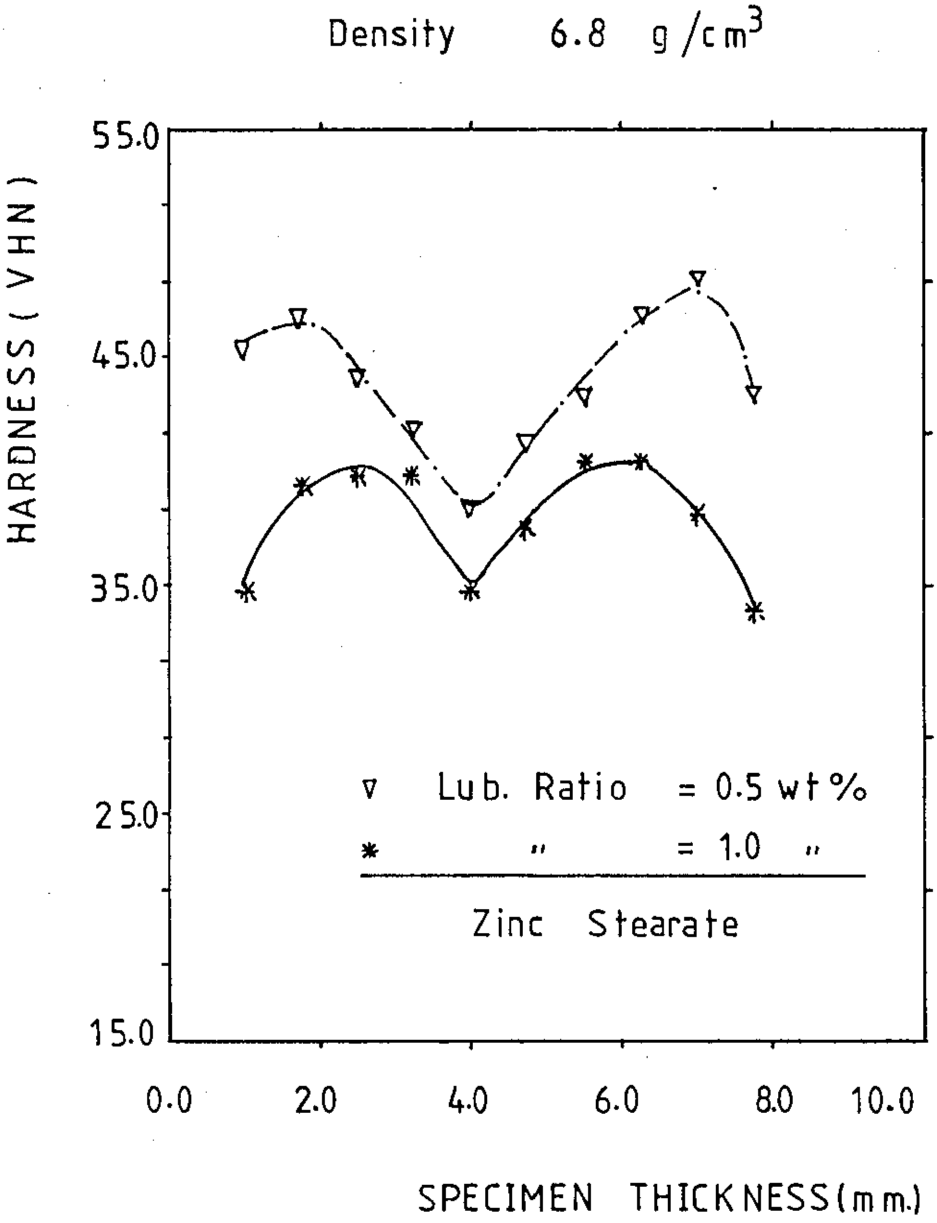

Density 6.8 g/cm$^3$
HARDNESS ( VHN )
55.0
45.0
35.0
25.0
15.0
0.0
2.0
4.0
6.0
8.0
10.0
SPECIMEN THICKNESS(mm.)
▽ Lub. Ratio = 0.5 wt %
* " = 1.0 "
Zinc Stearate

Fig. 37

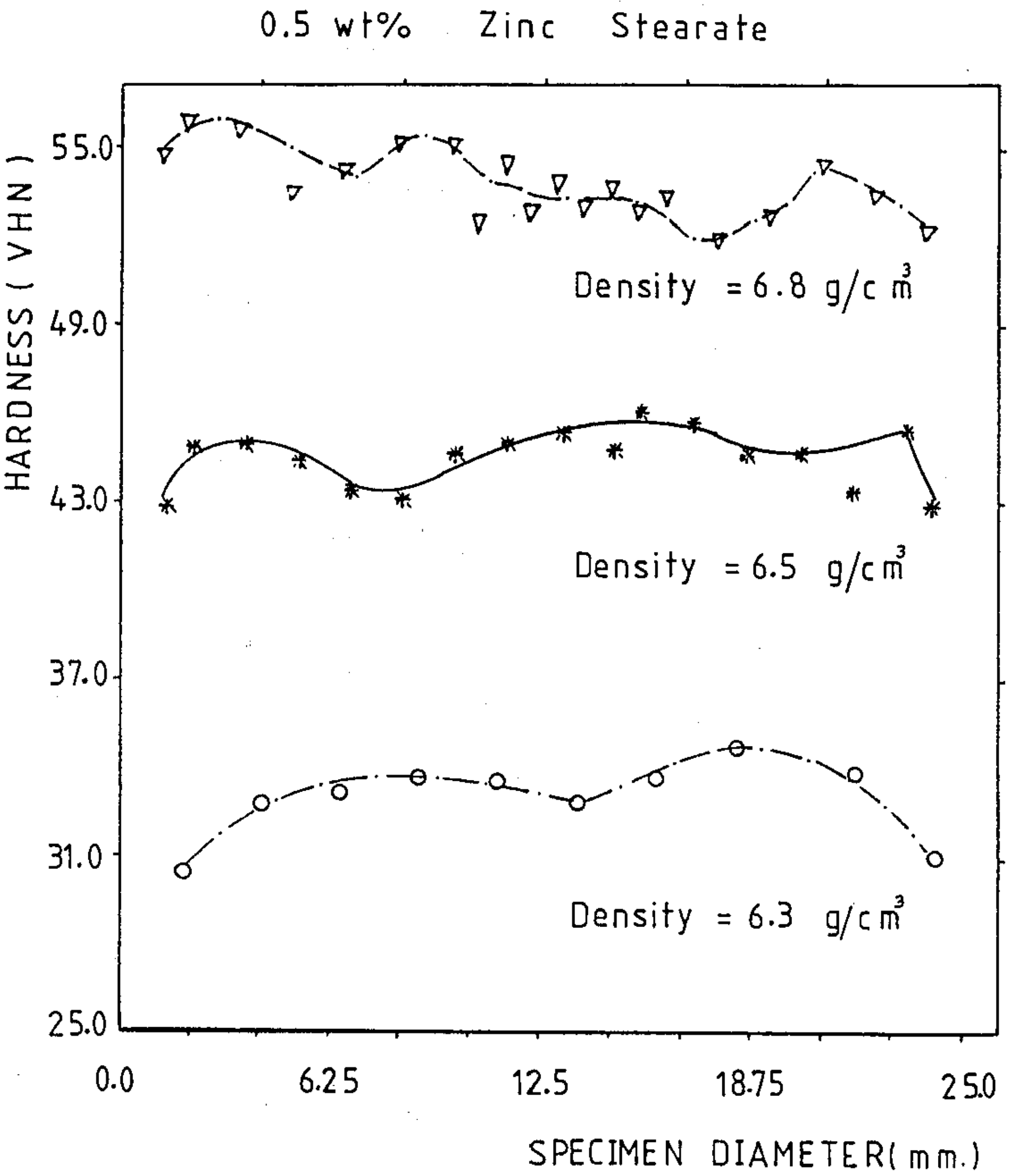

0.5 wt% Zinc Stearate
HARDNESS ( VHN )
55.0
49.0
43.0
37.0
31.0
25.0
0.0
6.25
12.5
18.75
25.0
SPECIMEN DIAMETER( mm.)
Density = 6.8 g/cm$^3$
Density = 6.5 g/cm$^3$
Density = 6.3 g/cm$^3$

Fig. 38

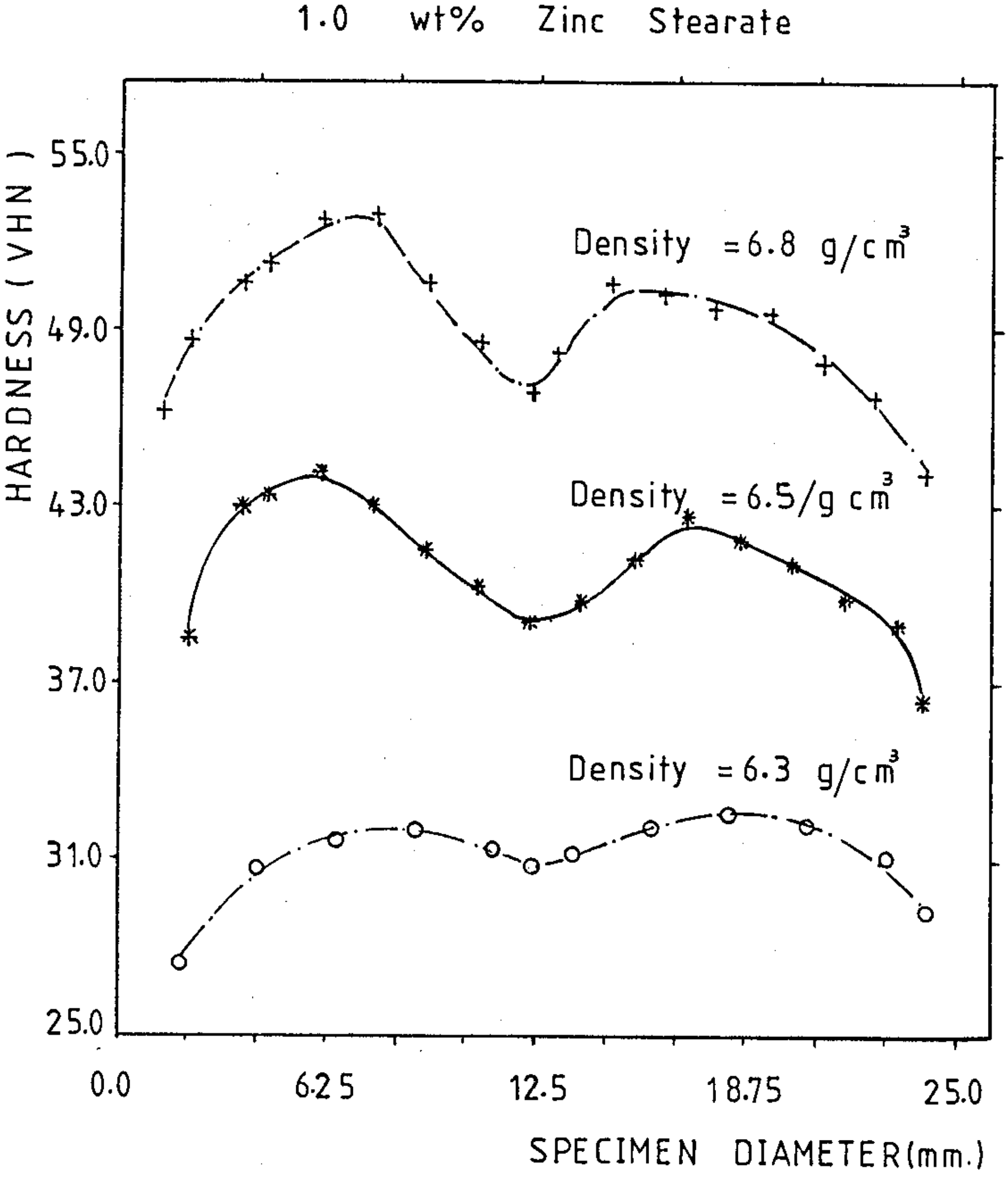

1.0 wt% Zinc Stearate
HARDNESS ( VHN )
55.0
49.0
43.0
37.0
31.0
25.0
0.0
6.25
12.5
18.75
25.0
SPECIMEN DIAMETER(mm.)
Density = 6.8 g/cm³
Density = 6.5/g cm³
Density = 6.3 g/cm³

Fig. 39

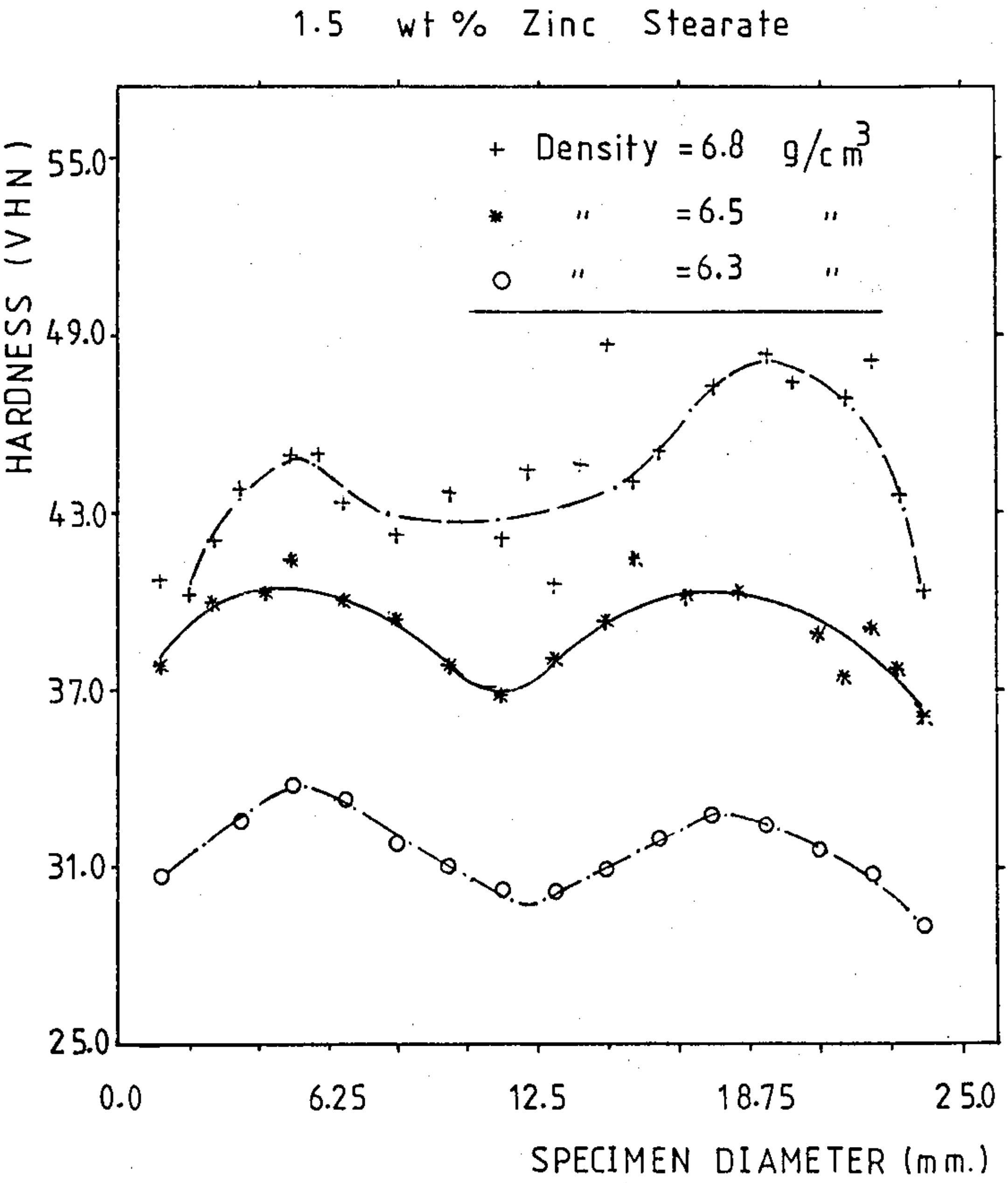

1.5 wt % Zinc Stearate
HARDNESS (VHN)
55.0
49.0
43.0
37.0
31.0
25.0
0.0
6.25
12.5
18.75
25.0
SPECIMEN DIAMETER (mm.)
+ Density = 6.8 g/cm$^3$
* " = 6.5 "
○ " = 6.3 "

Fig. 40

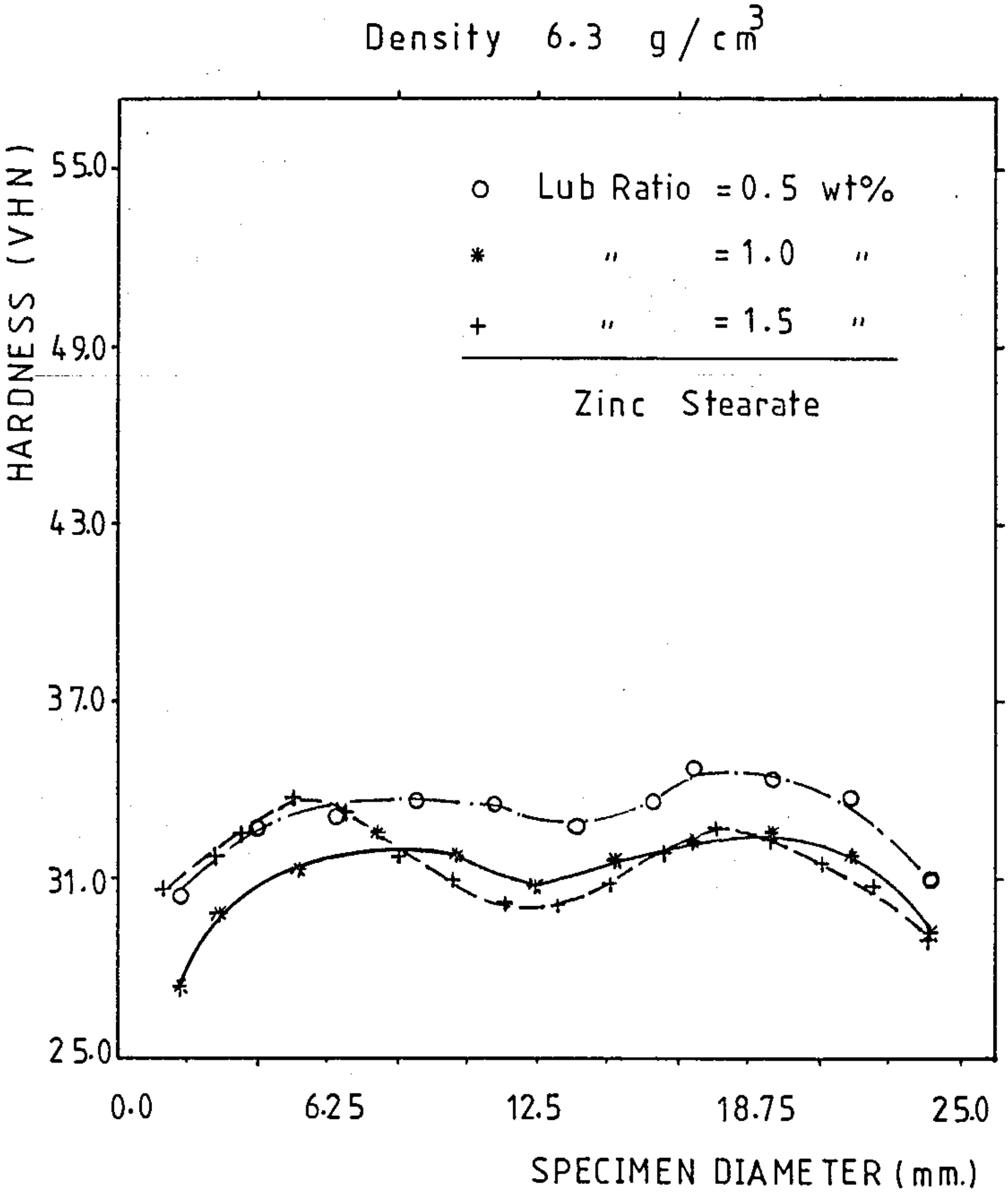

Density 6.3 g/cm$^3$
HARDNESS (VHN)
55.0
49.0
43.0
37.0
31.0
25.0
0.0
6.25
12.5
18.75
25.0
SPECIMEN DIAMETER (mm.)
○ Lub Ratio = 0.5 wt%
* " = 1.0 "
+ " = 1.5 "
Zinc Stearate

Fig. 41

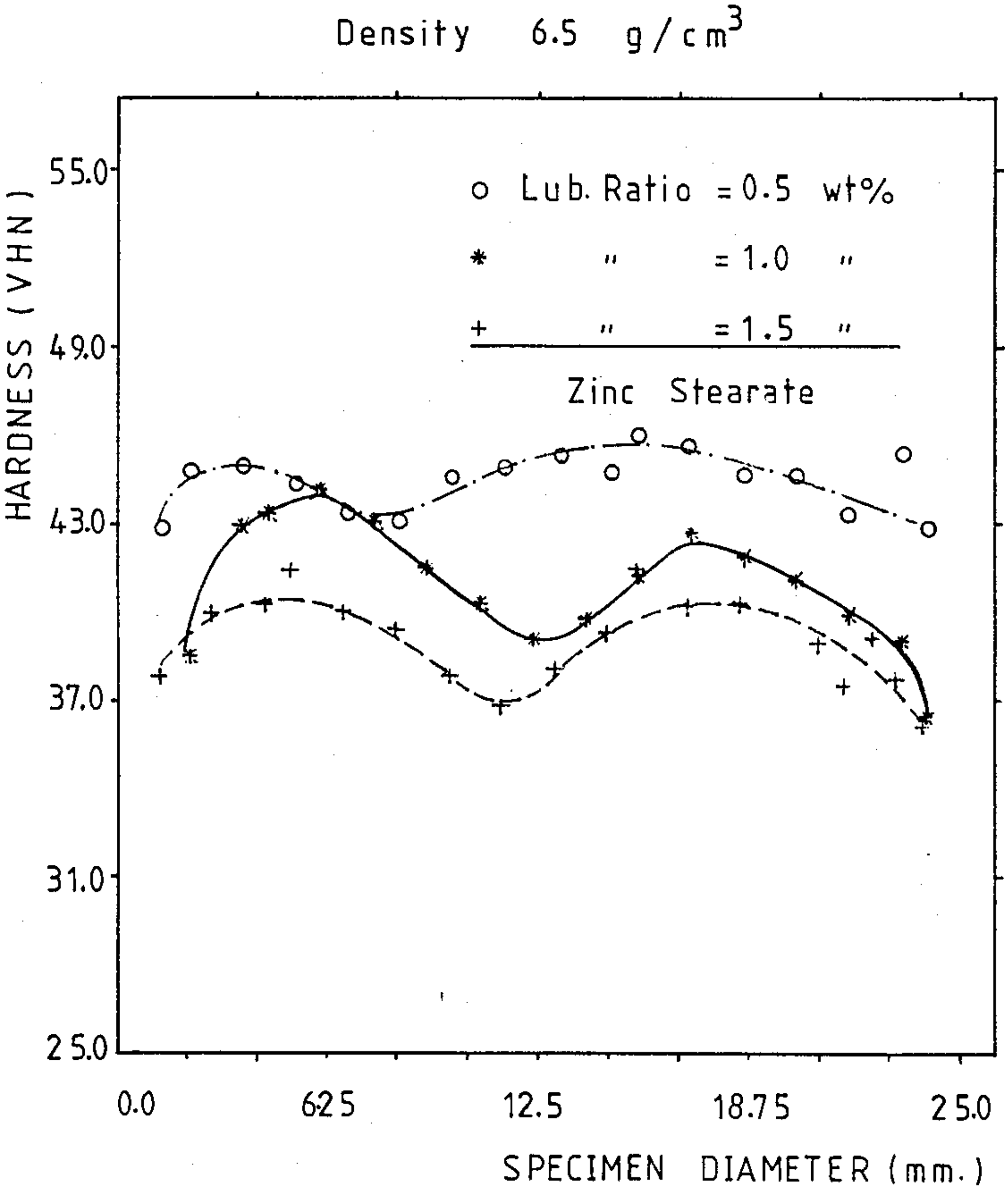

Density 6.5 g/cm³
HARDNESS (VHN)
55.0
49.0
43.0
37.0
31.0
25.0
0.0
6.25
12.5
18.75
25.0
SPECIMEN DIAMETER (mm.)
○ Lub. Ratio = 0.5 wt%
* " = 1.0 "
+ " = 1.5 "
Zinc Stearate

Fig. 4 2

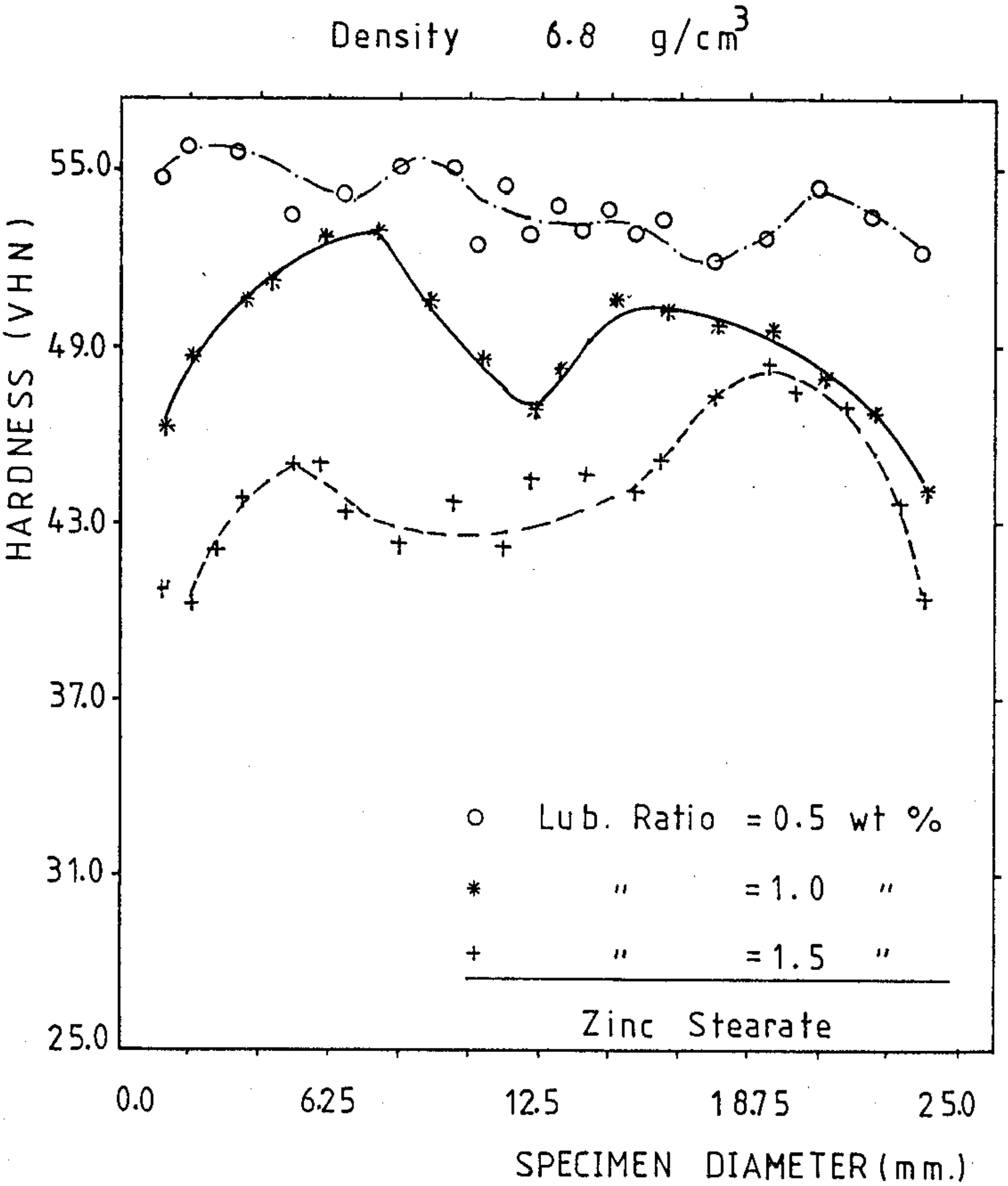

Density 6.8 g/cm$^3$
HARDNESS (VHN)
55.0
49.0
43.0
37.0
31.0
25.0
0.0
6.25
12.5
18.75
25.0
SPECIMEN DIAMETER (mm.)
○ Lub. Ratio = 0.5 wt %
* " = 1.0 "
+ " = 1.5 "
Zinc Stearate

Fig. 43

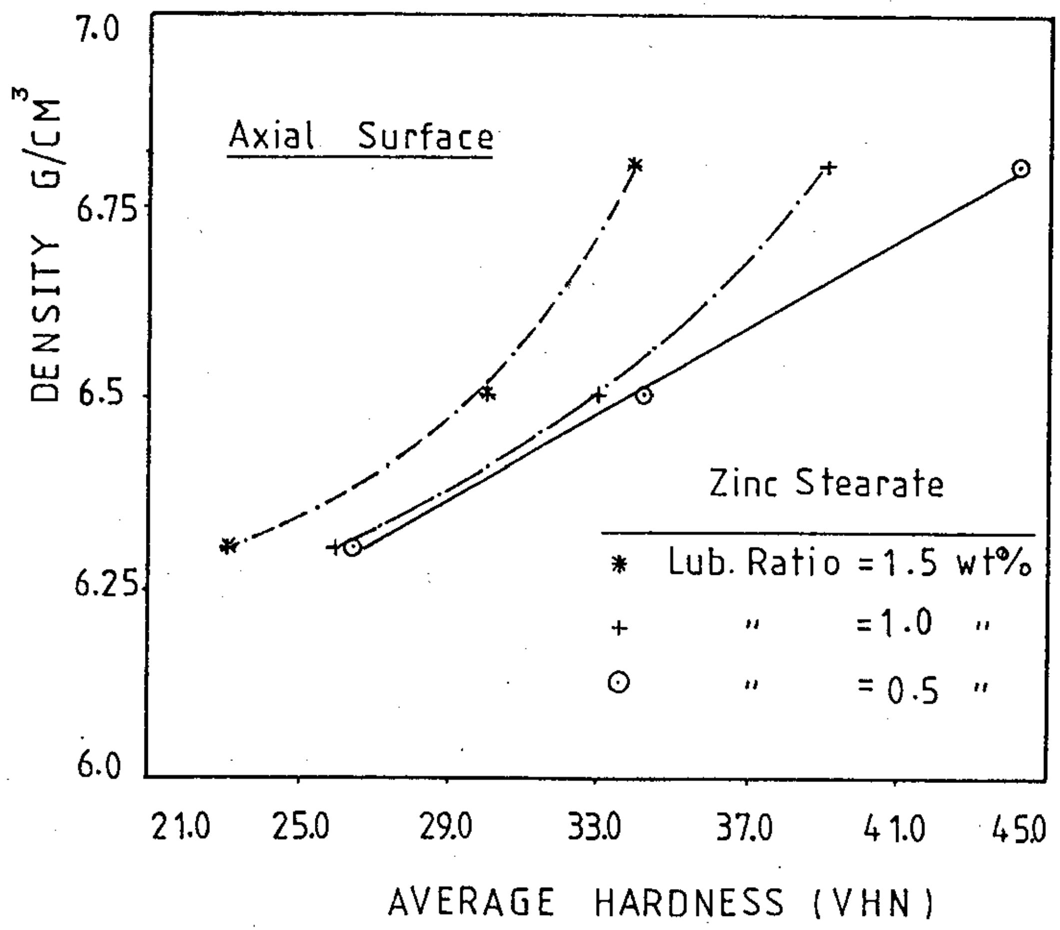

Axial Surface
DENSITY G/CM$^3$
7.0
6.75
6.5
6.25
6.0
21.0
25.0
29.0
33.0
37.0
41.0
45.0
AVERAGE HARDNESS (VHN)
Zinc Stearate
* Lub. Ratio = 1.5 wt%
+ " = 1.0 "
⊙ " = 0.5 "

Fig. 44

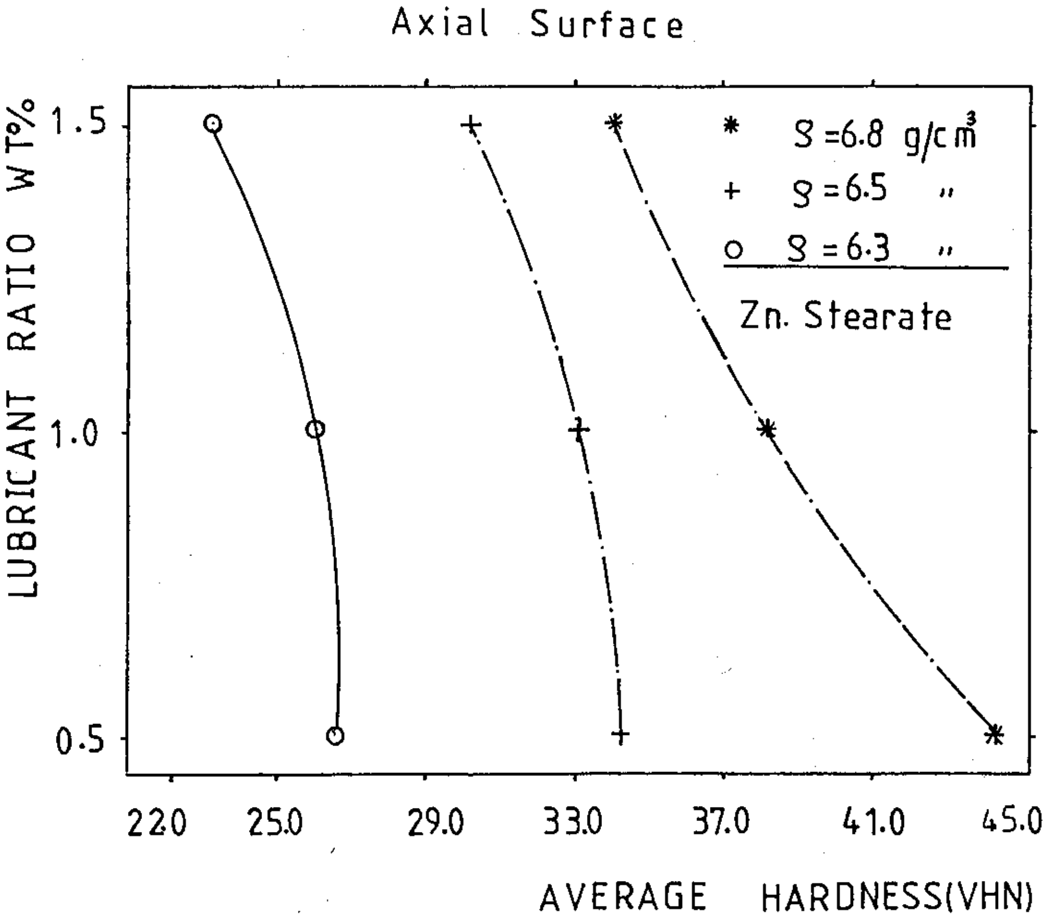
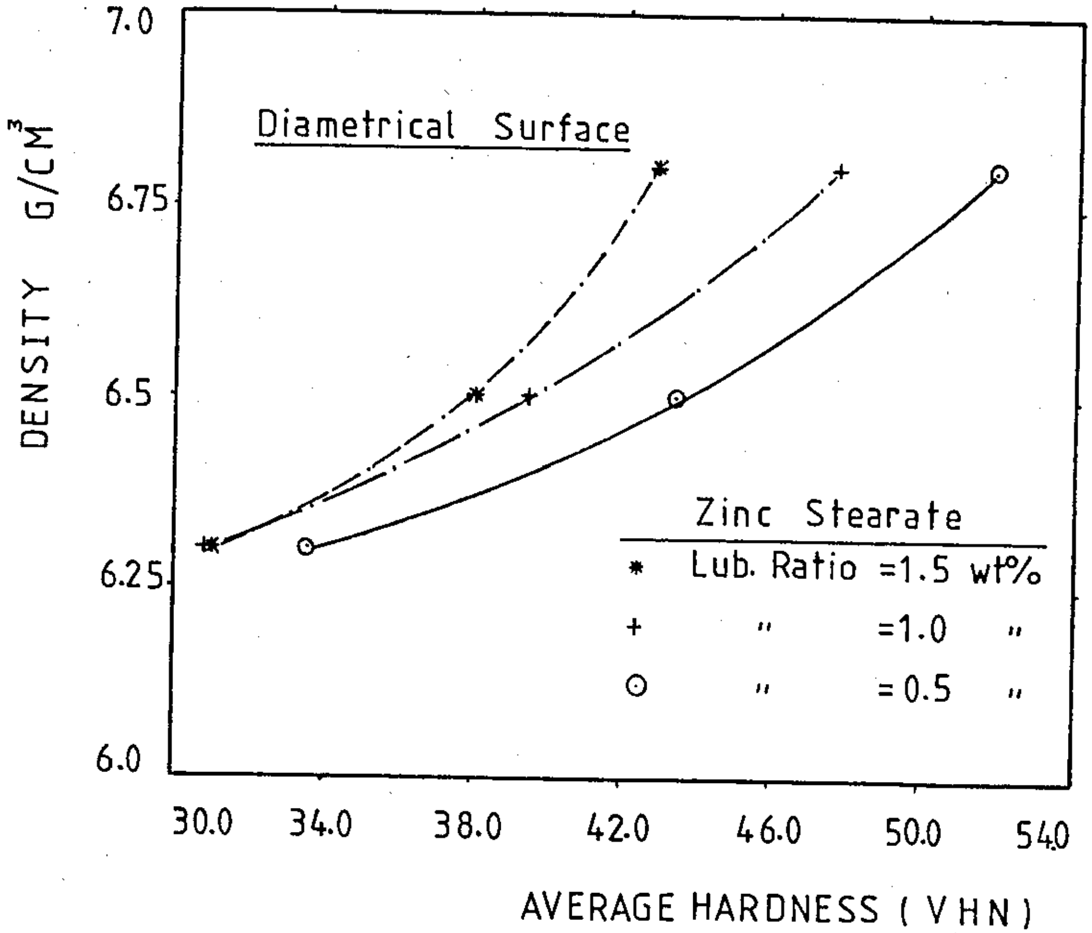

Axial Surface
LUBRICANT RATIO WT%
1.5
1.0
0.5
220
25.0
29.0
33.0
37.0
41.0
45.0
AVERAGE HARDNESS(VHN)
* ϱ =6.8 g/cm³
+ ϱ =6.5 "
o ϱ = 6.3 "
Zn. Stearate

Fig. 45



Diametrical Surface
DENSITY G/CM$^3$
7.0
6.75
6.5
6.25
6.0
30.0
34.0
38.0
42.0
46.0
50.0
54.0
AVERAGE HARDNESS ( VHN )
Zinc Stearate
* Lub. Ratio =1.5 wt%
+ " =1.0 "
⊙ " = 0.5 "

Fig. 46

Diametrical Surface

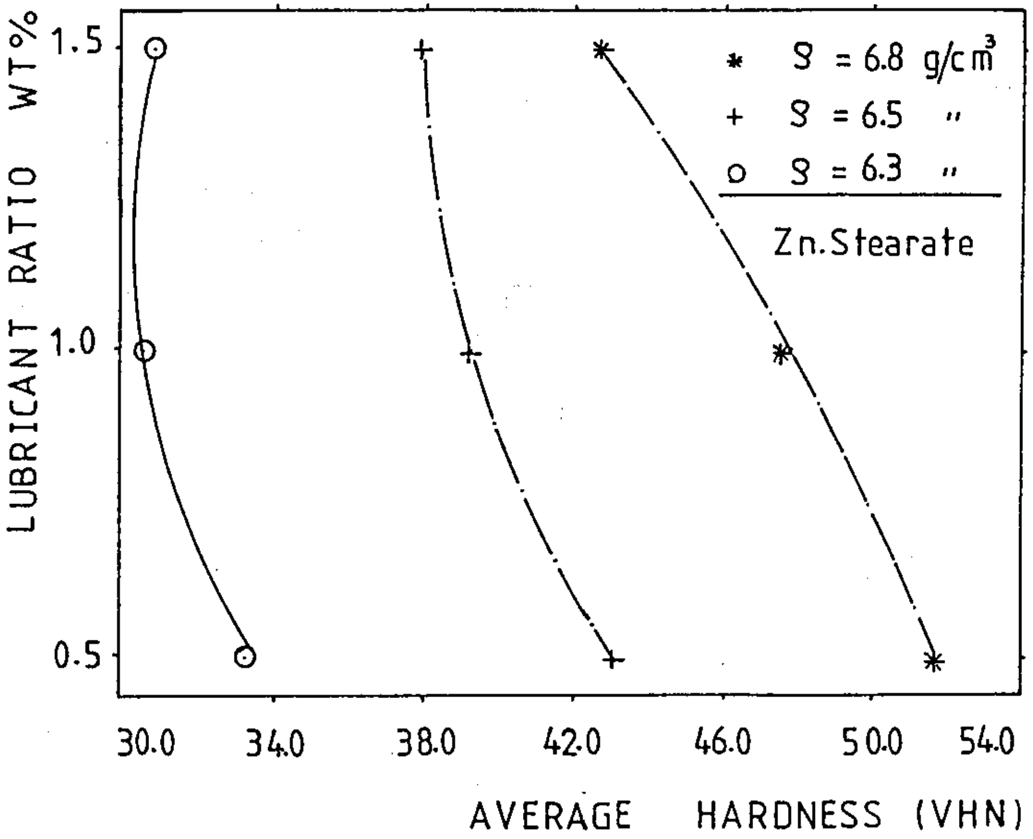


Fig. 47

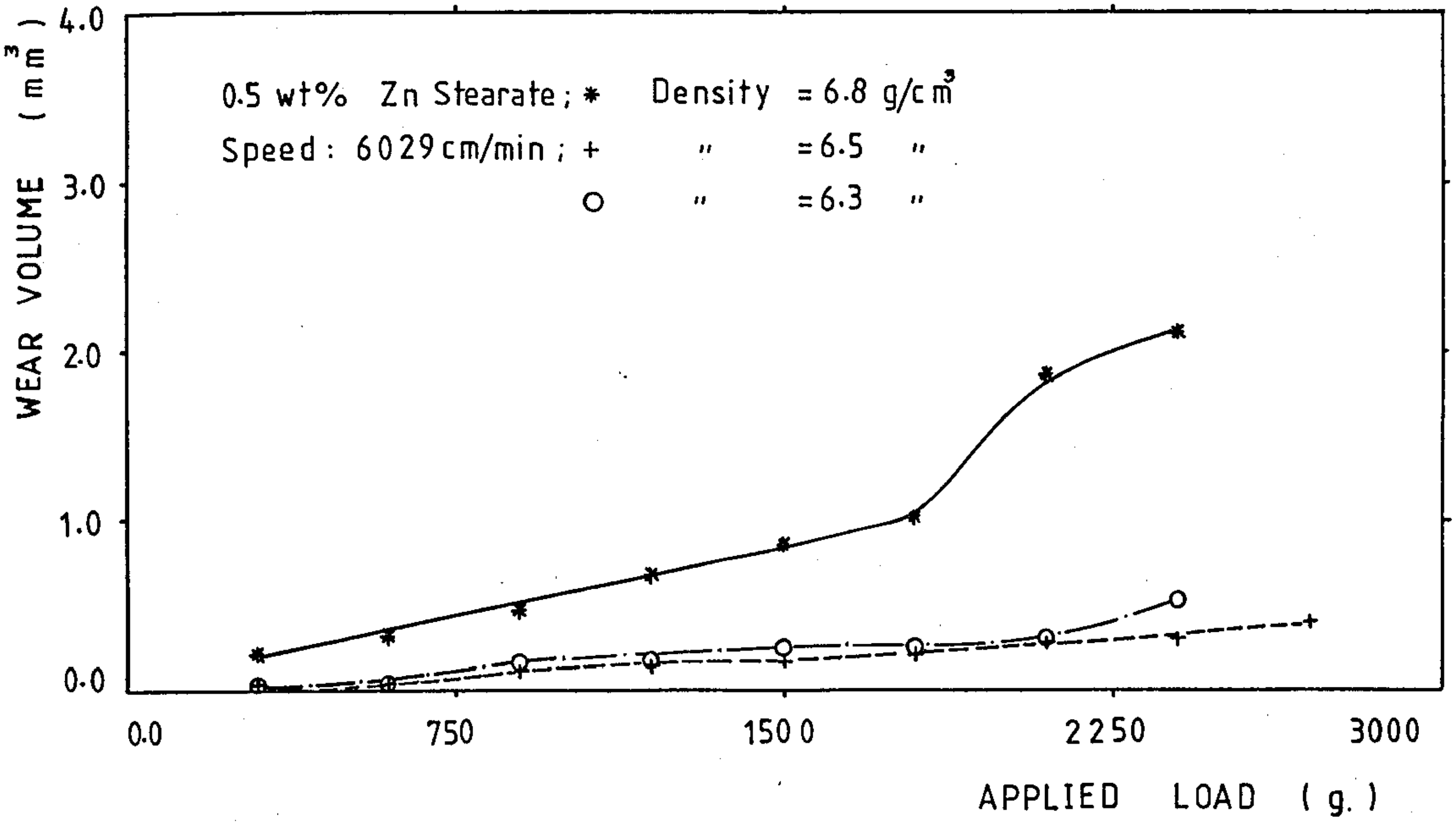
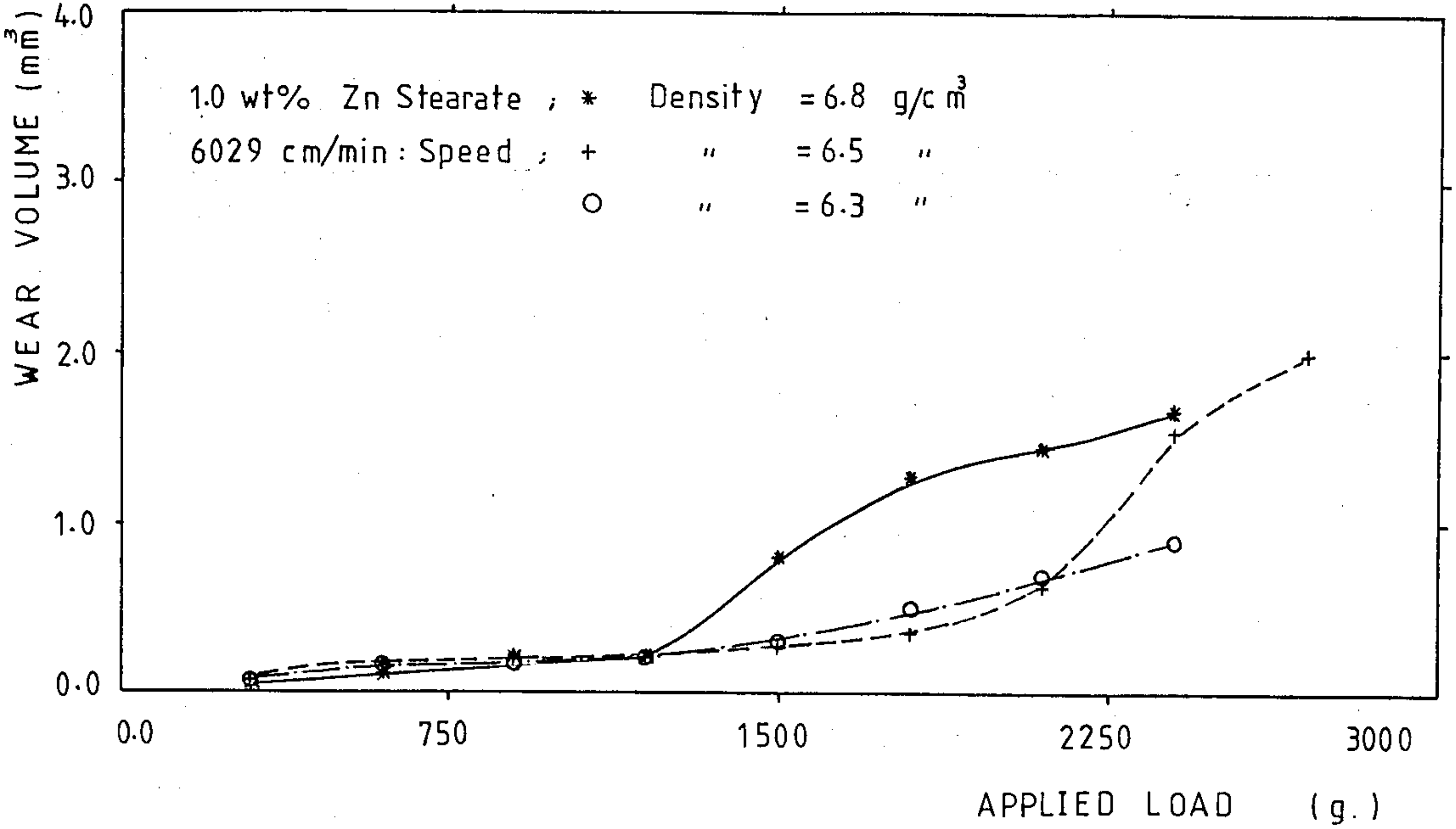

0.5 wt% Zn Stearate ; * Density = 6.8 g/cm³
Speed : 6029 cm/min ; + " = 6.5 "
○ " = 6.3 "
WEAR VOLUME (mm³)
4.0
3.0
2.0
1.0
0.0
0.0
750
1500
2250
3000
APPLIED LOAD (g.)

Fig. 48



WEAR VOLUME (mm$^3$)
4.0
3.0
2.0
1.0
0·0
0.0
750
1500
2250
3000
APPLIED LOAD (g.)
1.0 wt% Zn Stearate ; * Density = 6.8 g/cm$^3$
6029 cm/min : Speed ; + " = 6.5 "
○ " = 6.3 "

Fig. 49

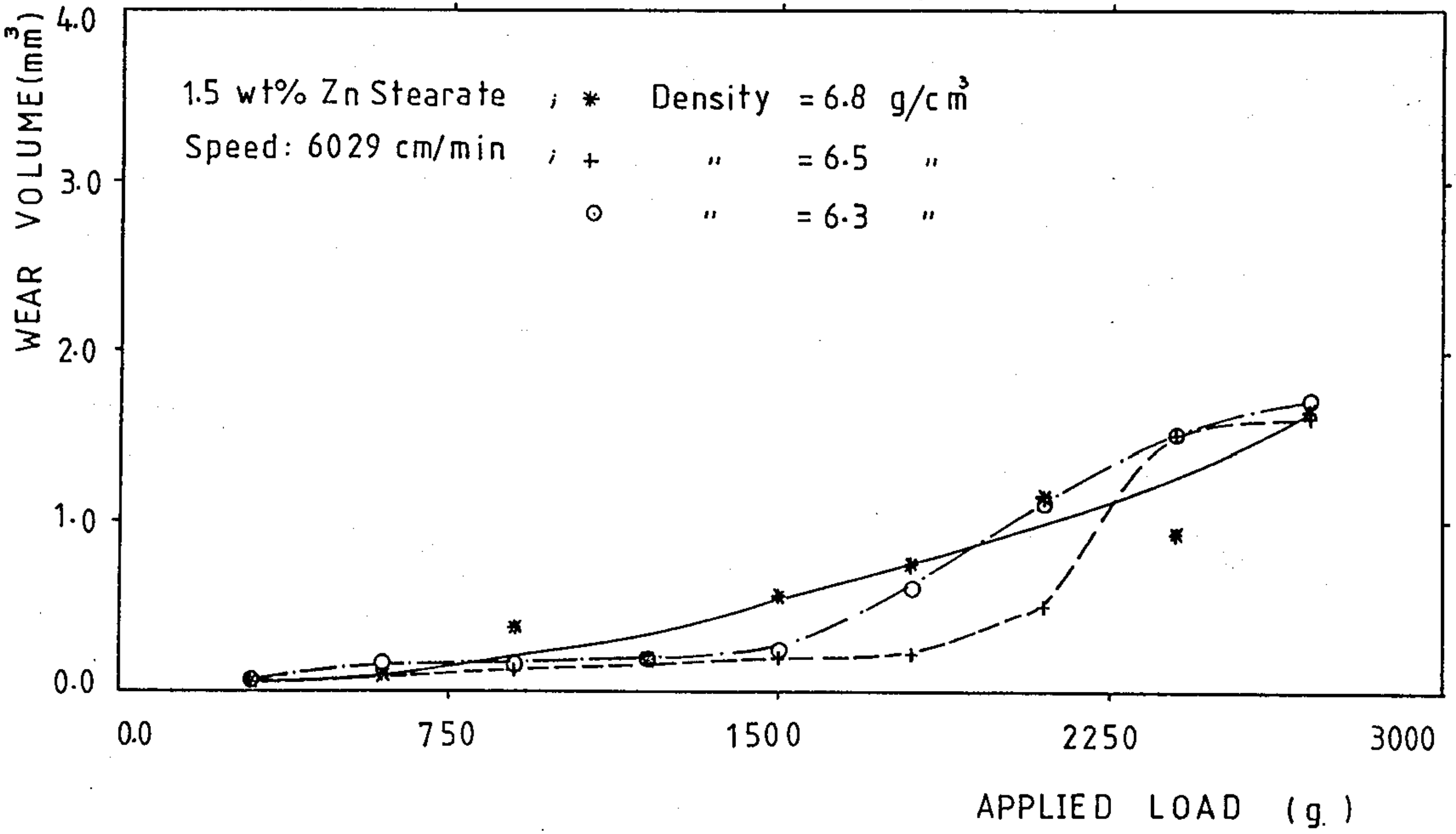

1.5 wt% Zn Stearate ; * Density = 6.8 g/cm³
Speed: 6029 cm/min ; + " = 6.5 "
⊙ " = 6.3 "
WEAR VOLUME(mm³)
4.0
3.0
2.0
1.0
0.0
0.0
750
1500
2250
3000
APPLIED LOAD (g.)

Fig. 50

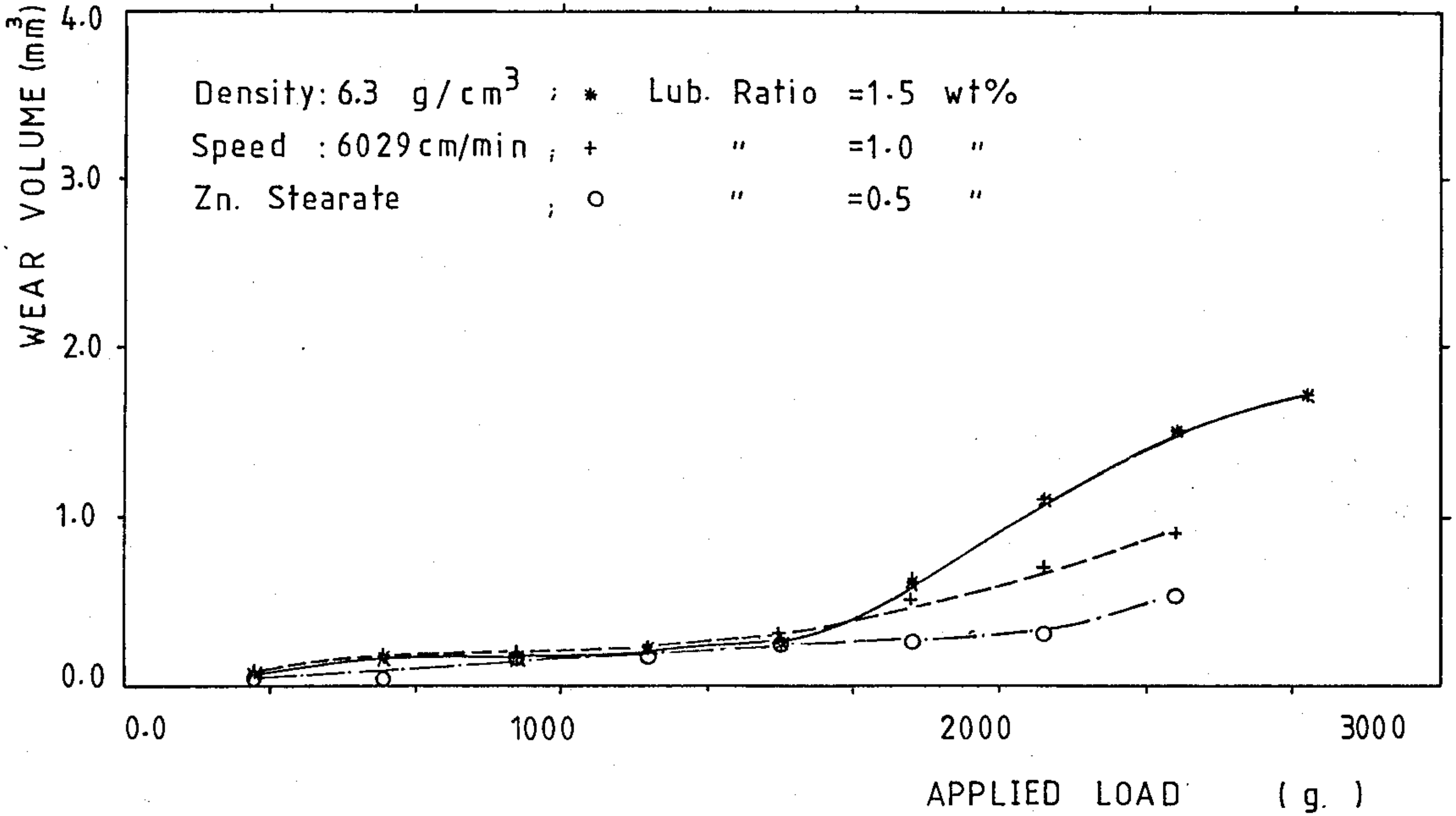

WEAR VOLUME ($mm^3$)
4.0
3.0
2.0
1.0
0.0
0.0
1000
2000
3000
APPLIED LOAD ( g. )
Density: 6.3 g/cm$^3$ ; * Lub. Ratio =1·5 wt%
Speed : 6029 cm/min ; + " =1·0 "
Zn. Stearate ; ○ " =0·5 "

Fig. 51

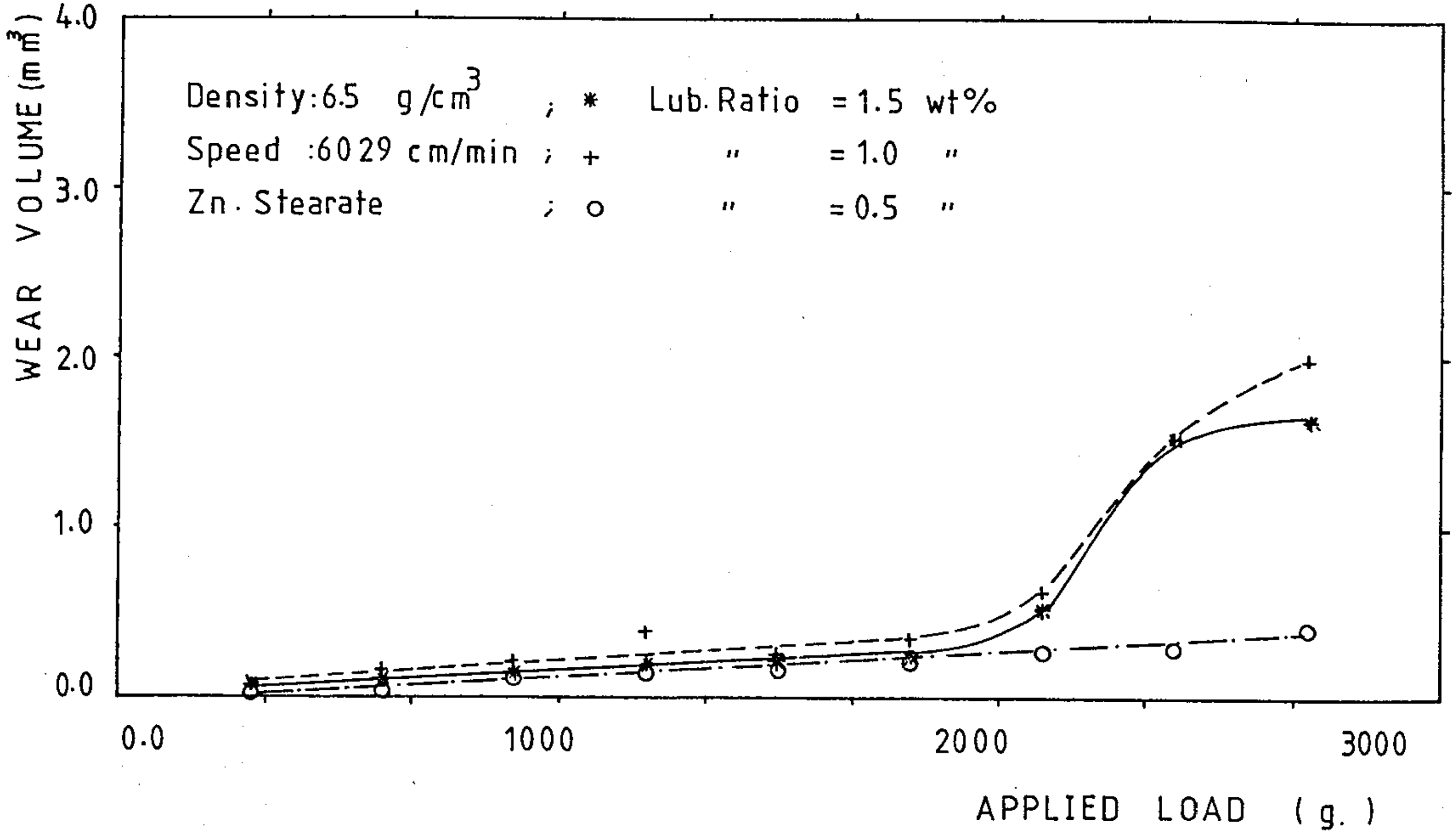

WEAR VOLUME (mm$^3$)
4.0
3.0
2.0
1.0
0.0
0.0
1000
2000
3000
APPLIED LOAD ( g. )
Density:6.5 g/cm$^3$ ; * Lub. Ratio = 1.5 wt%
Speed :6029 cm/min ; + " = 1.0 "
Zn. Stearate ; o " = 0.5 "

Fig. 52

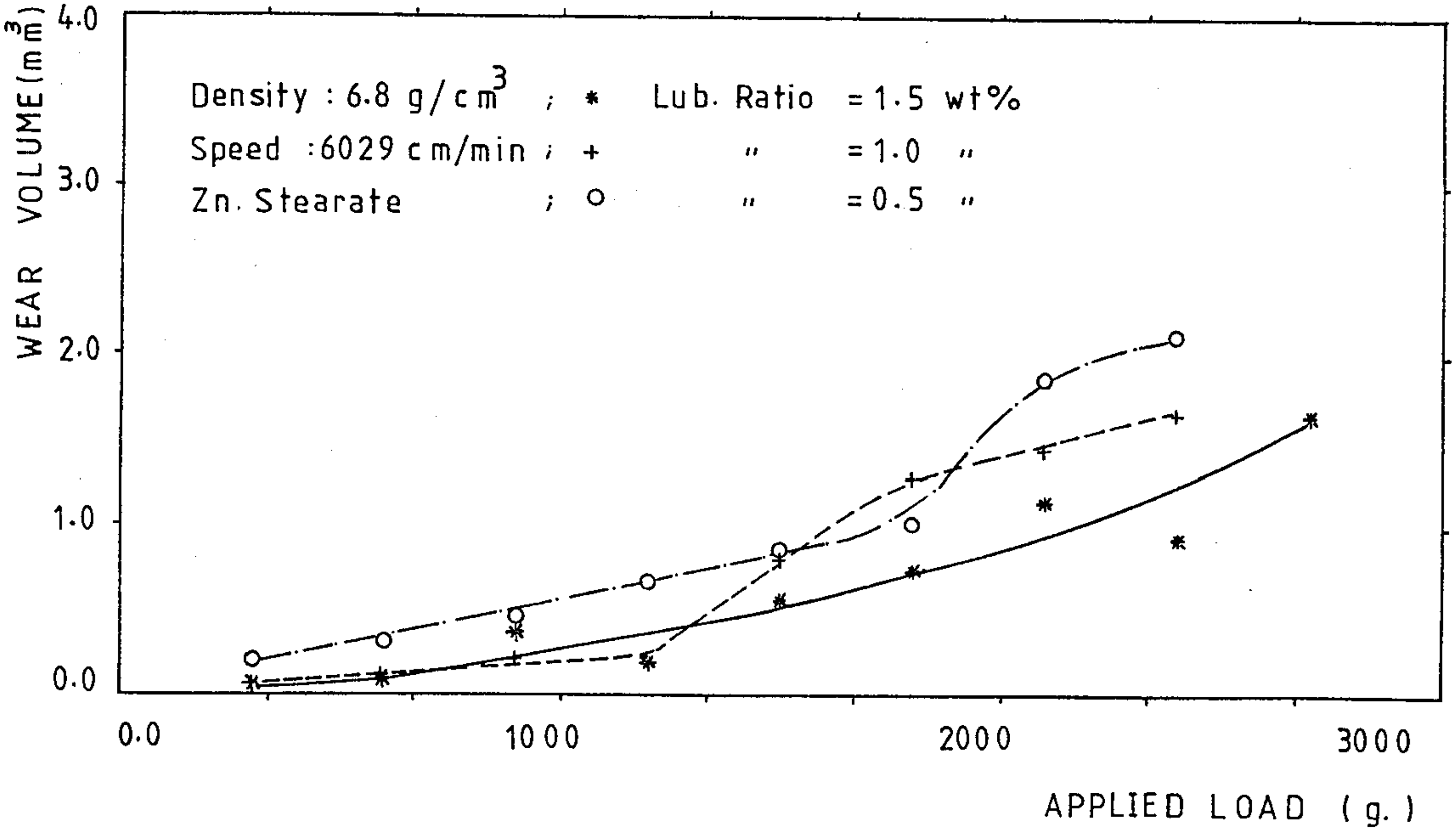

WEAR VOLUME (mm$^3$)
4.0
3.0
2.0
1.0
0.0
Density : 6.8 g/cm$^3$ ; * Lub. Ratio = 1.5 wt%
Speed : 6029 cm/min ; + " = 1.0 "
Zn. Stearate ; o " = 0.5 "
0.0
1000
2000
3000
APPLIED LOAD (g.)

Fig. 53

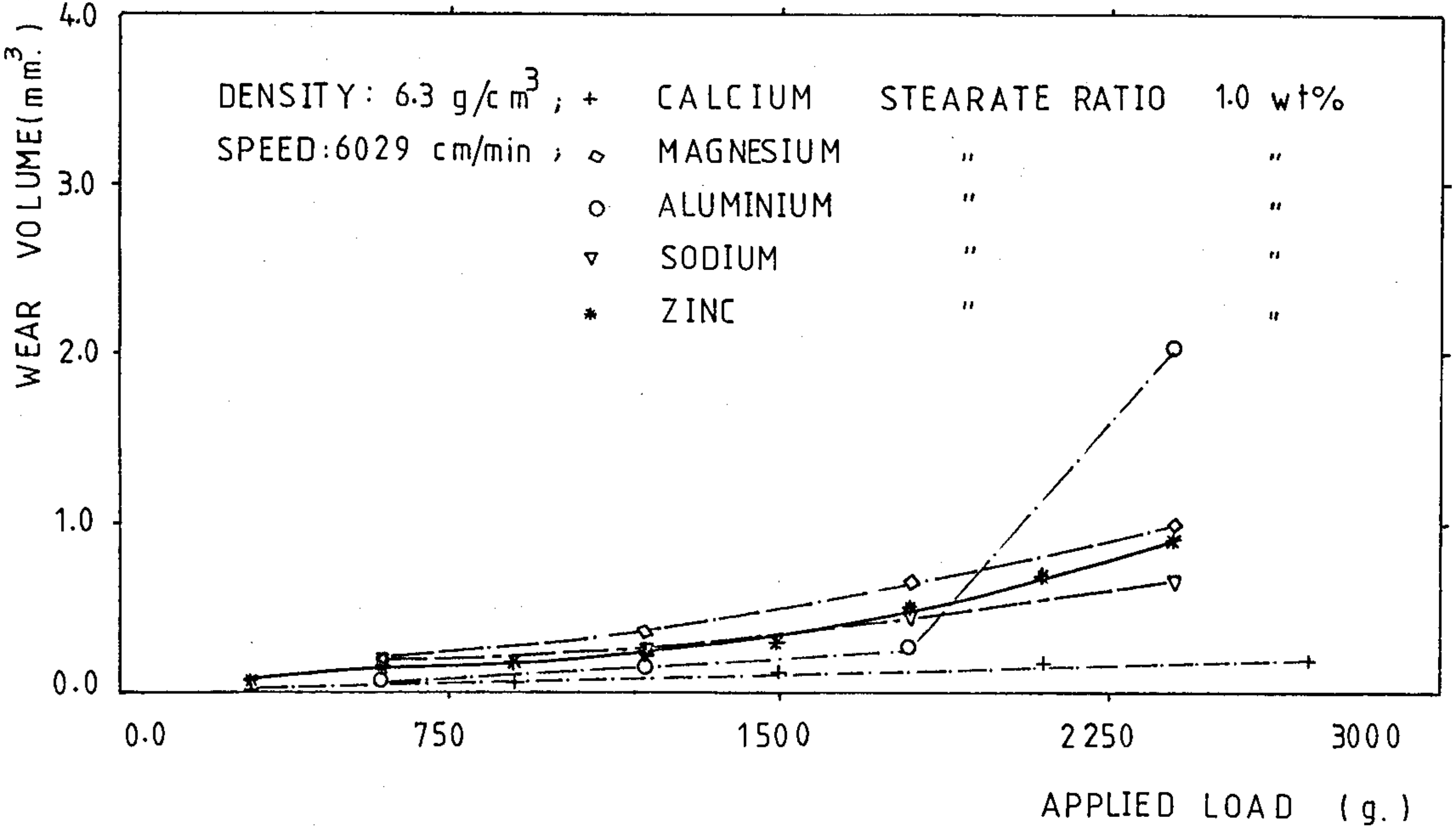

DENSITY: 6.3 g/cm³ ; SPEED: 6029 cm/min ;
+ CALCIUM STEARATE RATIO 1.0 wt%
◇ MAGNESIUM " "
○ ALUMINIUM " "
▽ SODIUM " "
* ZINC " "
WEAR VOLUME (mm.³)
4.0
3.0
2.0
1.0
0.0
0.0
750
1500
2250
3000
APPLIED LOAD (g.)

Fig. 54

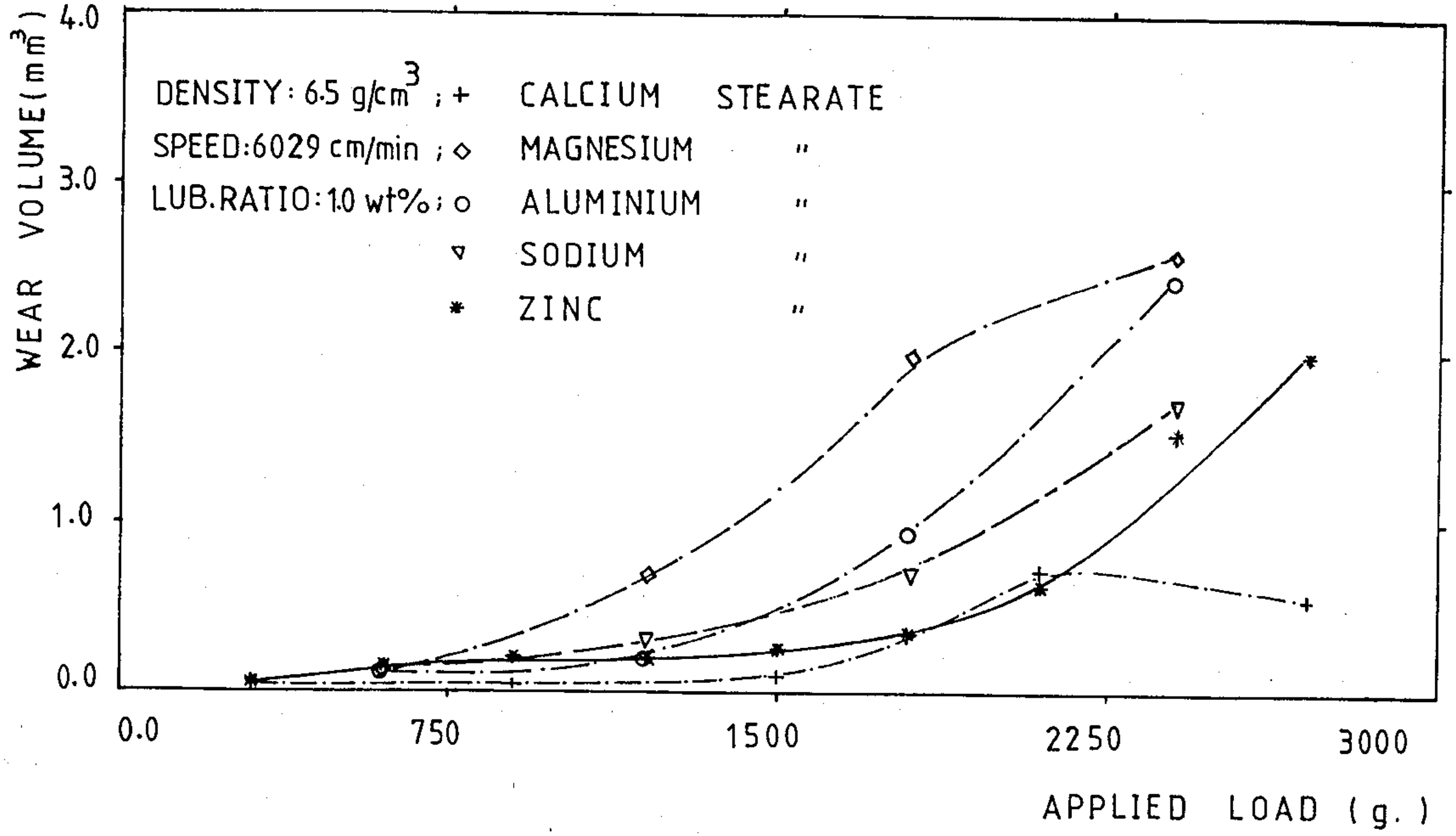

WEAR VOLUME (mm$^3$)
4.0
3.0
2.0
1.0
0.0
DENSITY: 6.5 g/cm$^3$ ; + CALCIUM STEARATE
SPEED: 6029 cm/min ; ◇ MAGNESIUM "
LUB. RATIO: 1.0 wt% ; ○ ALUMINIUM "
▽ SODIUM "
* ZINC "
0.0
750
1500
2250
3000
APPLIED LOAD (g.)

Fig. 55

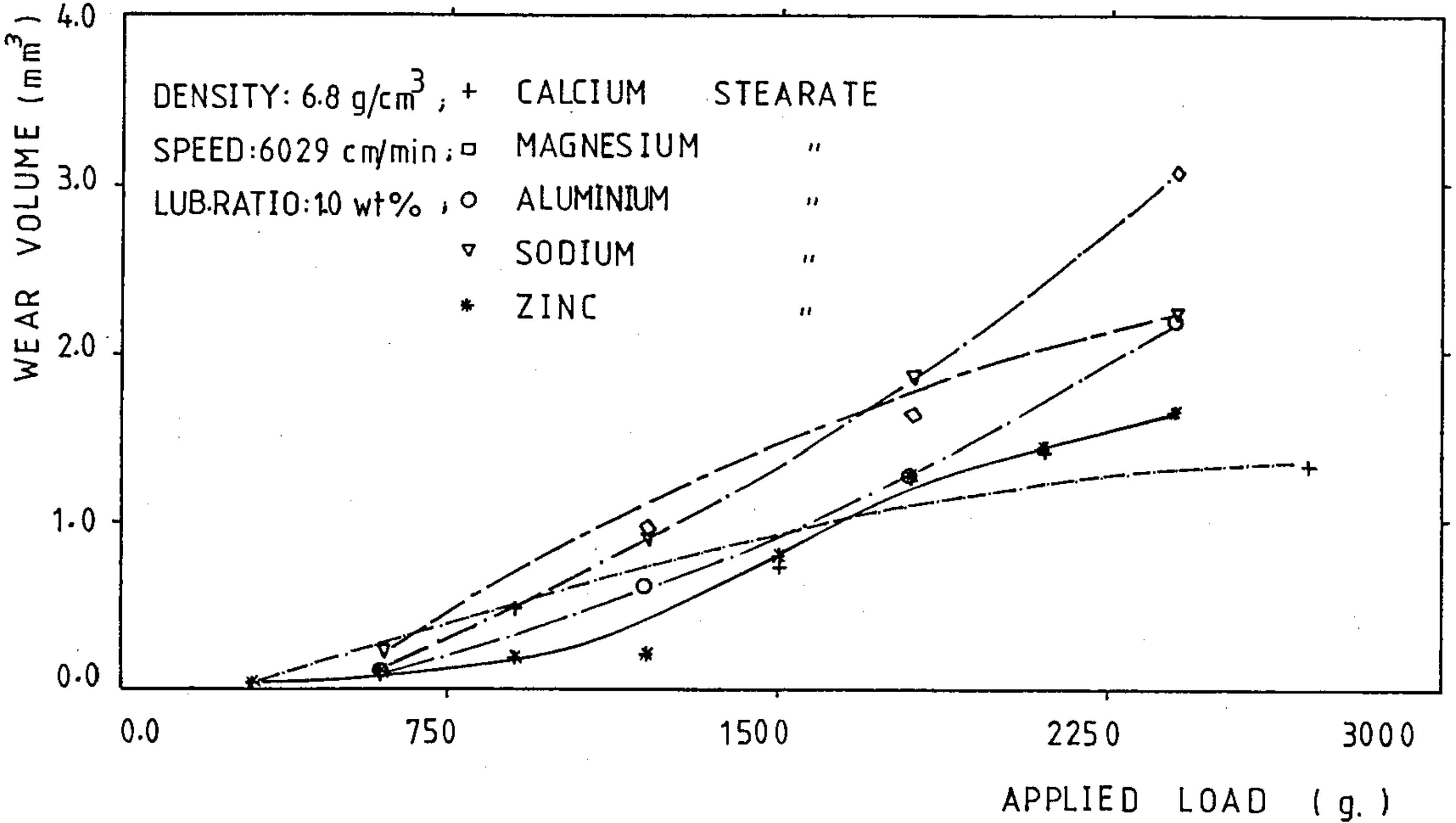

WEAR VOLUME (mm³)
4.0
3.0
2.0
1.0
0.0
0.0
750
1500
2250
3000
APPLIED LOAD (g.)
DENSITY: 6.8 g/cm³ ; + CALCIUM STEARATE
SPEED: 6029 cm/min ; □ MAGNESIUM "
LUB.RATIO: 1.0 wt% ; ○ ALUMINIUM "
▽ SODIUM "
* ZINC "

Fig. 56

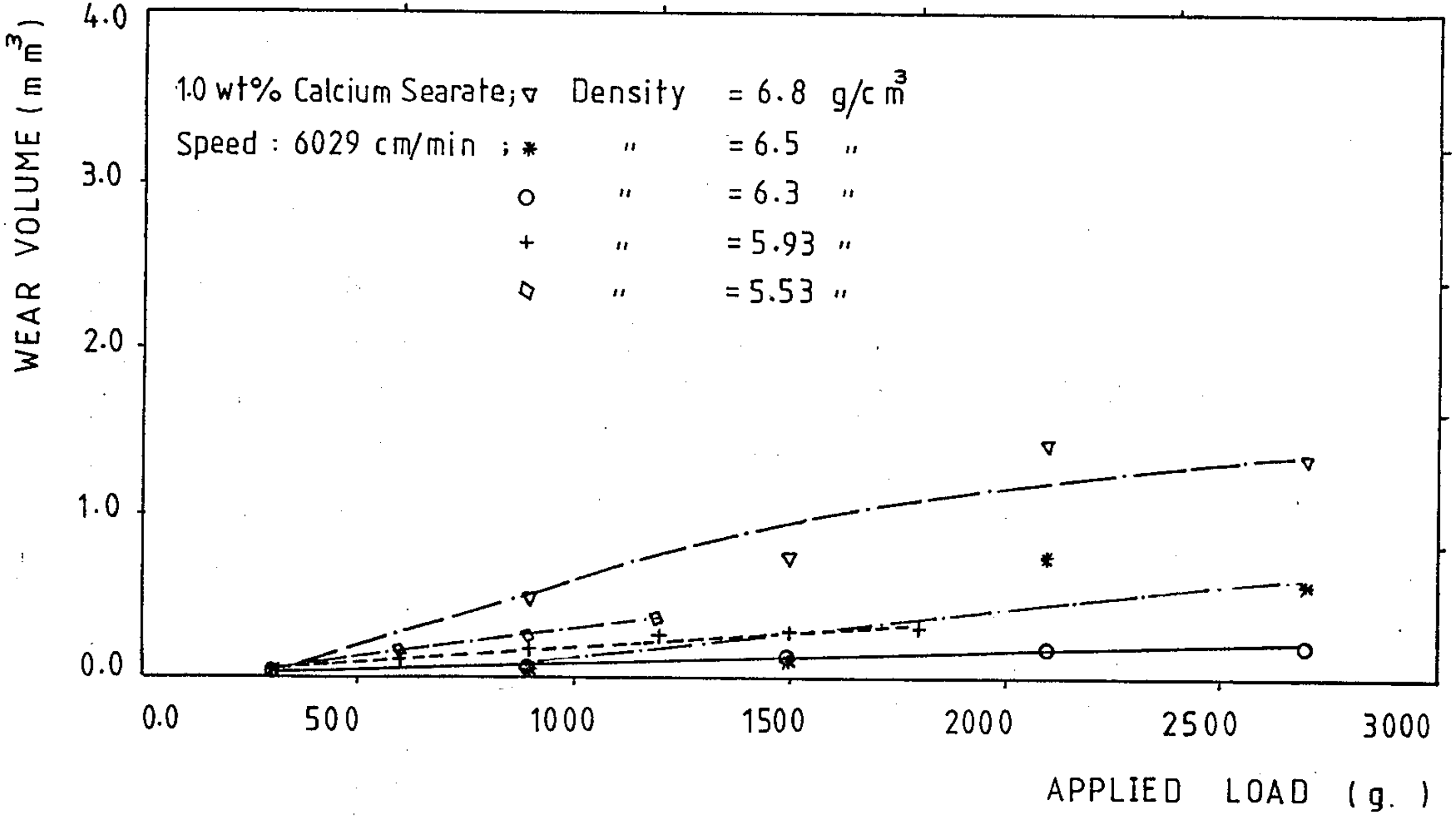

WEAR VOLUME ( m $m^3$ )
4.0
3.0
2.0
1.0
0.0
0.0
500
1000
1500
2000
2500
3000
APPLIED LOAD ( g. )
1.0 wt% Calcium Searate; ▽ Density = 6.8 g/c $m^3$
Speed : 6029 cm/min ; * " = 6.5 "
○ " = 6.3 "
+ " = 5.93 "
◇ " = 5.53 "

Fig. 57

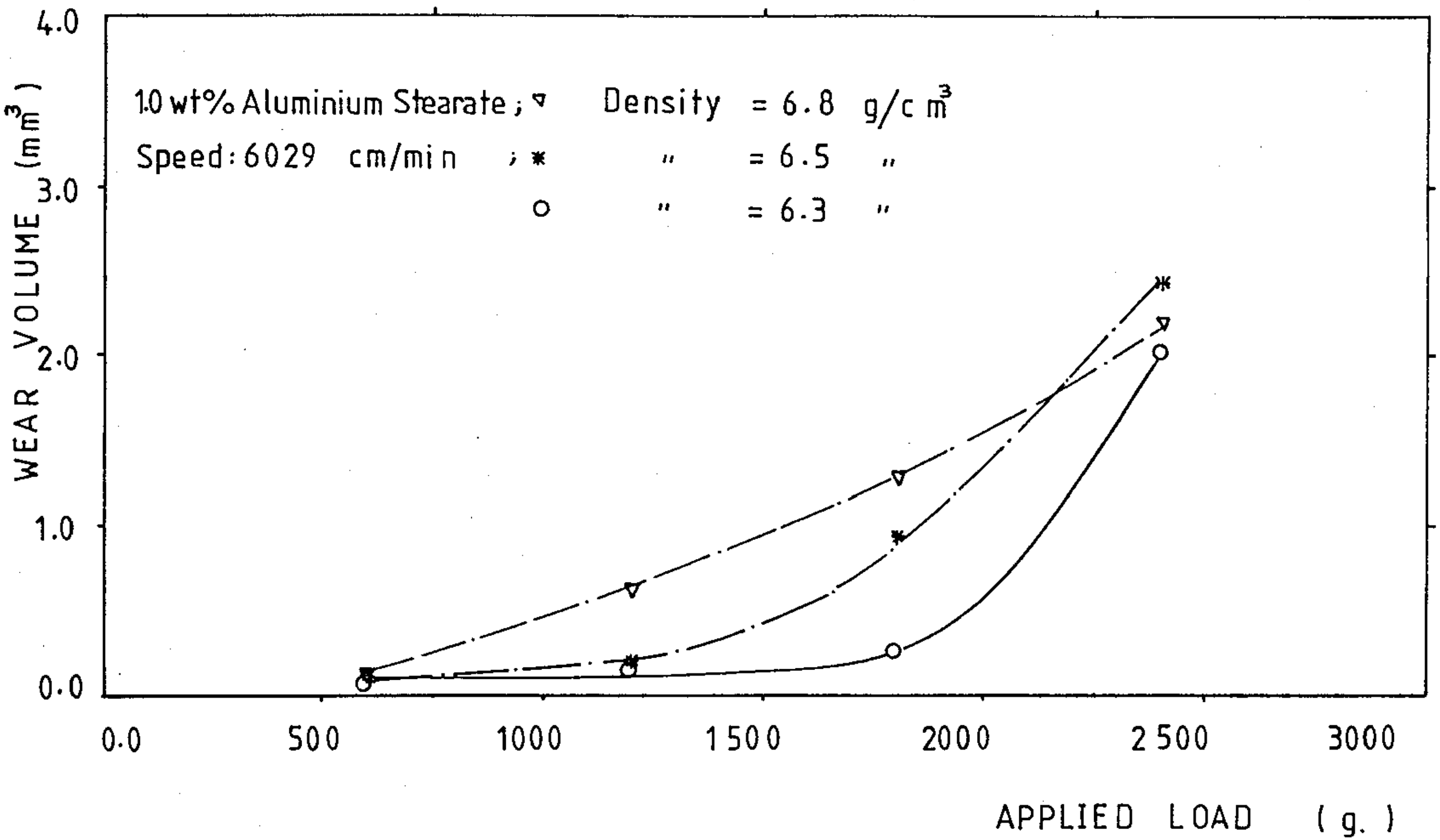

1.0 wt% Aluminium Stearate ; ▽ Density = 6.8 g/cm³
Speed: 6029 cm/min ; ✱ " = 6.5 "
○ " = 6.3 "
WEAR VOLUME (mm³)
4.0
3.0
2.0
1.0
0.0
0.0
500
1000
1500
2000
2500
3000
APPLIED LOAD (g.)

Fig. 58

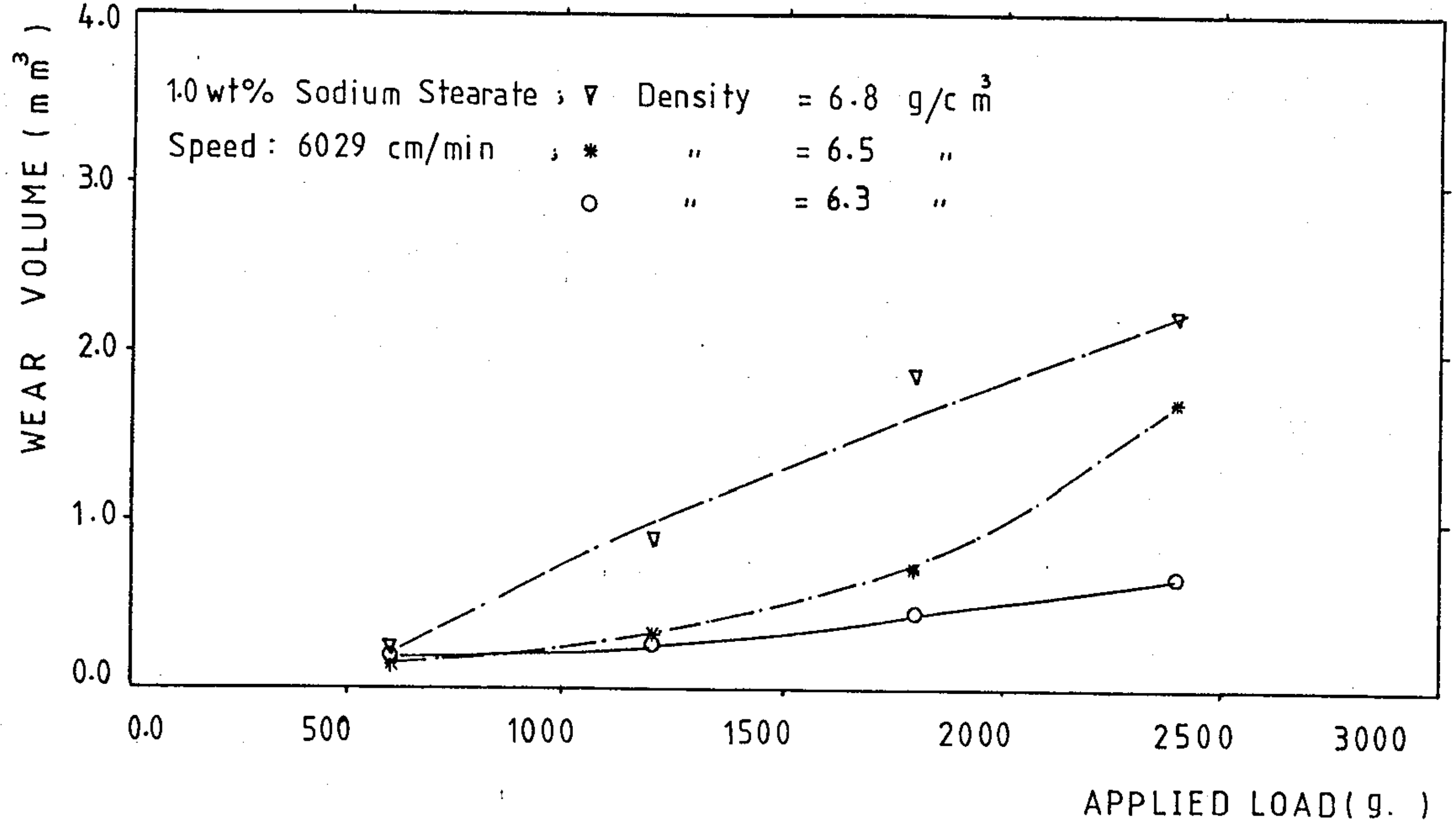

1.0 wt% Sodium Stearate ; ∇ Density = 6.8 g/cm³
Speed : 6029 cm/min ; * " = 6.5 "
○ " = 6.3 "
WEAR VOLUME ( mm³ )
4.0
3.0
2.0
1.0
0.0
0.0
500
1000
1500
2000
2500
3000
APPLIED LOAD( g. )

Fig. 59

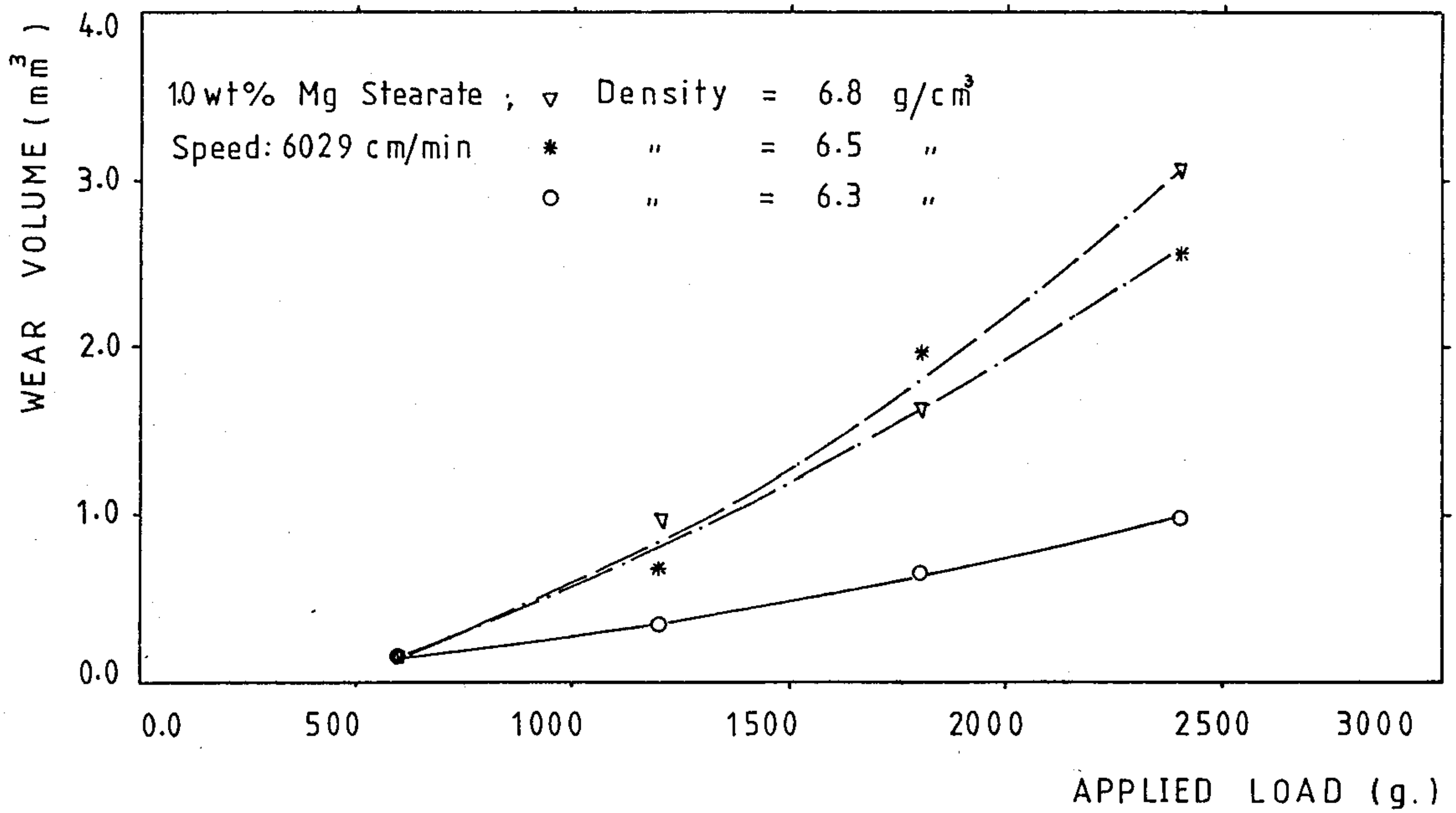

WEAR VOLUME ( $mm^3$ )
4.0
3.0
2.0
1.0
0.0
1.0 wt% Mg Stearate ; ▽ Density = 6.8 $g/cm^3$
Speed: 6029 cm/min * " = 6.5 "
○ " = 6.3 "
0.0
500
1000
1500
2000
2500
3000
APPLIED LOAD (g.)

Fig. 60

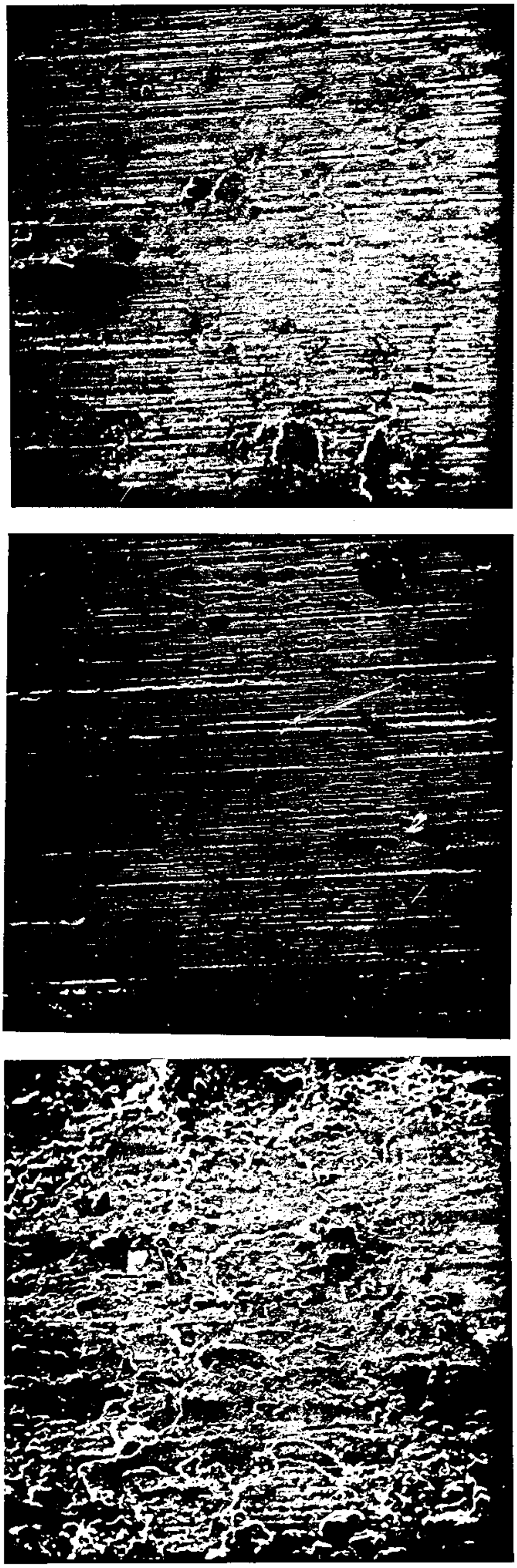


Fig.61a
S.E.M.Photographs for Wear Scars on Compacts from Load Trials.
Density: 6.5 g/cm$^3$
Lubricant contents: 1.0 wt % Zinc.
Loads: 1) 600, 2) 1200, 3) 2400 g.
All Photographs at: X 180

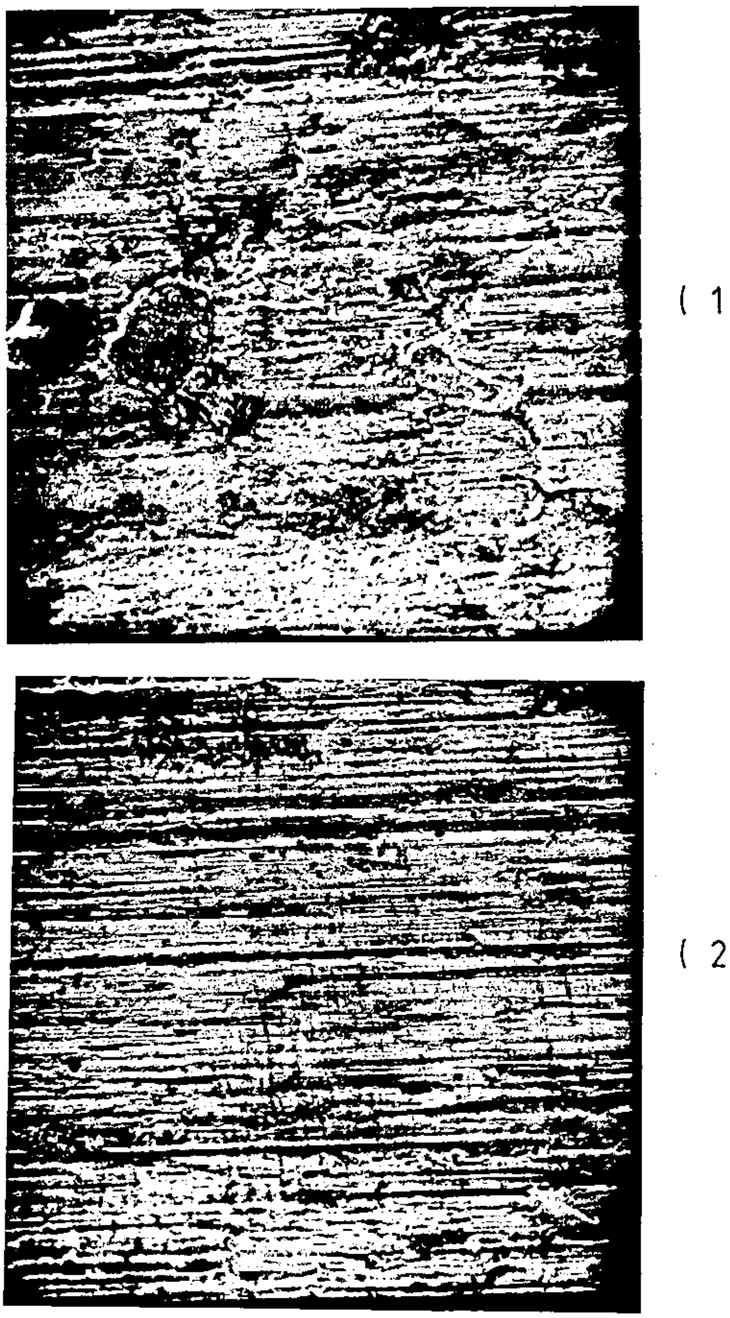


Fig. 61b S.E.M Photographs for Wear Scars on Compacts from Load Trials. Density: 6.5 g/cm$^3$; Lubricant Content: 1.0 wt% ; Loads 1 ) 600 ; 2 ) 1200 g.

All Photographs at X450

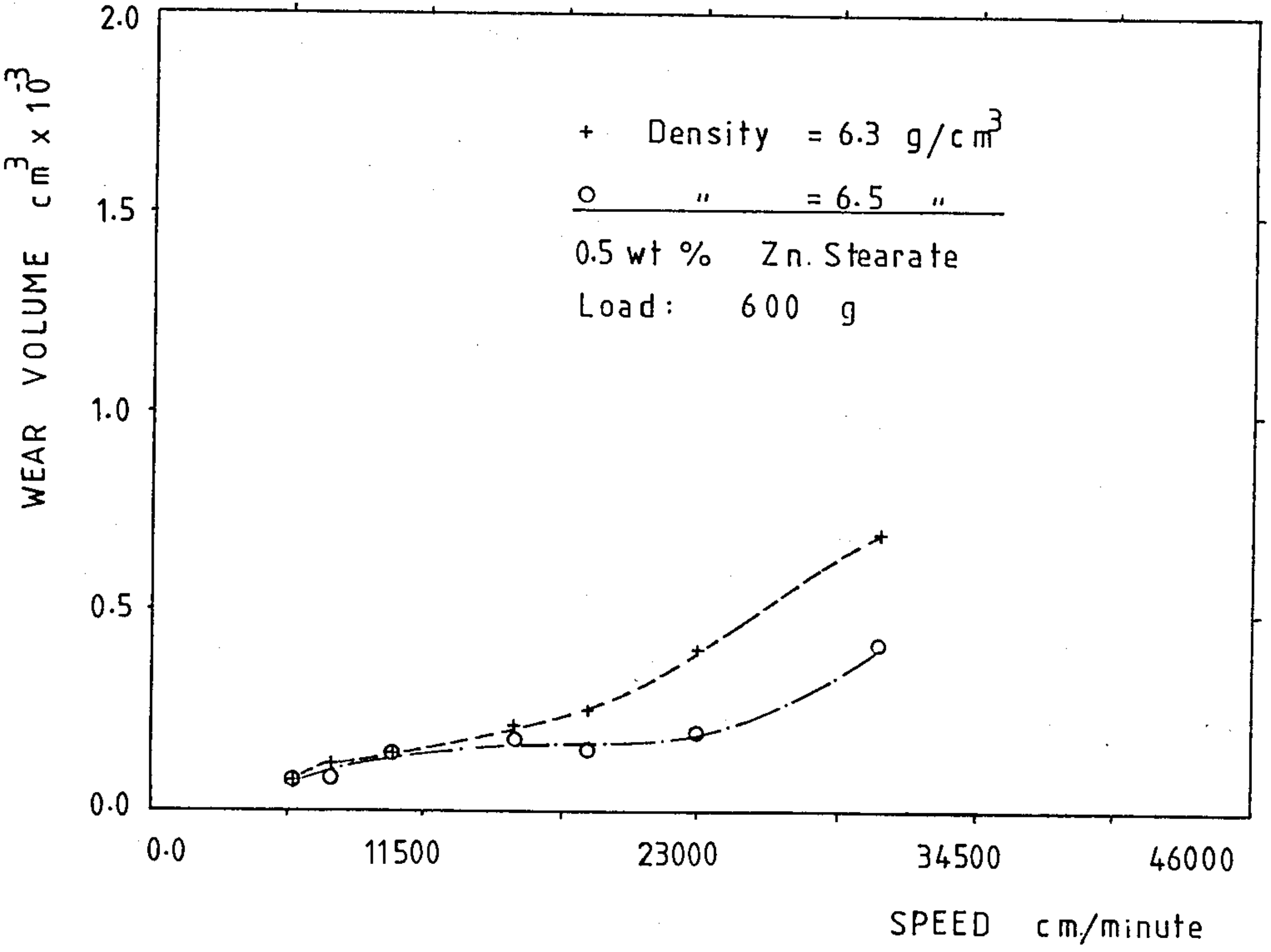

WEAR VOLUME $cm^3 \times 10^{-3}$
2.0
1.5
1.0
0.5
0.0
0.0
11500
23000
34500
46000
SPEED cm/minute
+ Density = 6.3 g/cm³
○ " = 6.5 "
0.5 wt % Zn. Stearate
Load: 600 g

Fig. 62

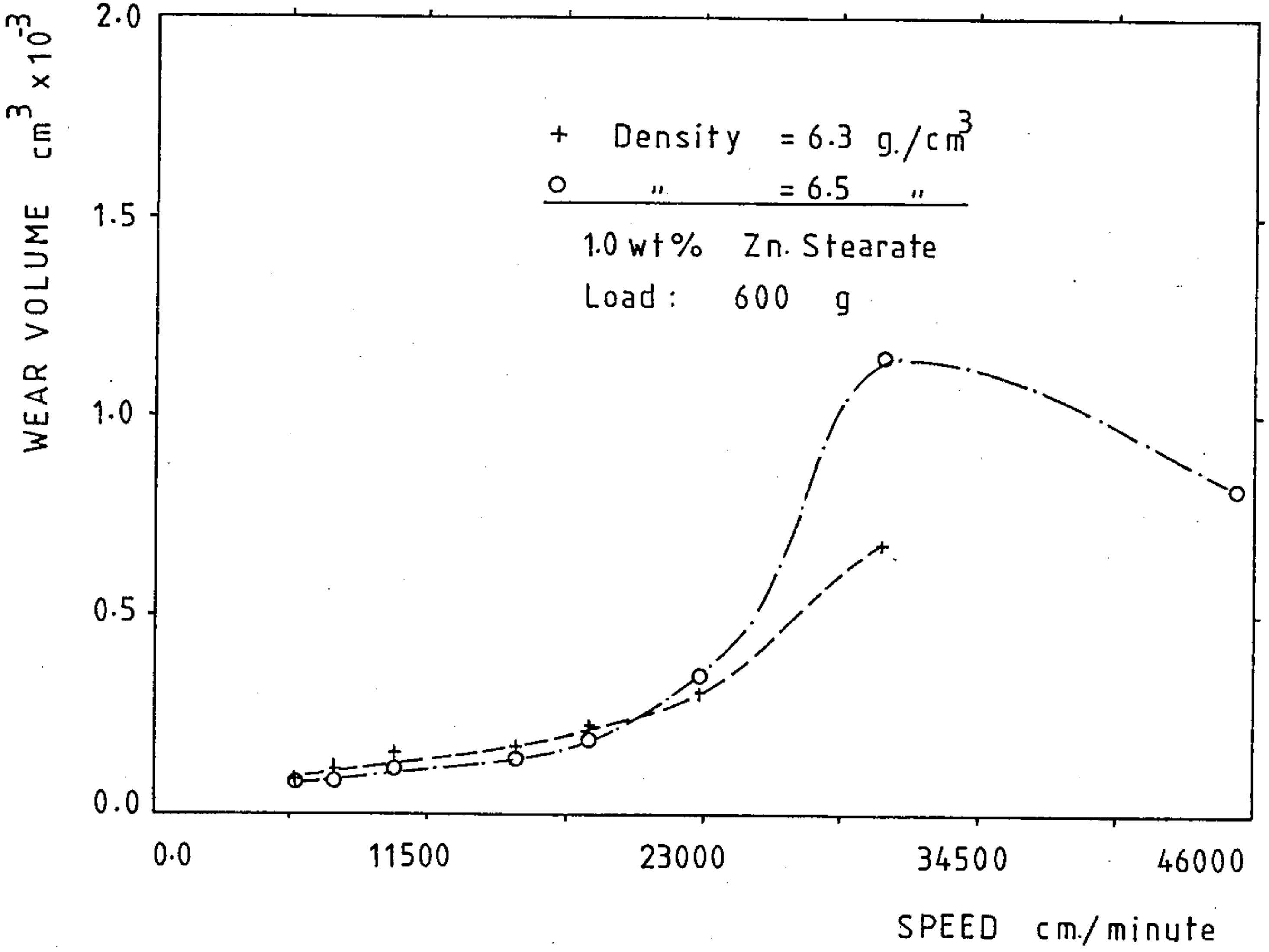

WEAR VOLUME $cm^3 \times 10^{-3}$
2.0
1.5
1.0
0.5
0.0
0.0
11500
23000
34500
46000
SPEED cm./minute
+ Density = 6.3 g./cm$^3$
○ " = 6.5 "
1.0 wt% Zn. Stearate
Load : 600 g

Fig. 63

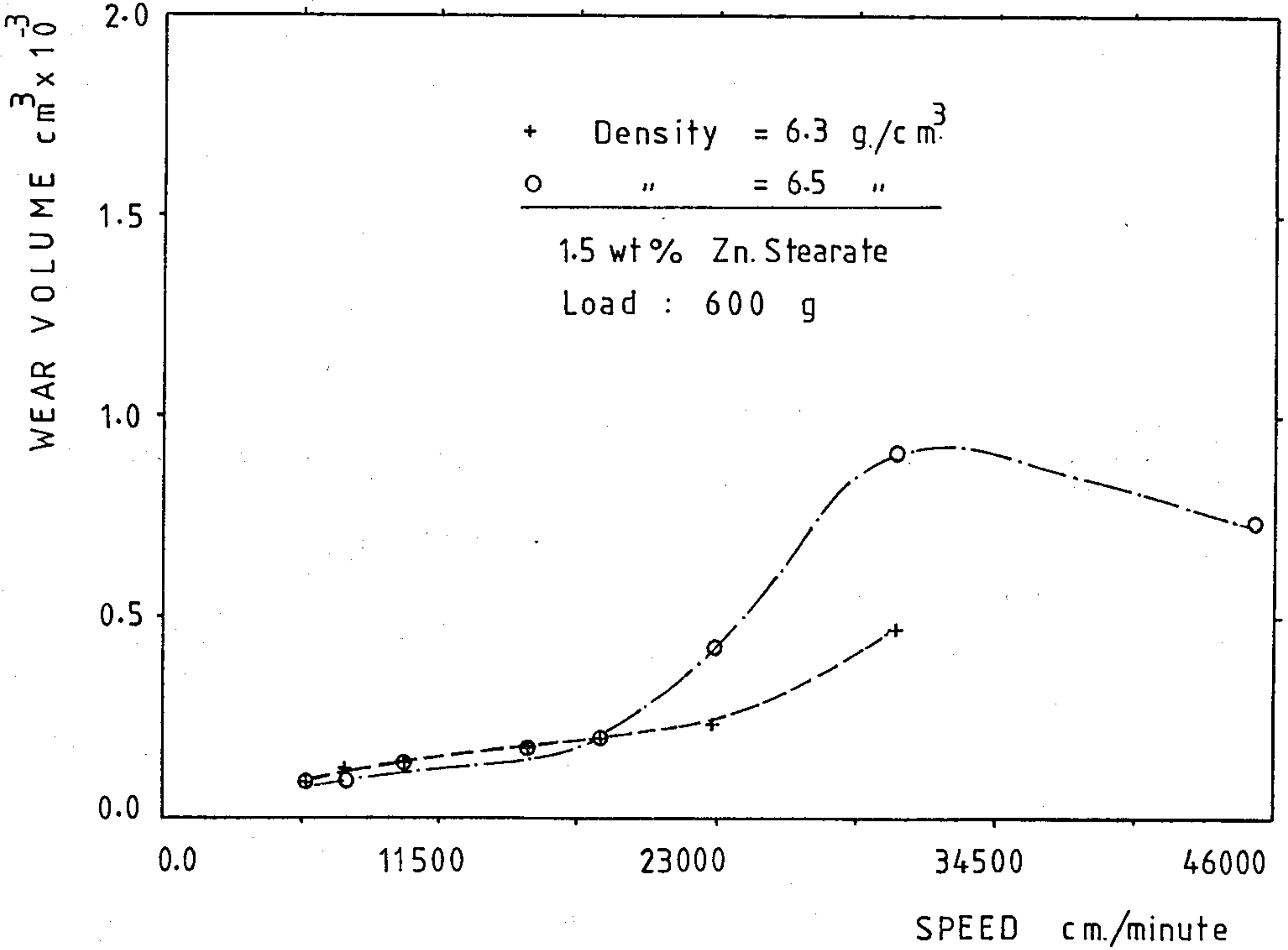

WEAR VOLUME $cm^3 \times 10^{-3}$
2.0
1.5
1.0
0.5
0.0
0.0
11500
23000
34500
46000
SPEED cm./minute
+ Density = 6.3 $g./cm^3$
○ " = 6.5 "
1.5 wt % Zn. Stearate
Load : 600 g

Fig. 64

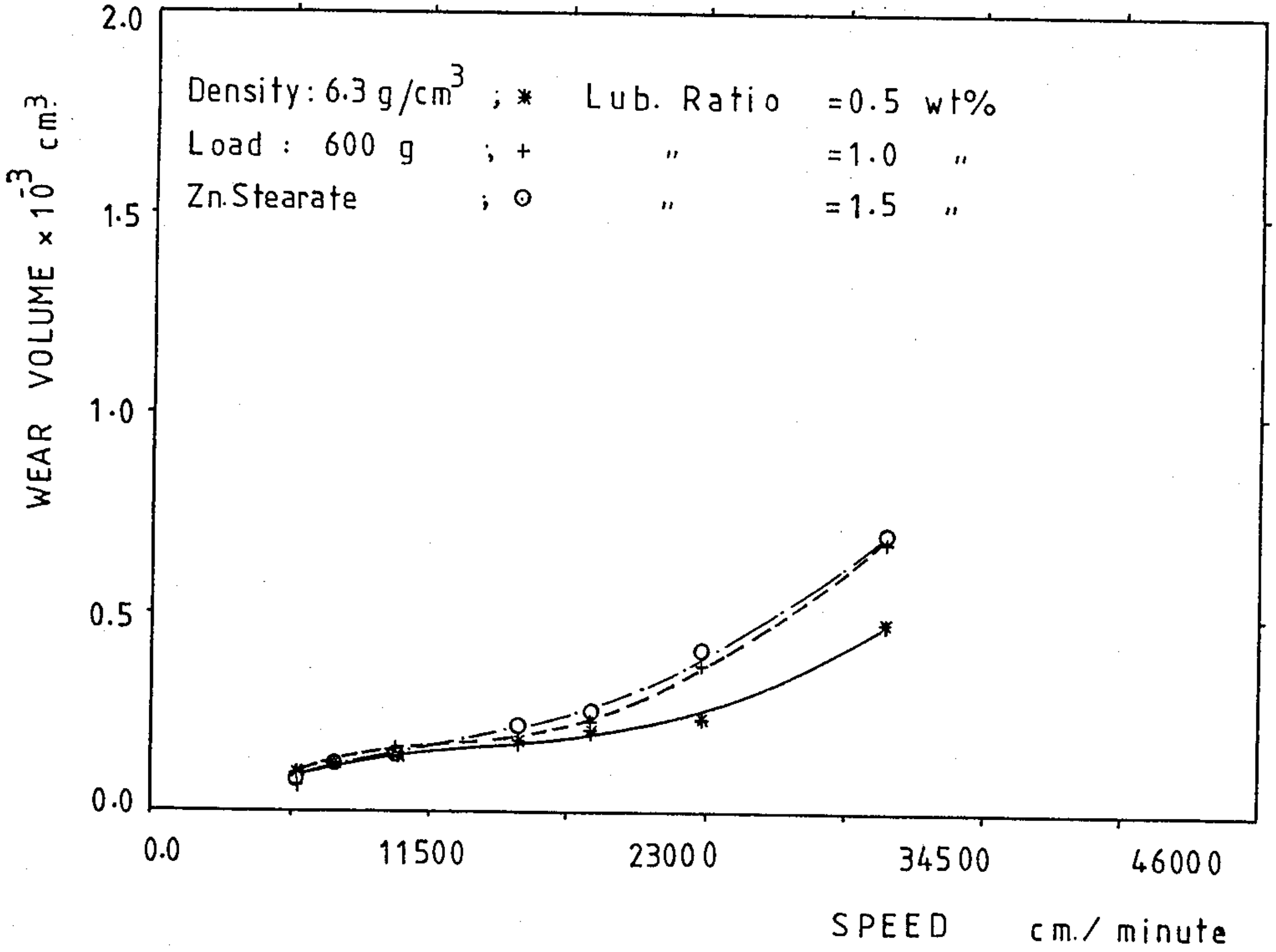
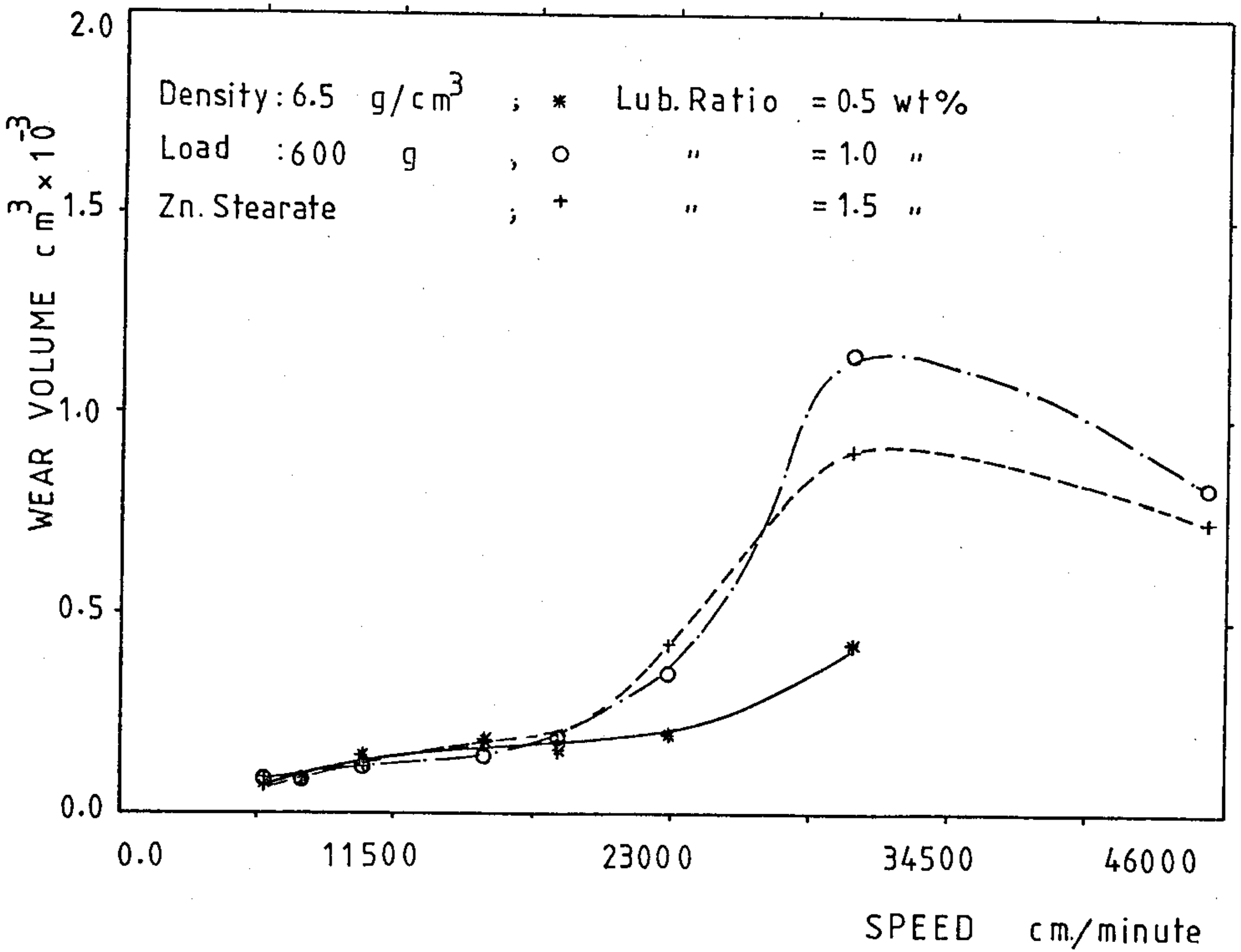

Density: 6.3 g/cm³ ; * Lub. Ratio =0.5 wt%
Load : 600 g ; + " =1.0 "
Zn.Stearate ; ⊙ " =1.5 "
WEAR VOLUME × 10⁻³ cm³
2.0
1.5
1.0
0.5
0.0
0.0
11500
23000
34500
46000
SPEED cm./ minute

Fig. 65



Density : 6.5 g/cm$^3$
Load : 600 g
Zn. Stearate
* Lub. Ratio = 0.5 wt%
○ " = 1.0 "
+ " = 1.5 "
WEAR VOLUME cm$^3$ × 10$^{-3}$
2.0
1.5
1.0
0.5
0.0
0.0
11500
23000
34500
46000
SPEED cm/minute

Fig. 66

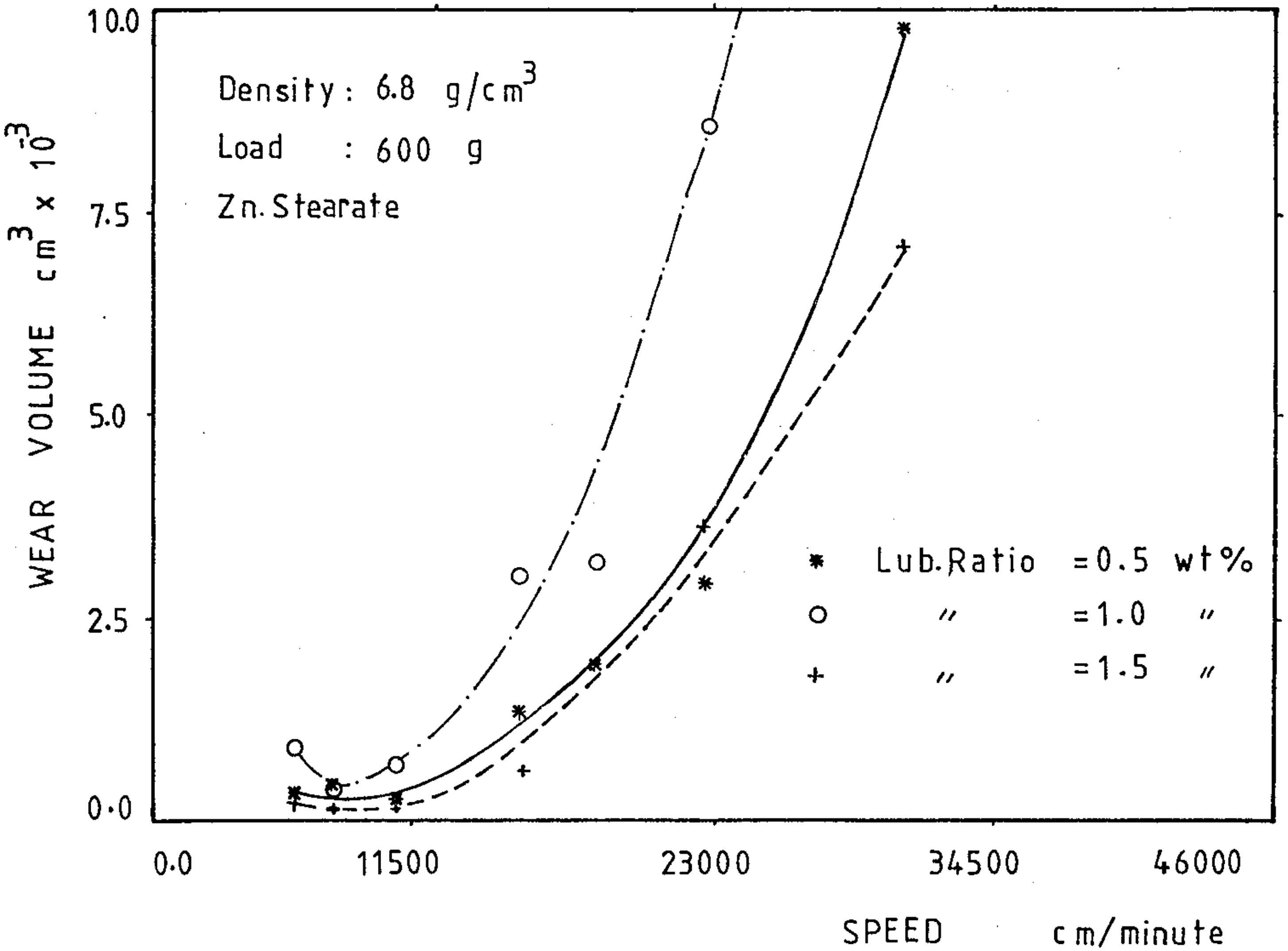

Density : 6.8 g/cm³
Load : 600 g
Zn. Stearate
WEAR VOLUME cm³ x 10⁻³
10.0
7.5
5.0
2.5
0.0
0.0
11500
23000
34500
46000
SPEED cm/minute
✱ Lub.Ratio = 0.5 wt%
○ 〃 = 1.0 〃
+ 〃 = 1.5 〃

Fig. 67

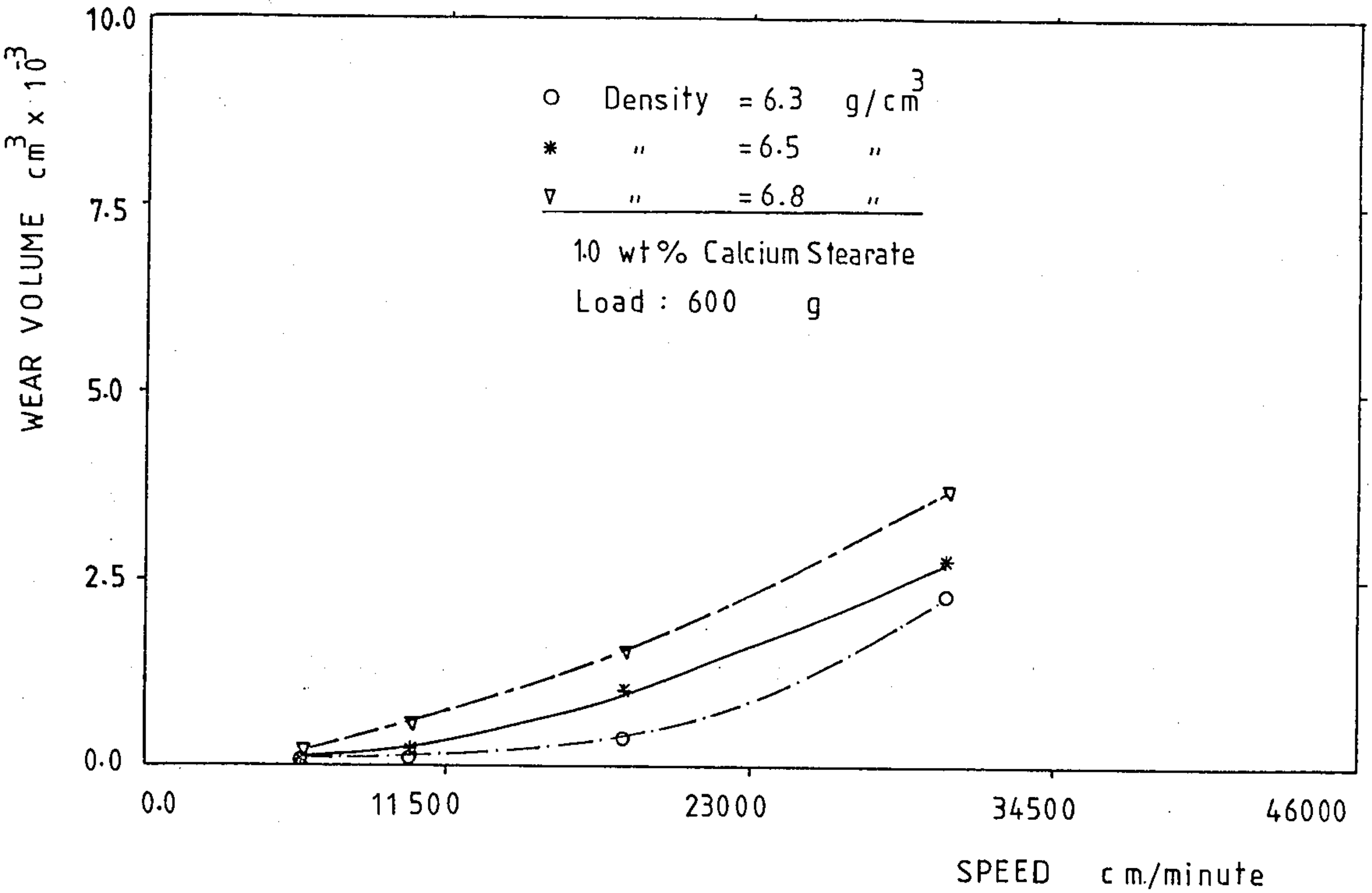

10.0
7.5
5.0
2.5
0.0
WEAR VOLUME $cm^3 \times 10^{-3}$
○ Density = 6.3 $g/cm^3$
✱ " = 6.5 "
▽ " = 6.8 "
1.0 wt % Calcium Stearate
Load : 600 g
0.0
11500
23000
34500
46000
SPEED cm./minute

Fig. 68

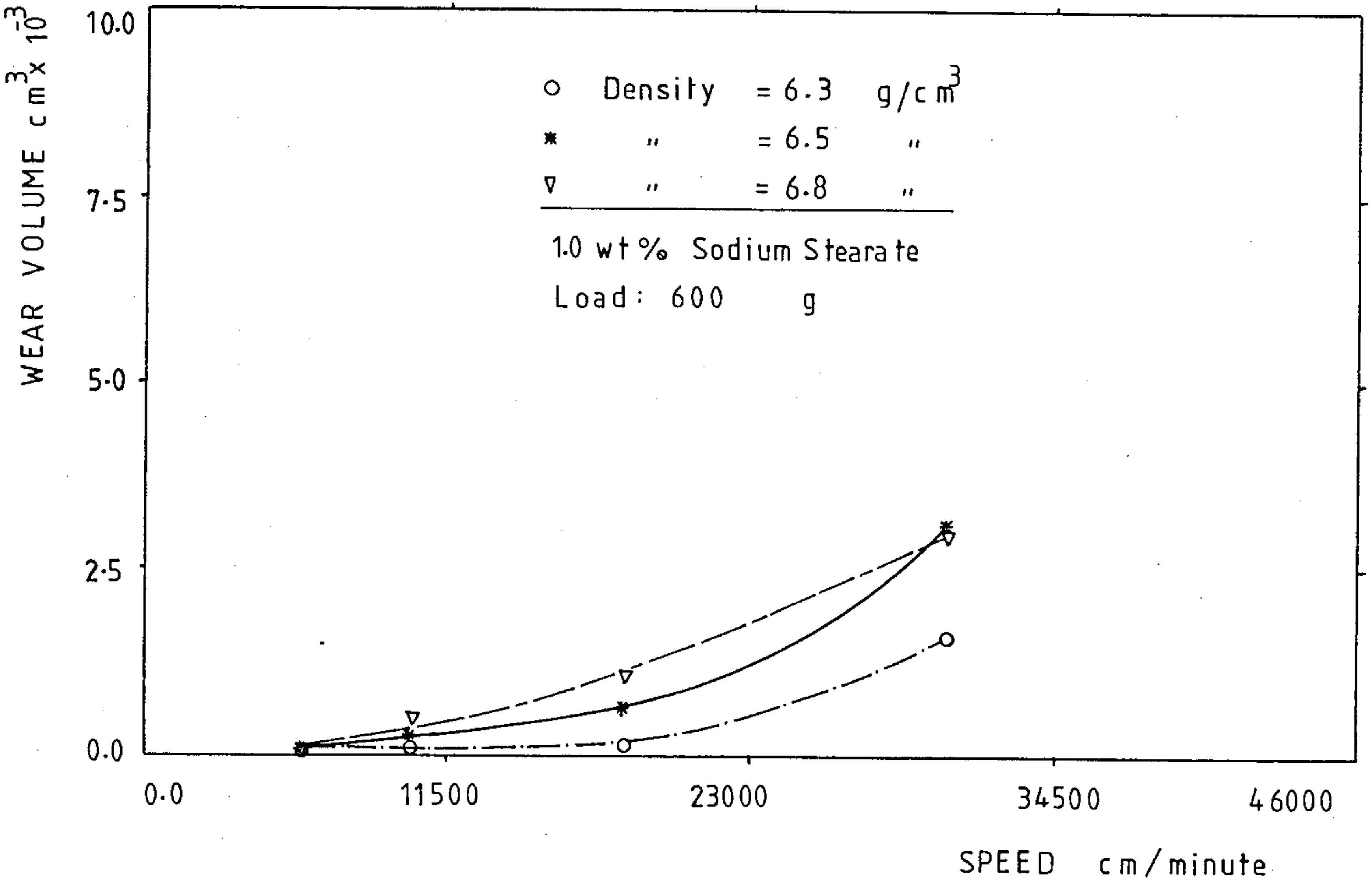

WEAR VOLUME cm³x 10⁻³
10.0
7·5
5·0
2·5
0.0
0·0
11500
23000
34500
46000
SPEED cm/minute
○ Density = 6.3 g/cm³
✱ " = 6.5 "
▽ " = 6.8 "
1.0 wt % Sodium Stearate
Load: 600 g

Fig. 69

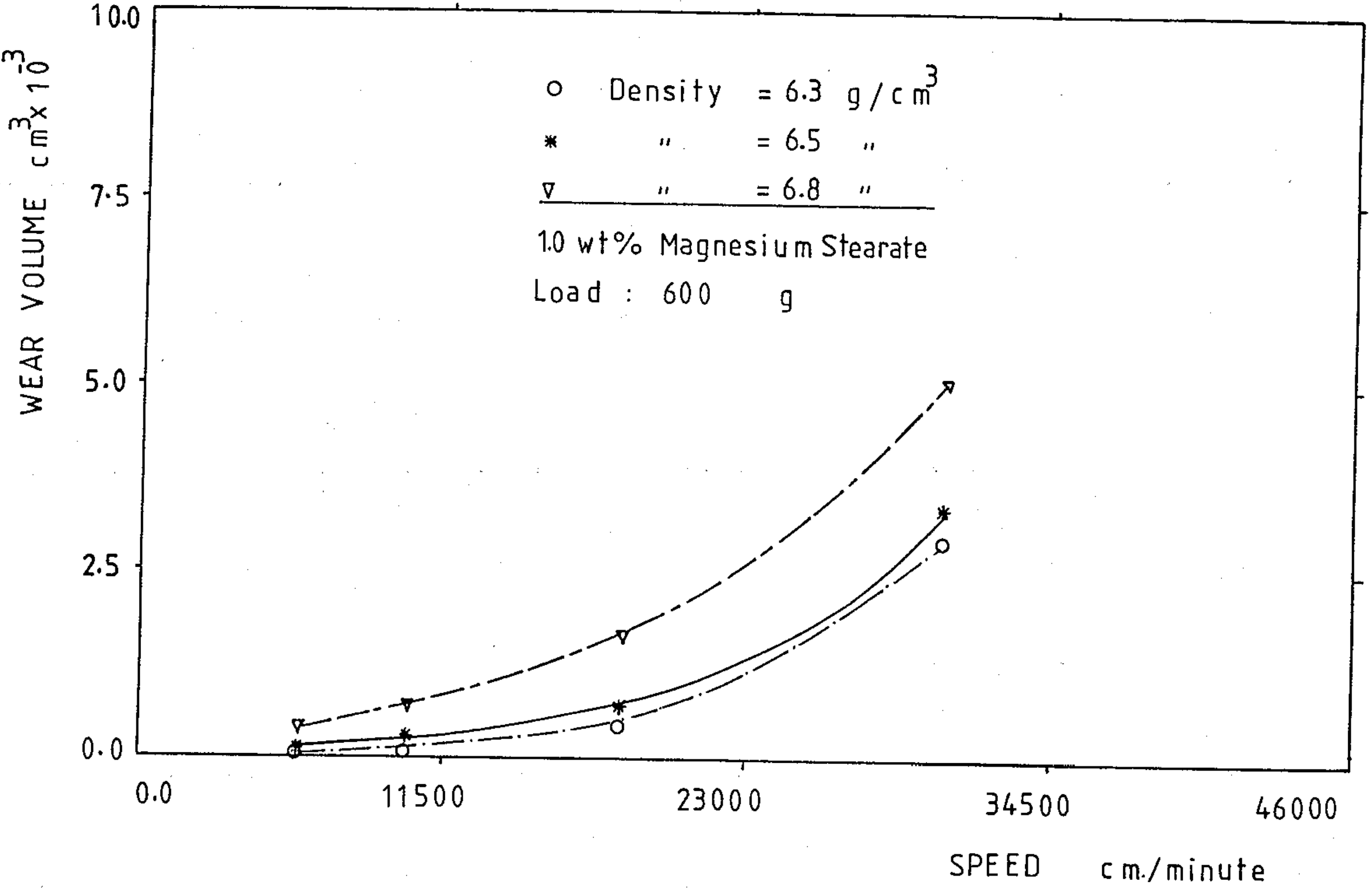

WEAR VOLUME cm$^3$ x 10$^{-3}$
10.0
7·5
5·0
2.5
0.0
0.0
11500
23000
34500
46000
SPEED cm./minute
○ Density = 6.3 g/cm$^3$
✱ " = 6.5 "
∇ " = 6.8 "
1.0 wt% Magnesium Stearate
Load : 600 g

Fig. 70

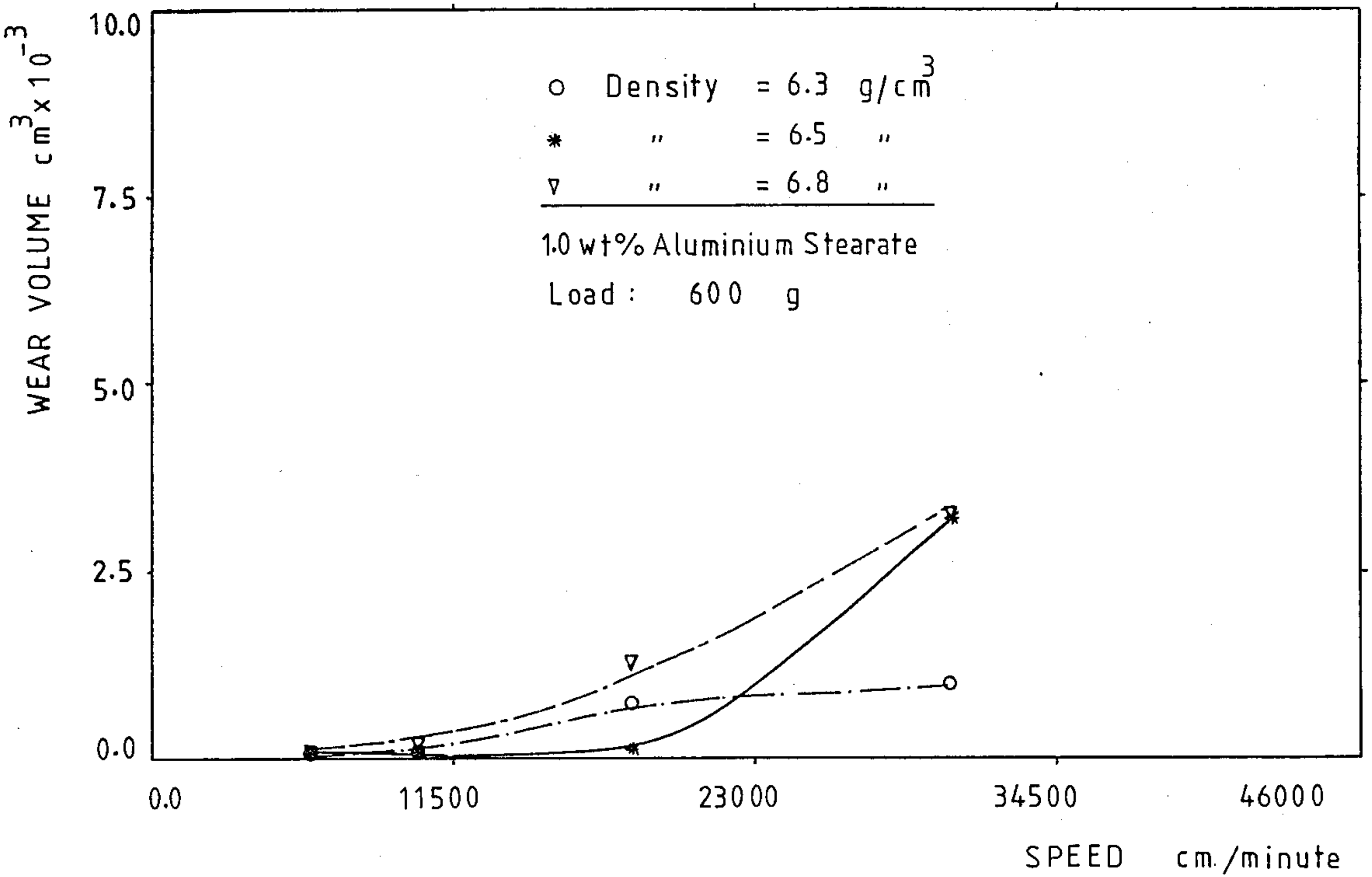
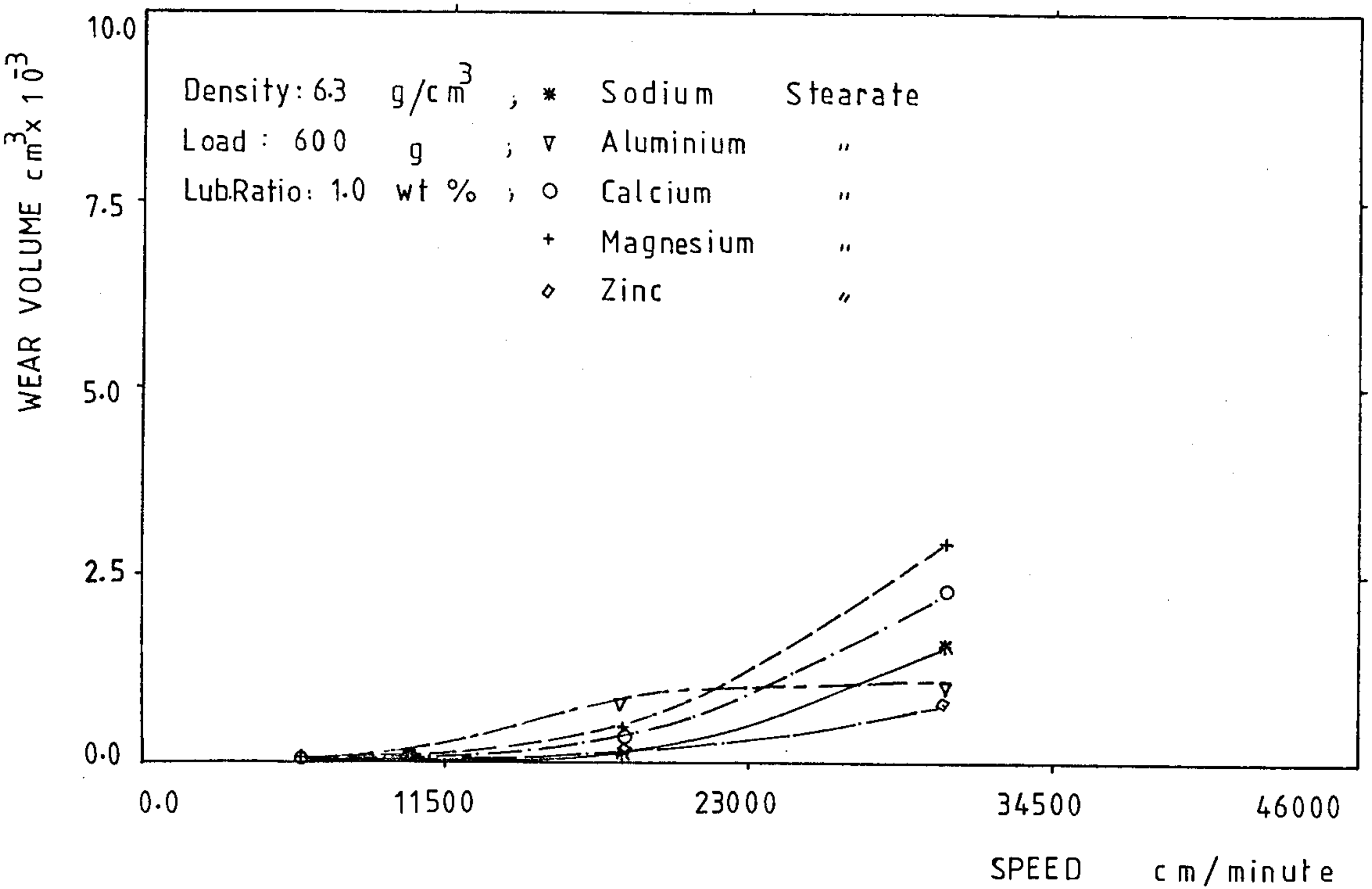
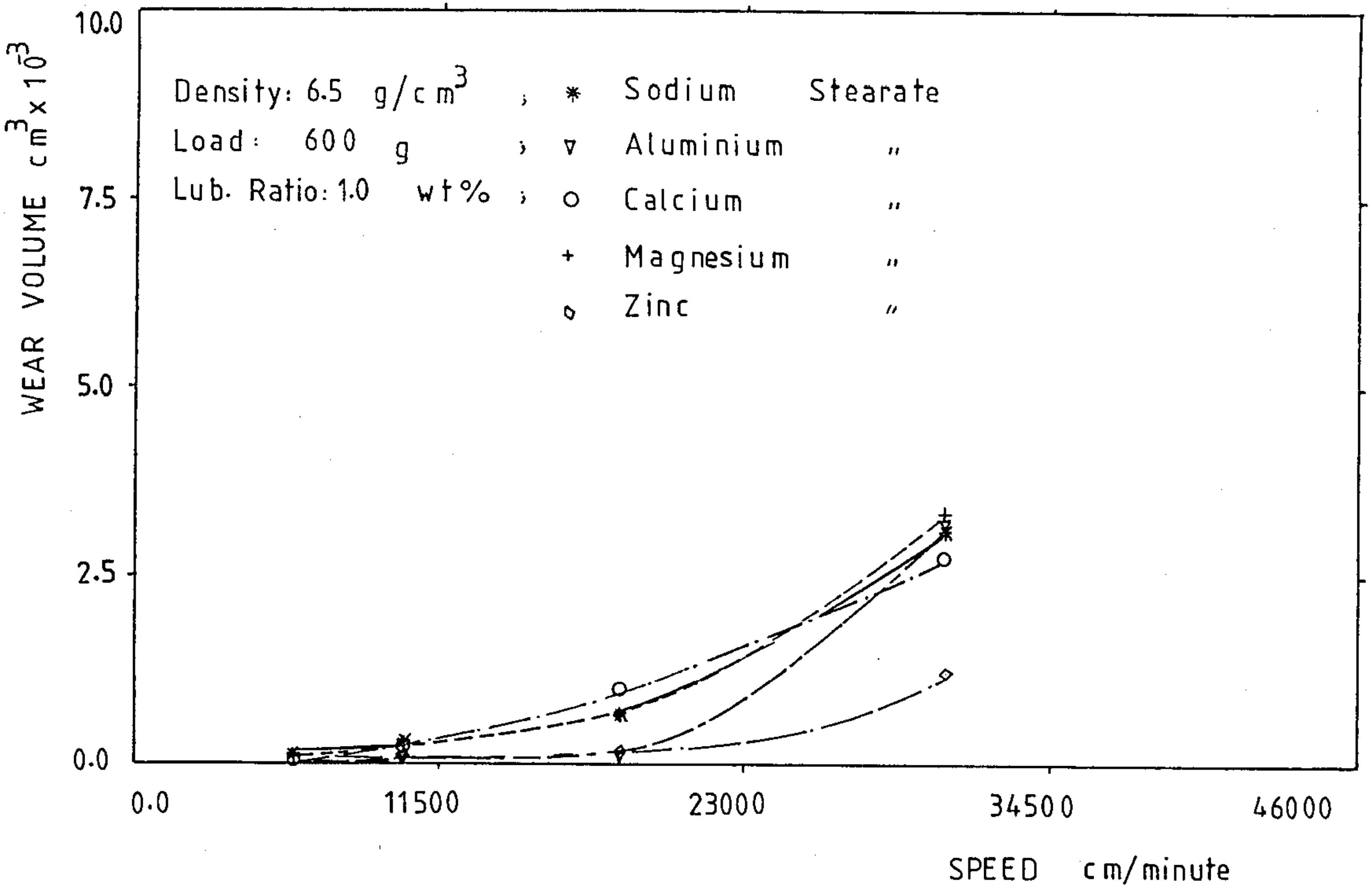

WEAR VOLUME $cm^3 \times 10^{-3}$
10.0
7.5
5.0
2.5
0.0
0.0
11500
23000
34500
46000
SPEED cm./minute
○ Density = 6.3 $g/cm^3$
* " = 6.5 "
▽ " = 6.8 "
1.0 wt% Aluminium Stearate
Load : 600 g

Fig. 71



WEAR VOLUME cm$^3$x 10$^{-3}$
10.0
7.5
5.0
2.5
0.0
0.0
11500
23000
34500
46000
SPEED cm/minute
Density: 6.3 g/cm$^3$ ; ✱ Sodium Stearate
Load : 600 g ; ▽ Aluminium "
Lub.Ratio: 1.0 wt % ; ○ Calcium "
+ Magnesium "
◇ Zinc "

Fig. 72



10.0
7.5
5.0
2.5
0.0
WEAR VOLUME $cm^3 \times 10^{-3}$
Density: 6.5 $g/cm^3$ ; ✱ Sodium Stearate
Load: 600 g ; ▽ Aluminium "
Lub. Ratio: 1.0 wt% ; ○ Calcium "
+ Magnesium "
◇ Zinc "
0.0
11500
23000
34500
46000
SPEED cm/minute

Fig. 73

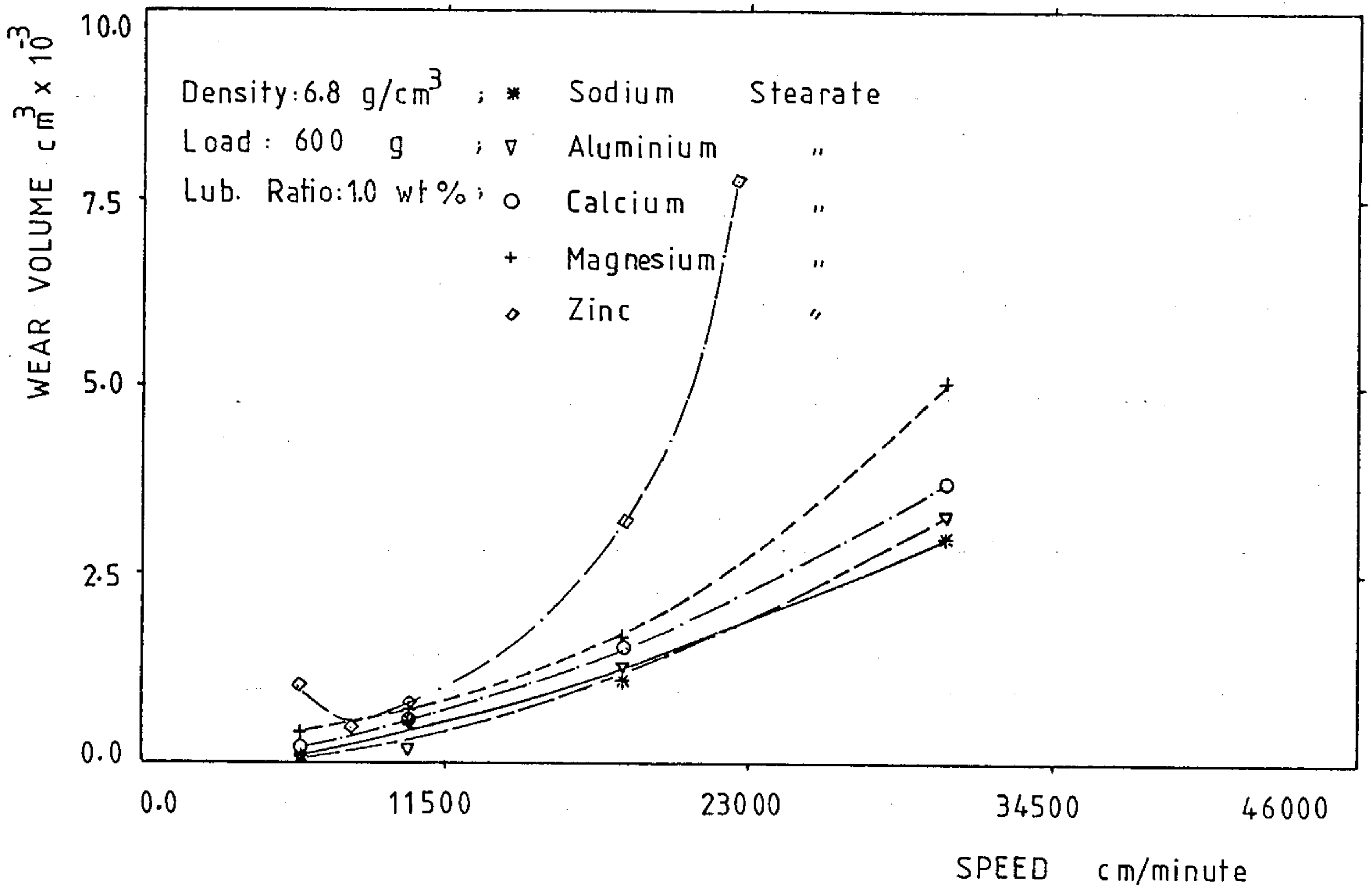

WEAR VOLUME $cm^3 \times 10^{-3}$
10.0
7.5
5.0
2.5
0.0
0.0
11500
23000
34500
46000
SPEED cm/minute
Density: 6.8 g/cm$^3$ ;
Load : 600 g ;
Lub. Ratio: 1.0 wt % ;
✱ Sodium Stearate
▽ Aluminium "
○ Calcium "
+ Magnesium "
◇ Zinc "

Fig. 74

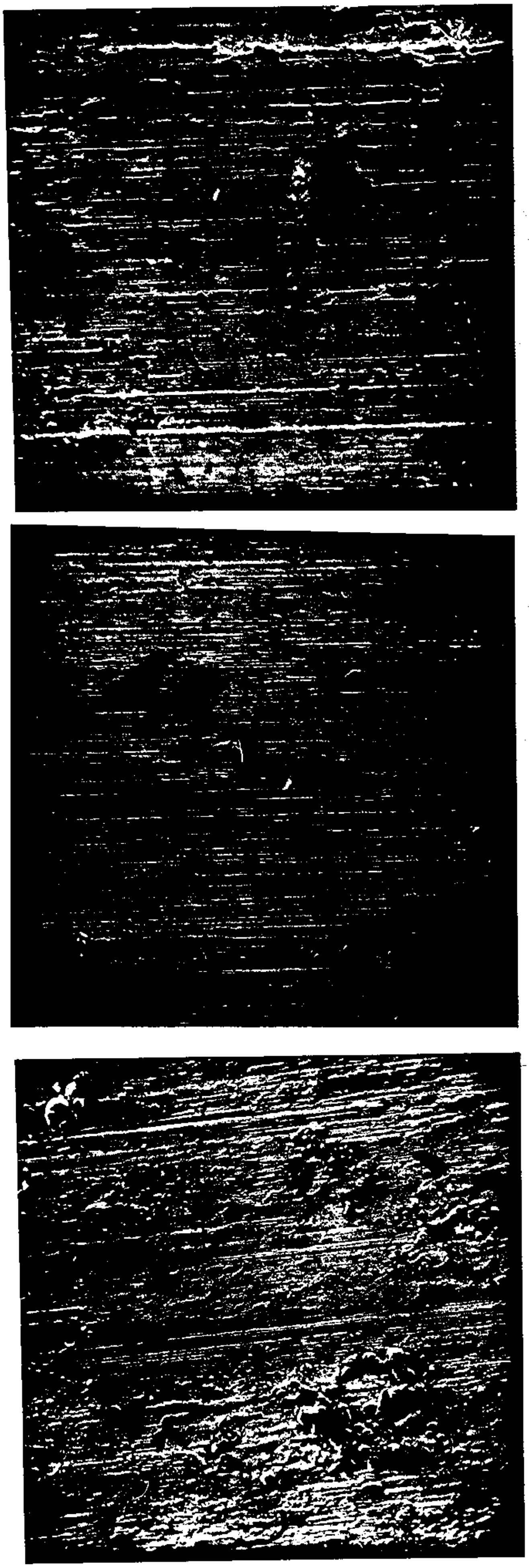


Fig. 75 a

S.E.M Photographs for Wear Scars on Compacts from Speed Trials.

Density : 6.5 $g/cm^3$

Lubricant contents : 1.0 wt % Zinc

Speeds 1) 6029 ; 2) 15230, 3) 30461 cm/minute.

All Photographs at : X180

Fig. 75b

S.E.M Photographs for Wear Scars on Compacts from Speed Trials.

Density : 6.5 g/cm$^3$

Lubricant contents: 1.0 wt %Zinc.

Speeds 1) 6029 ; 2) 15230, 3) 30461 cm/minute.

All Photographs at : X 450.

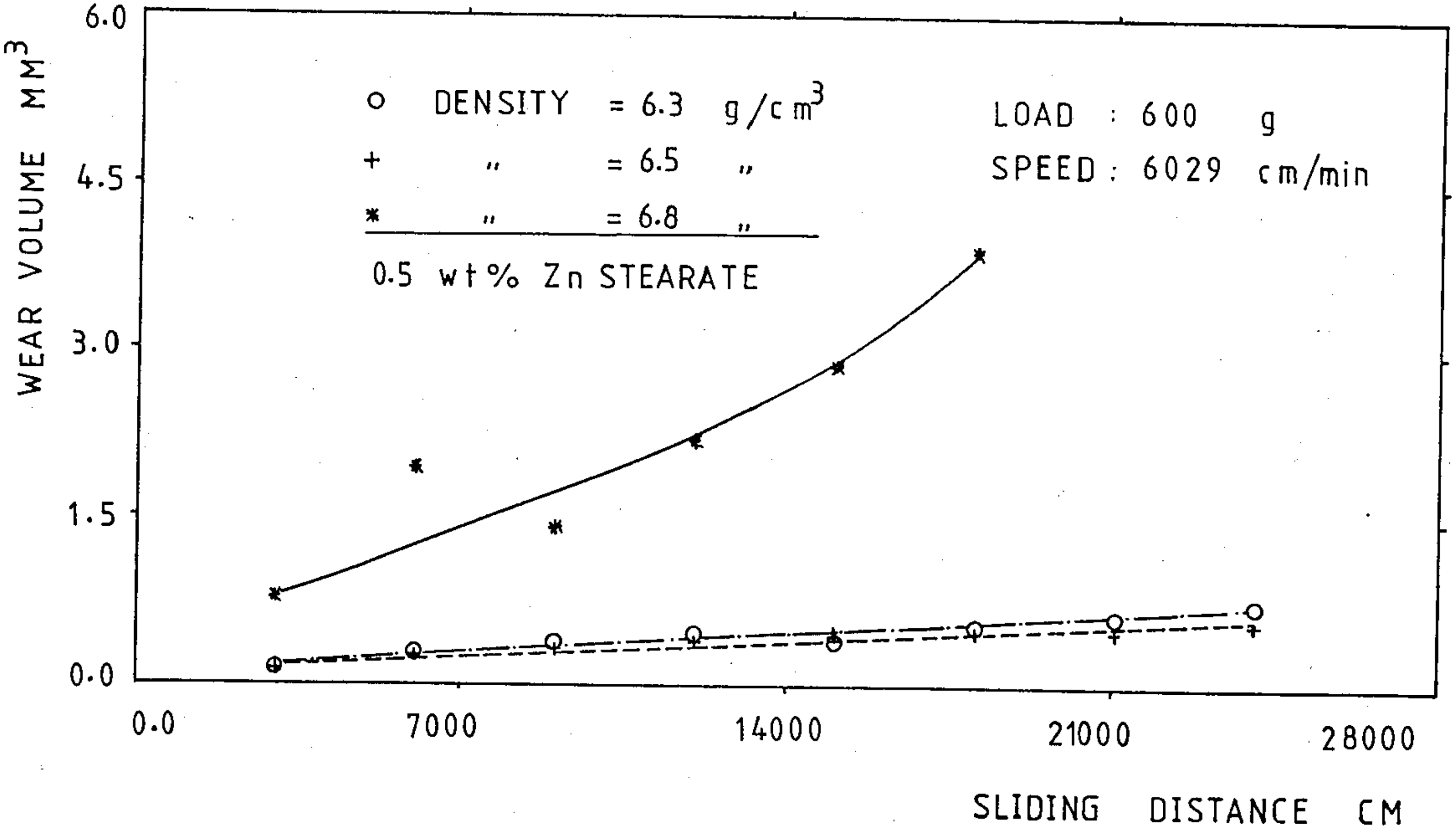

6.0
4.5
3.0
1.5
0.0
WEAR VOLUME MM$^3$
○ DENSITY = 6.3 g/cm$^3$
+ " = 6.5 "
* " = 6.8 "
0.5 wt% Zn STEARATE
LOAD : 600 g
SPEED : 6029 cm/min
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM

Fig. 76

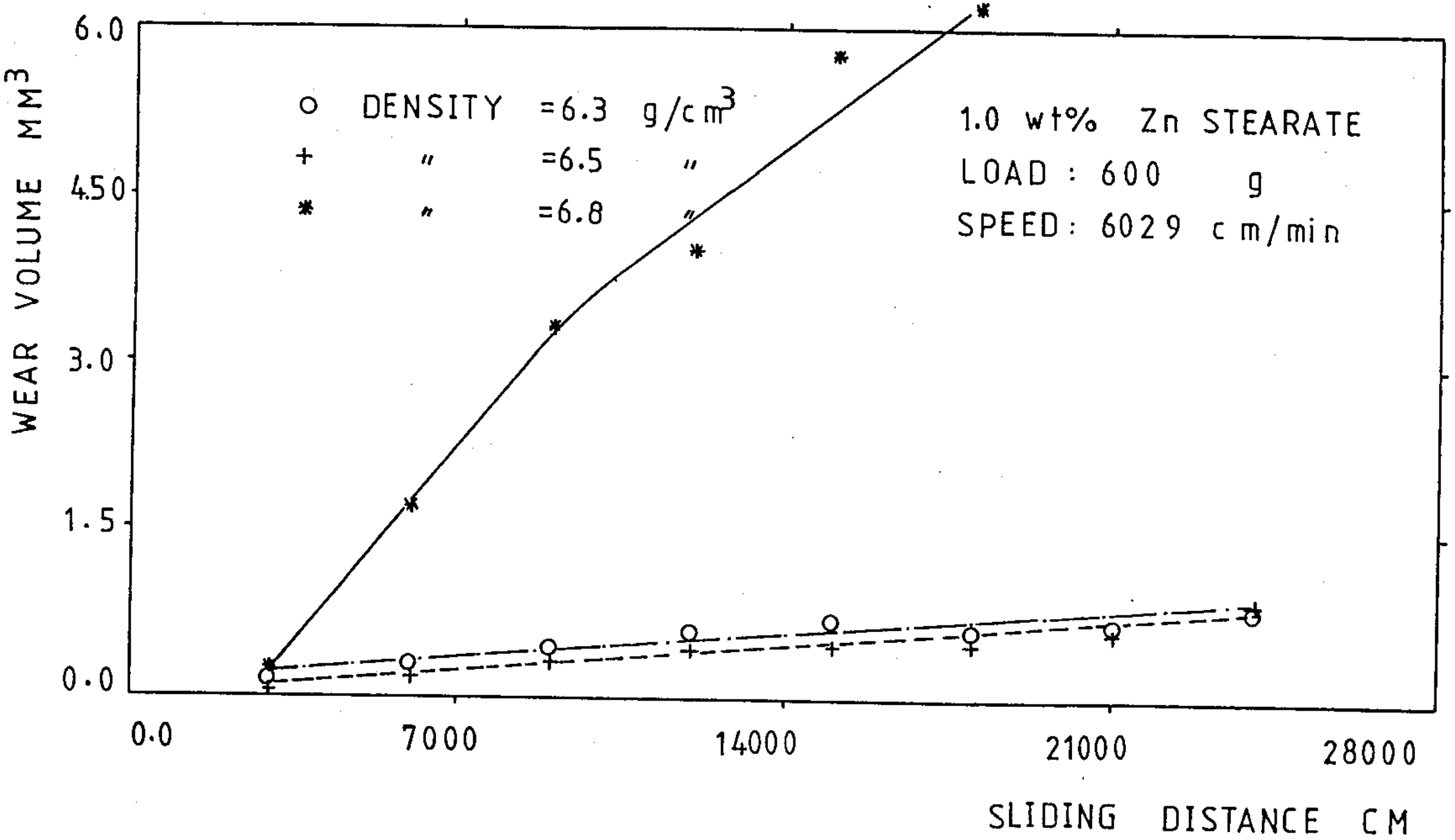

WEAR VOLUME MM$^3$
6.0
4.50
3.0
1.5
0.0
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM
○ DENSITY =6.3 g/cm$^3$
+ " =6.5 "
✱ " =6.8 "
1.0 wt% Zn STEARATE
LOAD : 600 g
SPEED : 6029 cm/min

Fig 77

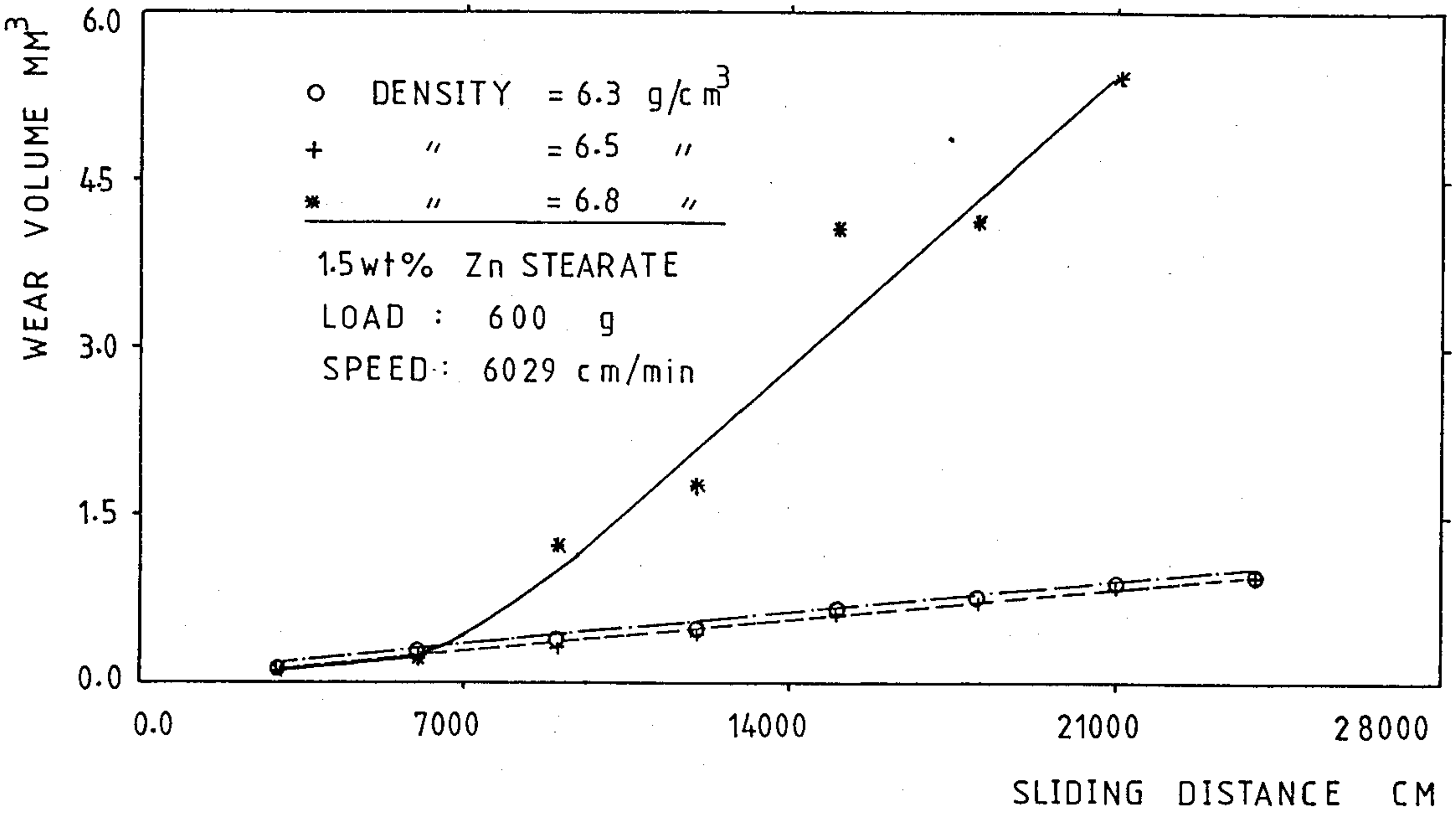

WEAR VOLUME MM$^3$
6.0
4.5
3.0
1.5
0.0
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM
○ DENSITY = 6.3 g/cm$^3$
+ " = 6.5 "
* " = 6.8 "
1.5wt% Zn STEARATE
LOAD : 600 g
SPEED : 6029 cm/min

Fig. 78

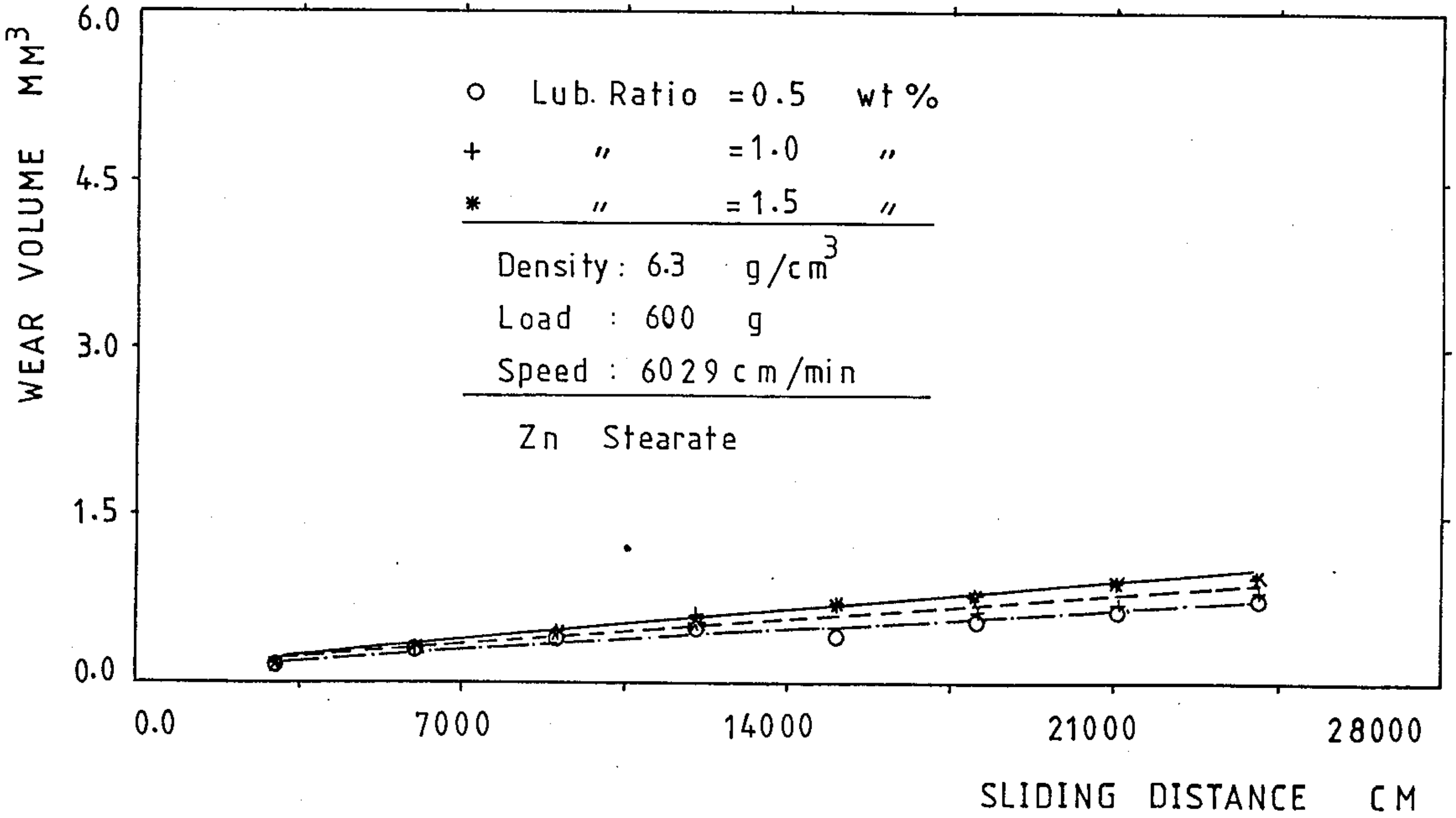

○ Lub. Ratio = 0.5 wt %
+ " = 1.0 "
✱ " = 1.5 "
Density : 6.3 g/cm3
Load : 600 g
Speed : 6029 cm/min
Zn Stearate
WEAR VOLUME MM3
6.0
4.5
3.0
1.5
0.0
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM

Fig. 79

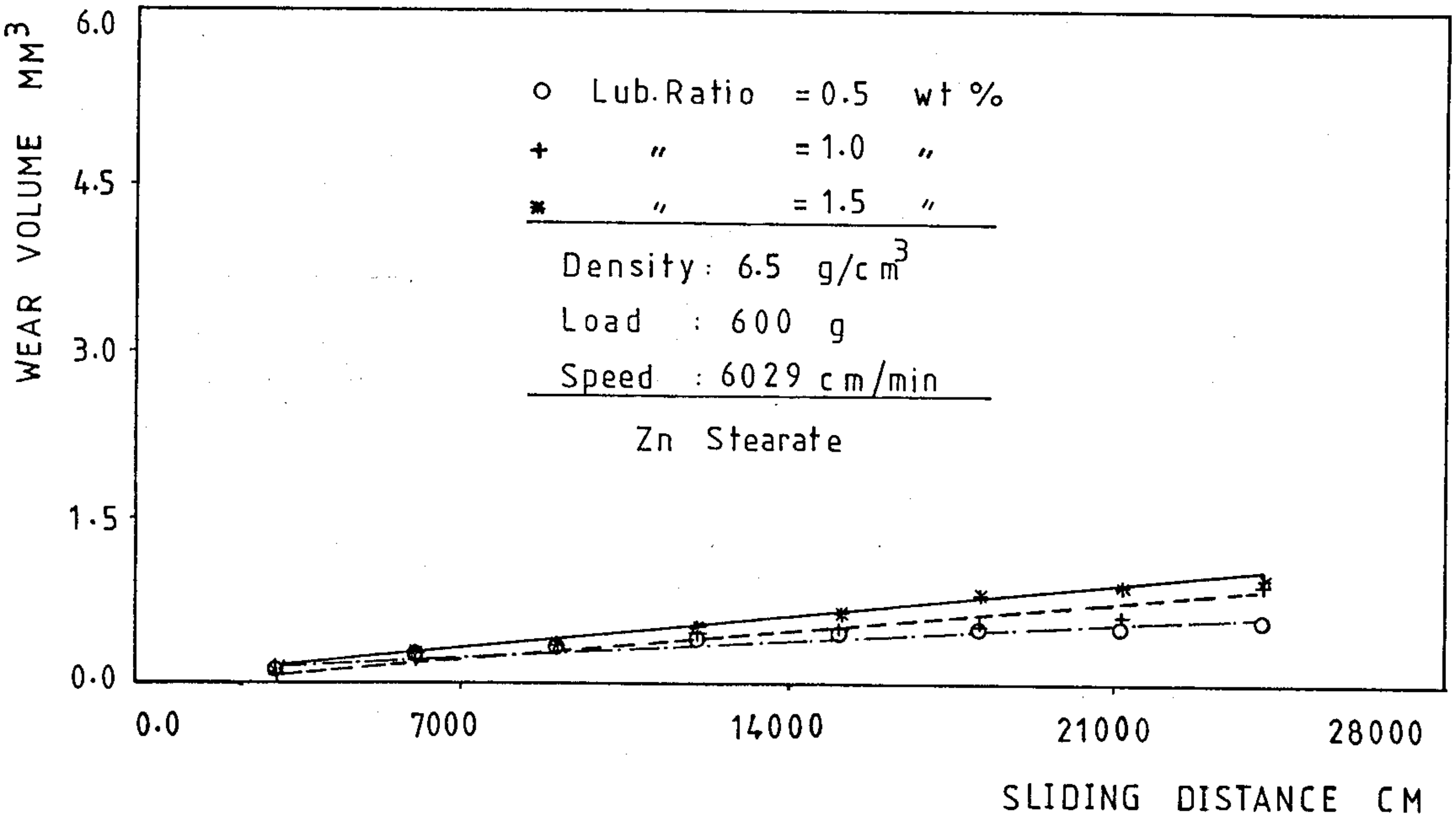

WEAR VOLUME MM3
6.0
4.5
3.0
1.5
0.0
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM
○ Lub.Ratio = 0.5 wt %
+ " = 1.0 "
✱ " = 1.5 "
Density : 6.5 g/cm3
Load : 600 g
Speed : 6029 cm/min
Zn Stearate

Fig. 80

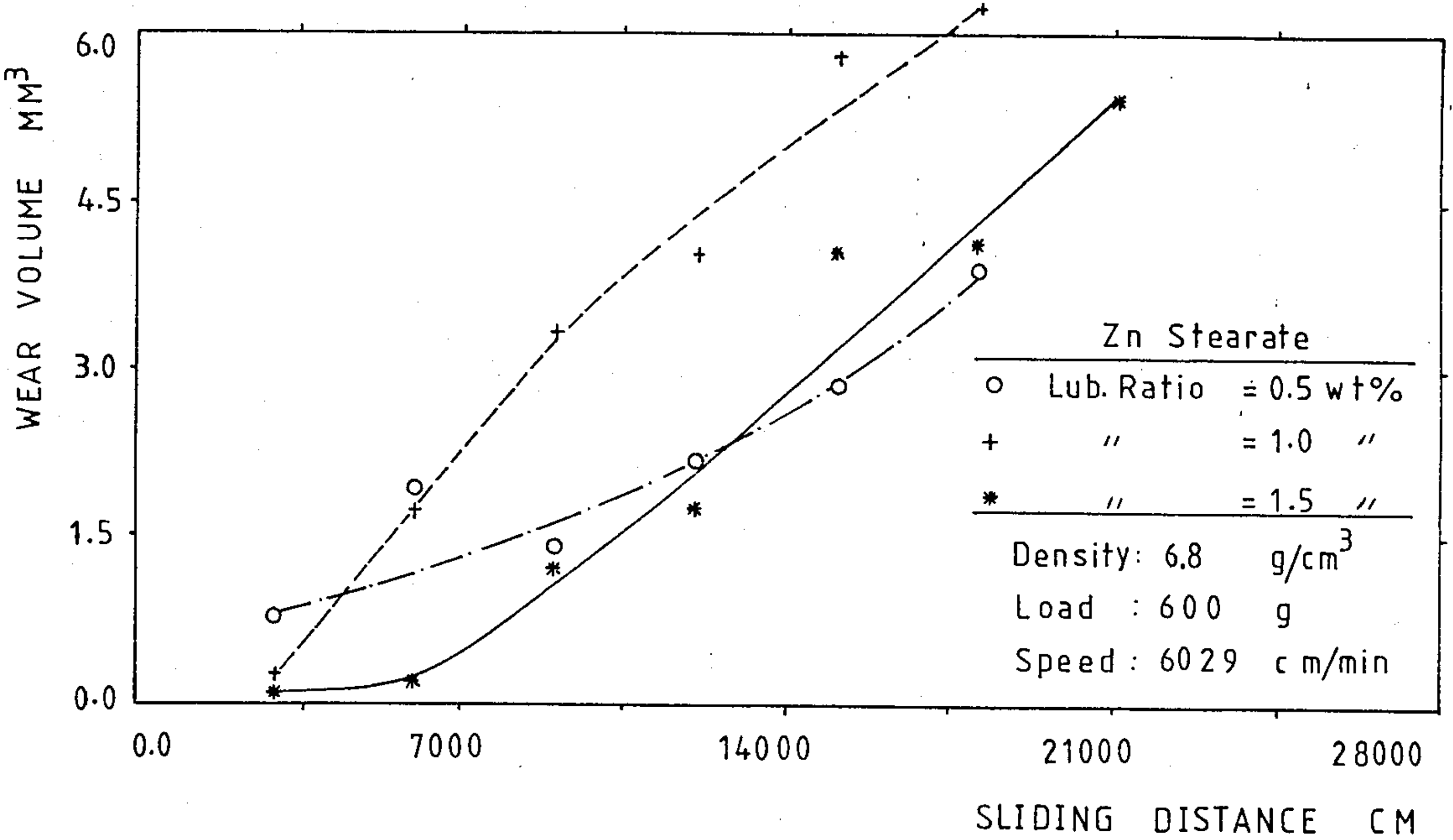

6.0
4.5
3.0
1.5
0.0
WEAR VOLUME MM3
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM
Zn Stearate
○ Lub. Ratio = 0.5 wt%
+ " = 1.0 "
* " = 1.5 "
Density: 6.8 g/cm3
Load : 600 g
Speed : 6029 cm/min

Fig. 81

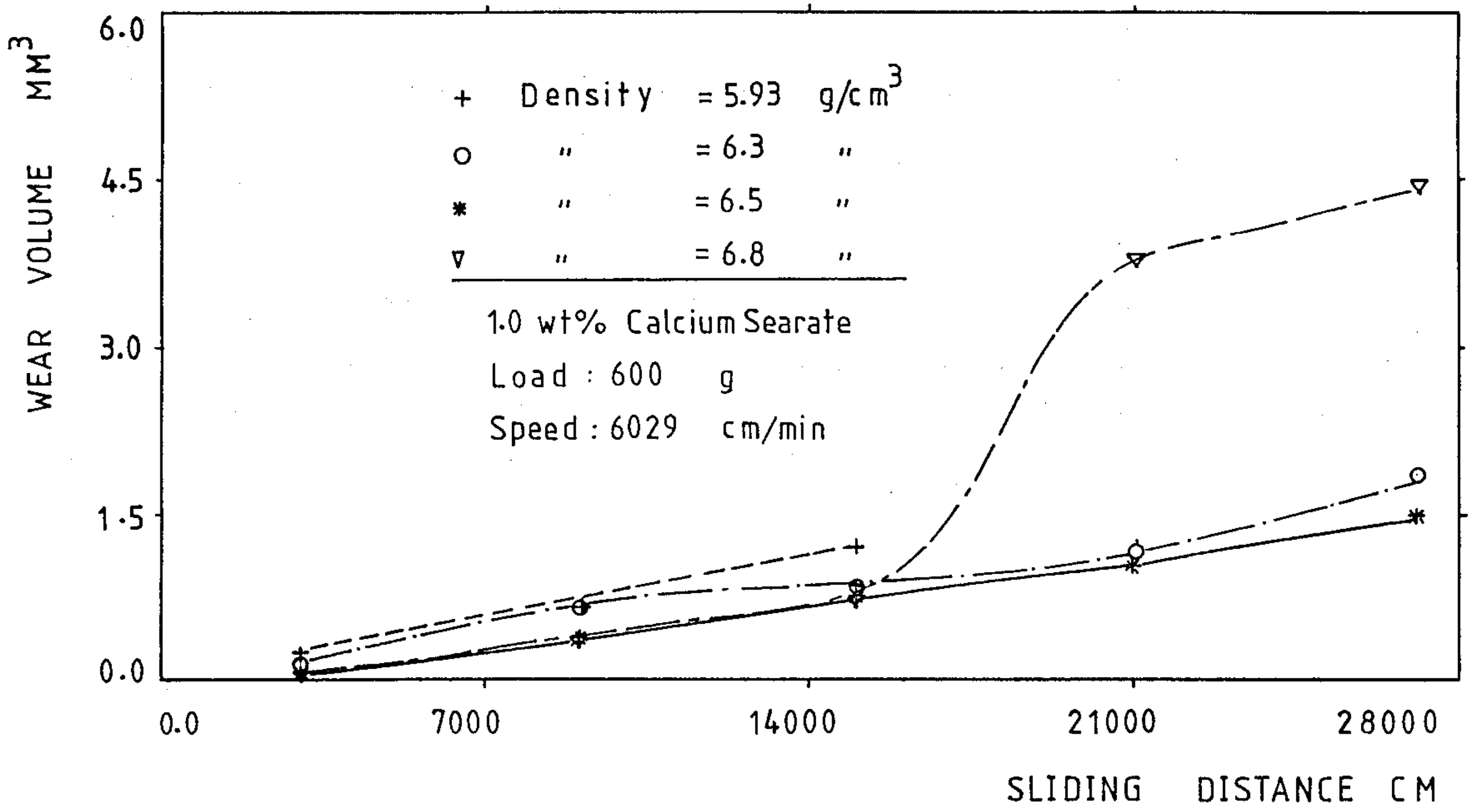

+ Density = 5.93 g/cm³
○ " = 6.3 "
✱ " = 6.5 "
▽ " = 6.8 "
1.0 wt% Calcium Searate
Load : 600 g
Speed : 6029 cm/min
WEAR VOLUME MM³
6.0
4.5
3.0
1.5
0.0
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM

Fig. 82

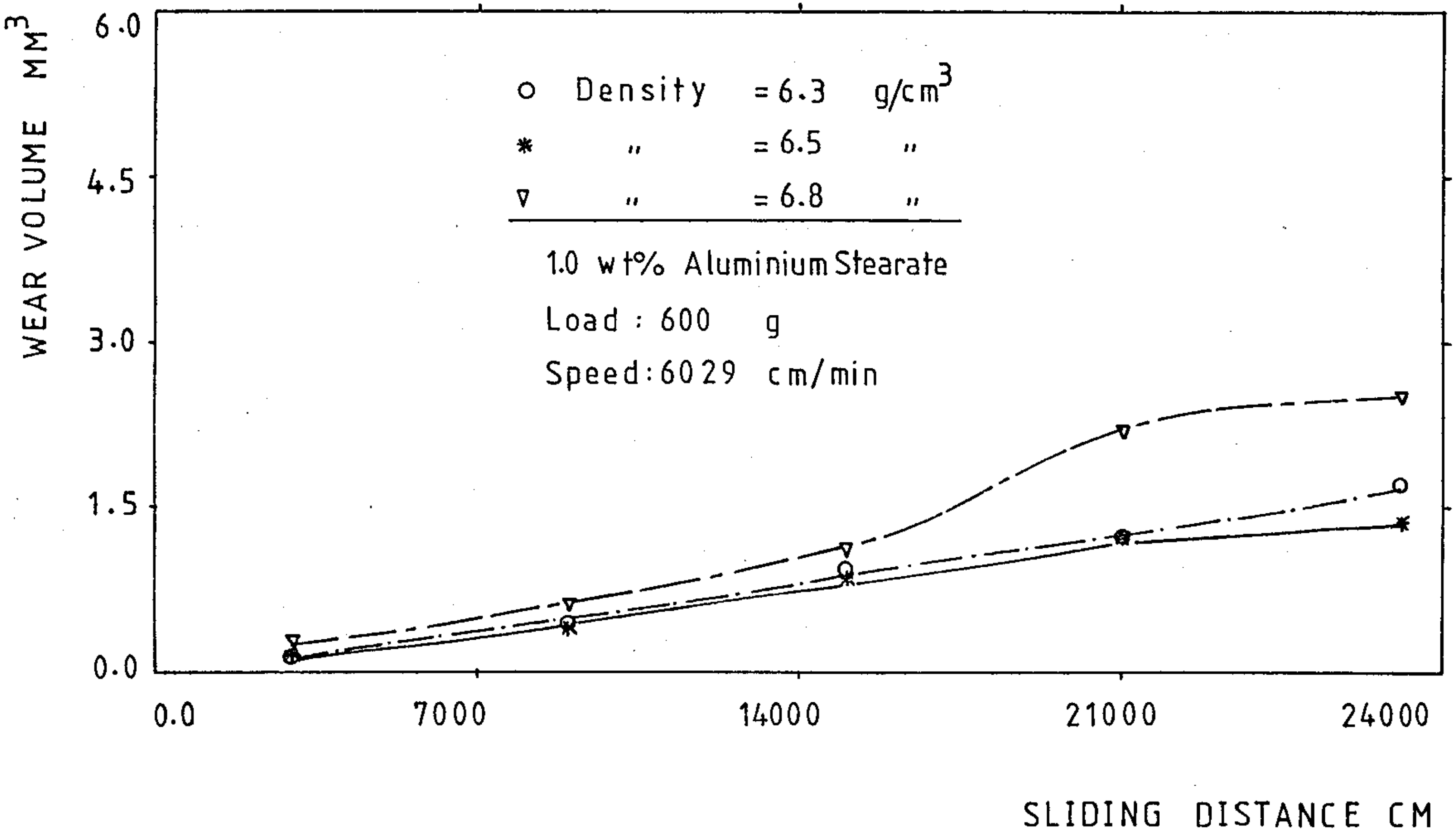

WEAR VOLUME MM$^3$
6.0
4.5
3.0
1.5
0.0
0.0
7000
14000
21000
24000
SLIDING DISTANCE CM
○ Density = 6.3 g/cm$^3$
✱ " = 6.5 "
▽ " = 6.8 "
1.0 wt% Aluminium Stearate
Load : 600 g
Speed: 6029 cm/min

Fig. 83

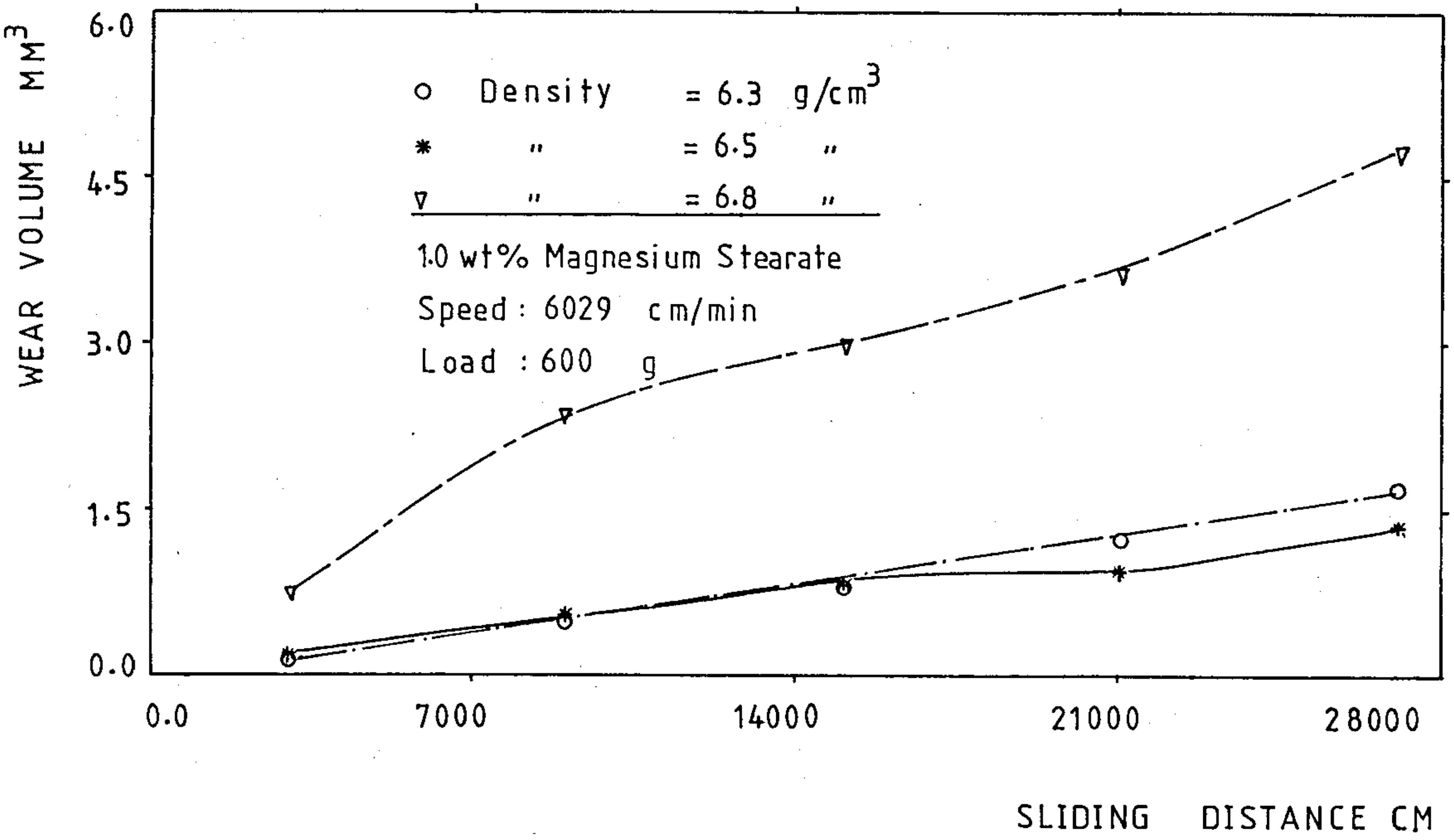
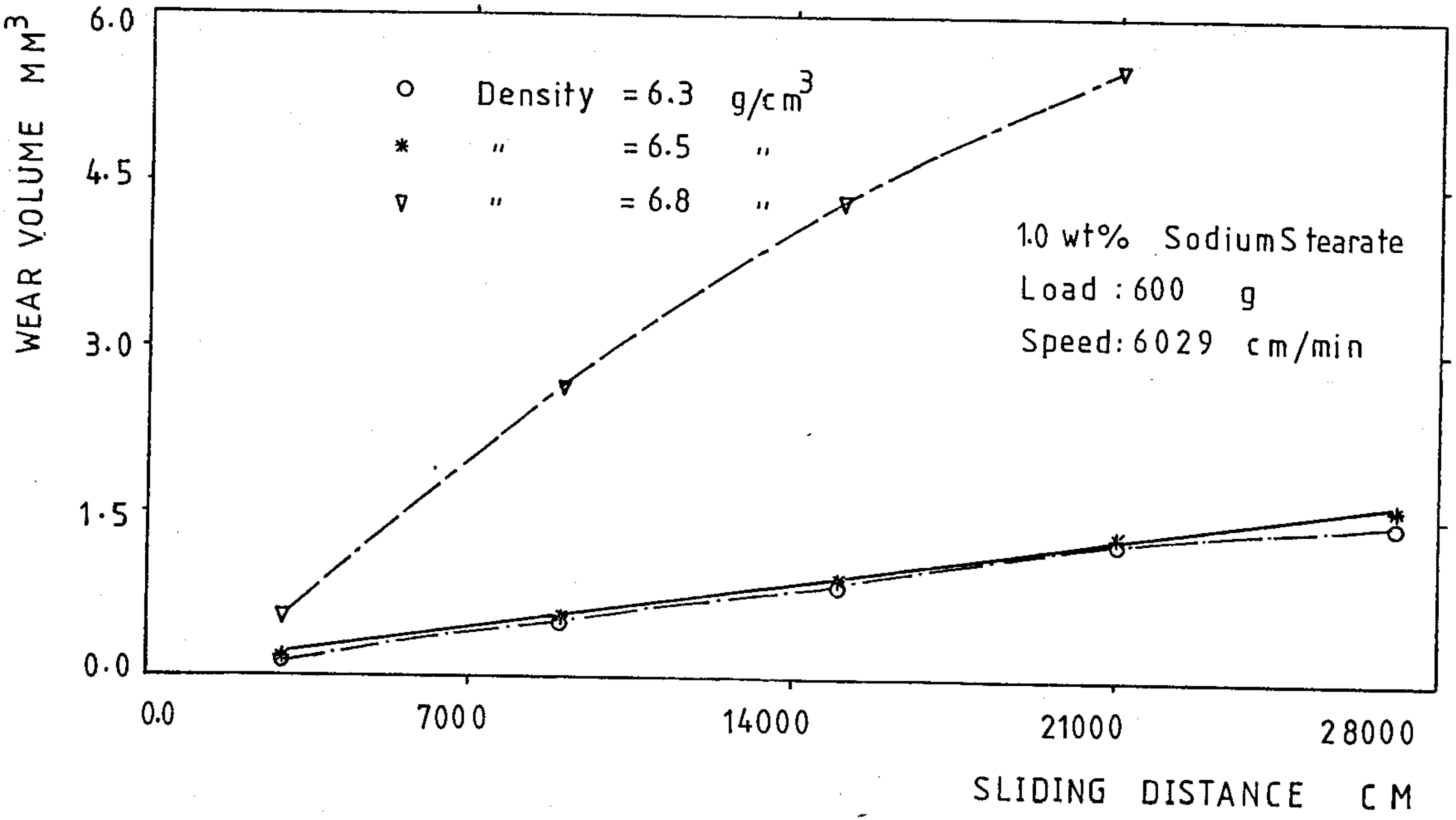
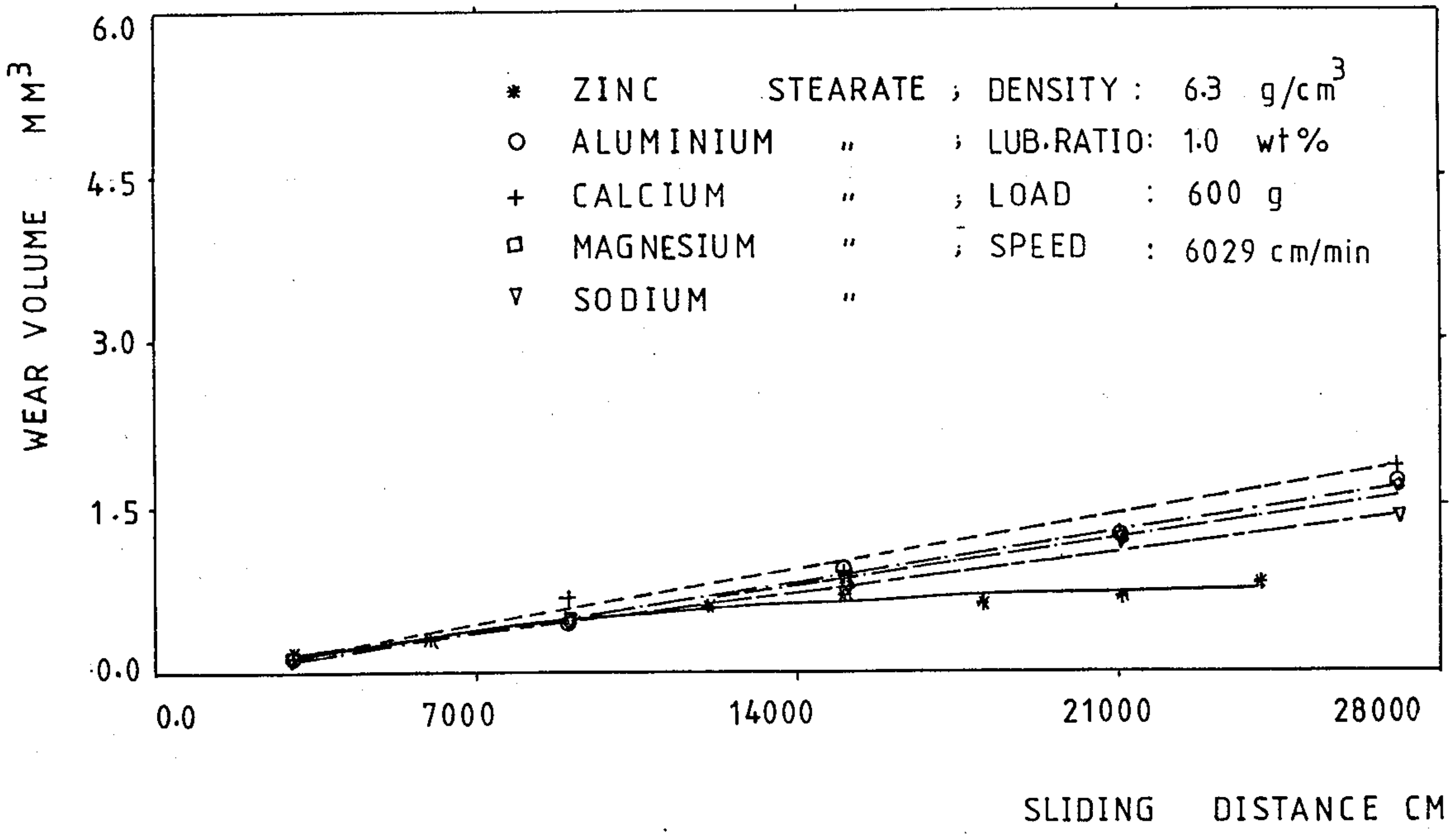

WEAR VOLUME MM$^3$
6.0
4.5
3.0
1.5
0.0
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM
○ Density = 6.3 g/cm$^3$
* " = 6.5 "
▽ " = 6.8 "
1.0 wt% Magnesium Stearate
Speed : 6029 cm/min
Load : 600 g

Fig. 84



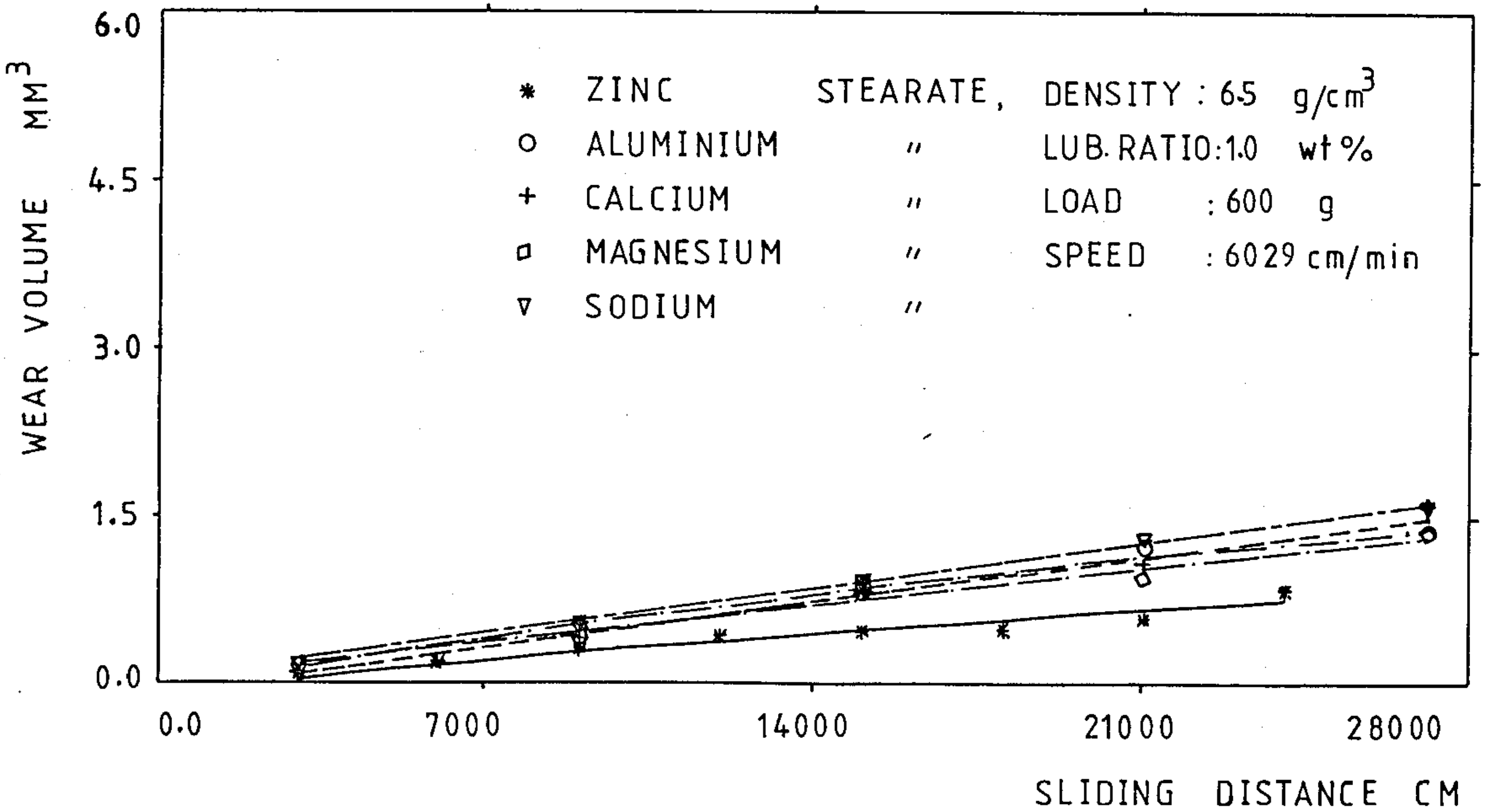
6.0
4.5
3.0
1.5
0.0
WEAR VOLUME MM$^3$
○ Density = 6.3 g/cm$^3$
* " = 6.5 "
∇ " = 6.8 "
1.0 wt% Sodium Stearate
Load : 600 g
Speed: 6029 cm/min
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM

Fig. 85



WEAR VOLUME MM$^3$
6.0
4.5
3.0
1.5
0.0
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM
* ZINC STEARATE ; DENSITY : 6.3 g/cm$^3$
○ ALUMINIUM " ; LUB.RATIO: 1.0 wt%
+ CALCIUM " ; LOAD : 600 g
□ MAGNESIUM " ; SPEED : 6029 cm/min
▽ SODIUM "

Fig. 86



WEAR VOLUME MM$^3$
6.0
4.5
3.0
1.5
0.0
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM
* ZINC STEARATE,
○ ALUMINIUM "
+ CALCIUM "
□ MAGNESIUM "
▽ SODIUM "
DENSITY : 6.5 g/cm$^3$
LUB. RATIO: 1.0 wt %
LOAD : 600 g
SPEED : 6029 cm/min

Fig. 87

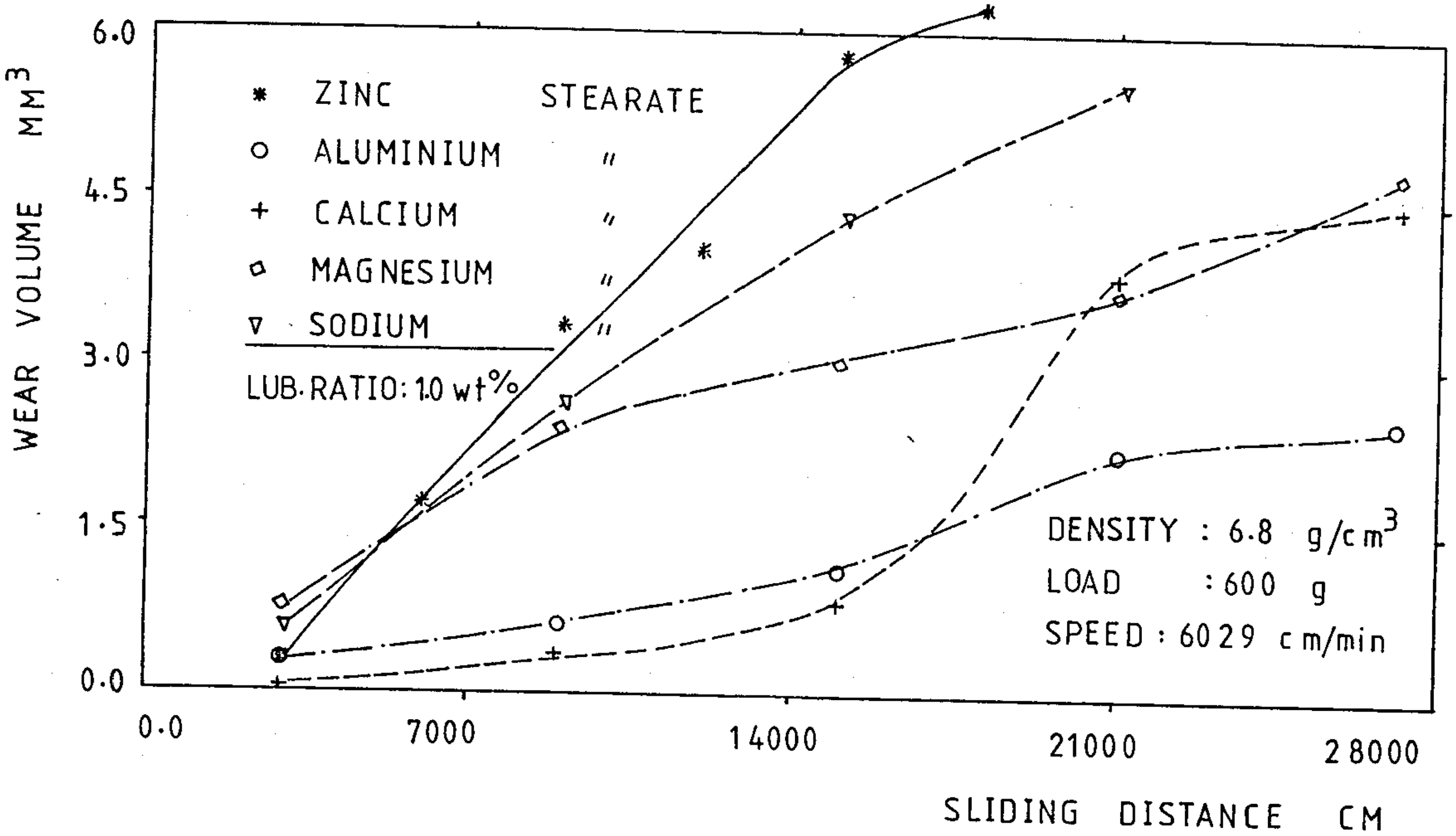
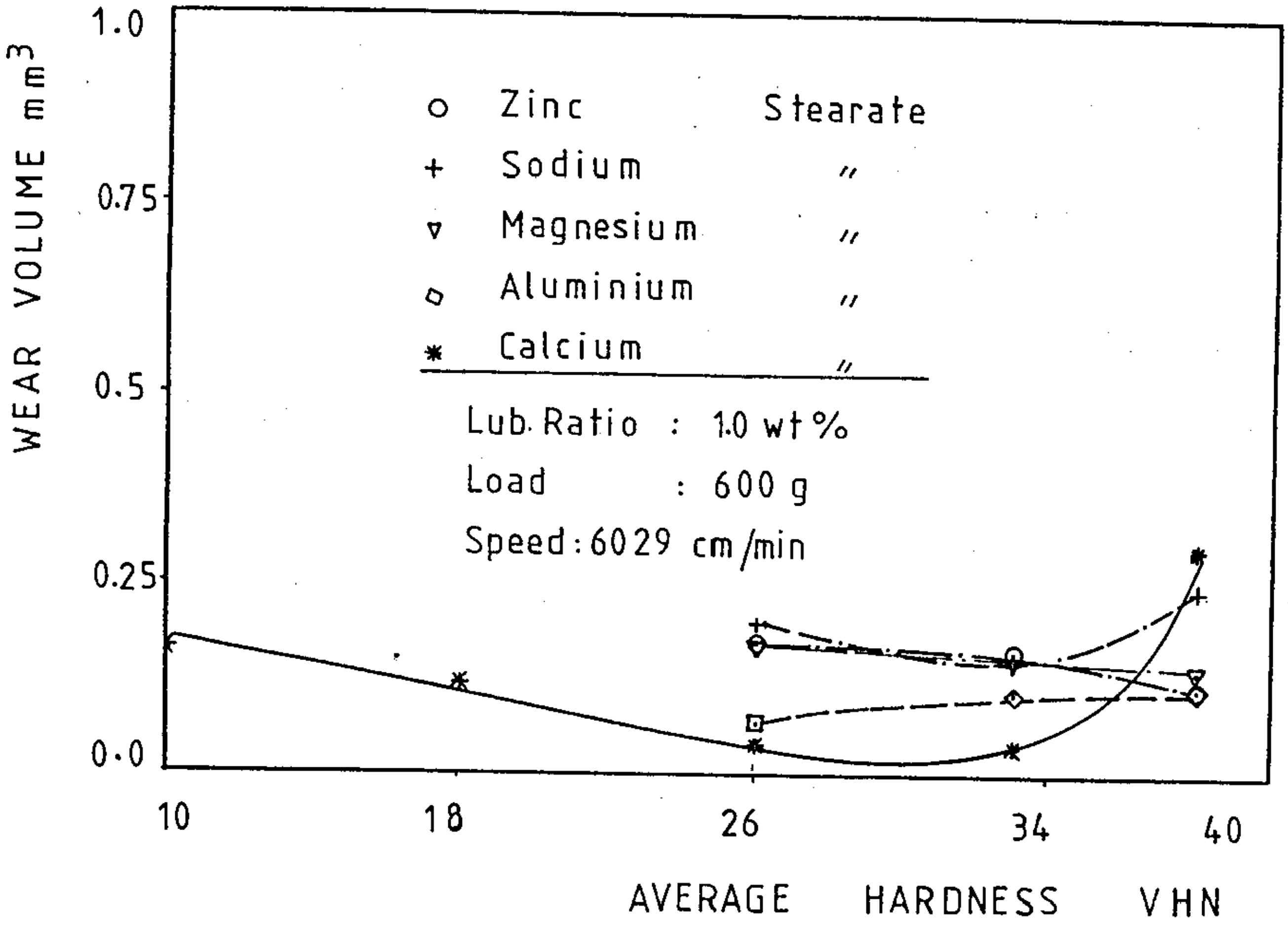

WEAR VOLUME MM$^3$
6.0
4.5
3.0
1.5
0.0
0.0
7000
14000
21000
28000
SLIDING DISTANCE CM
* ZINC STEARATE
○ ALUMINIUM "
+ CALCIUM "
◇ MAGNESIUM "
▽ SODIUM "
LUB. RATIO: 1.0 wt%
DENSITY : 6.8 g/cm$^3$
LOAD : 600 g
SPEED : 6029 cm/min

Fig. 88

Fig. 89

S.E.M Photographs for Wear Scars on Compacts from Distance Trials.
Density : 6.5 g/cm$^3$
Lubricant contents :
1.0 wt % Zinc.
Distance: 1) 60287 ; 2) 150718 ; 3) 241149 cm.
All Photogrphs at :
X 180.



WEAR VOLUME $mm^3$
1.0
0.75
0.5
0.25
0.0
10
18
26
34
40
AVERAGE HARDNESS VHN
○ Zinc Stearate
+ Sodium "
▽ Magnesium "
◇ Aluminium "
✱ Calcium "
Lub. Ratio : 1.0 wt %
Load : 600 g
Speed : 6029 cm/min

Fig. 90

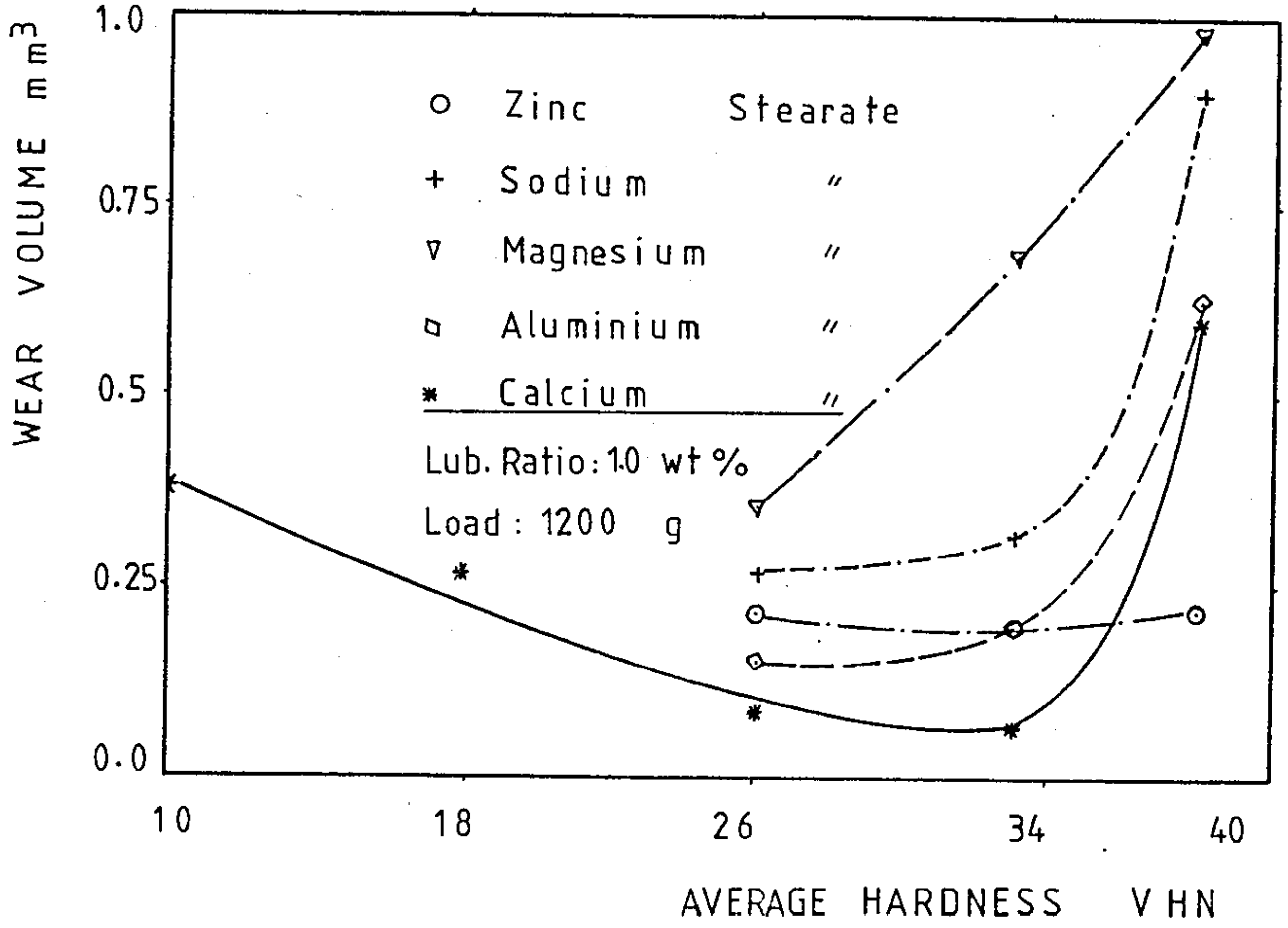

WEAR VOLUME mm³
1.0
0.75
0.5
0.25
0.0
○ Zinc Stearate
+ Sodium "
▽ Magnesium "
◇ Aluminium "
✱ Calcium "
Lub. Ratio: 1.0 wt %
Load : 1200 g
10
18
26
34
40
AVERAGE HARDNESS VHN

Fig. 91

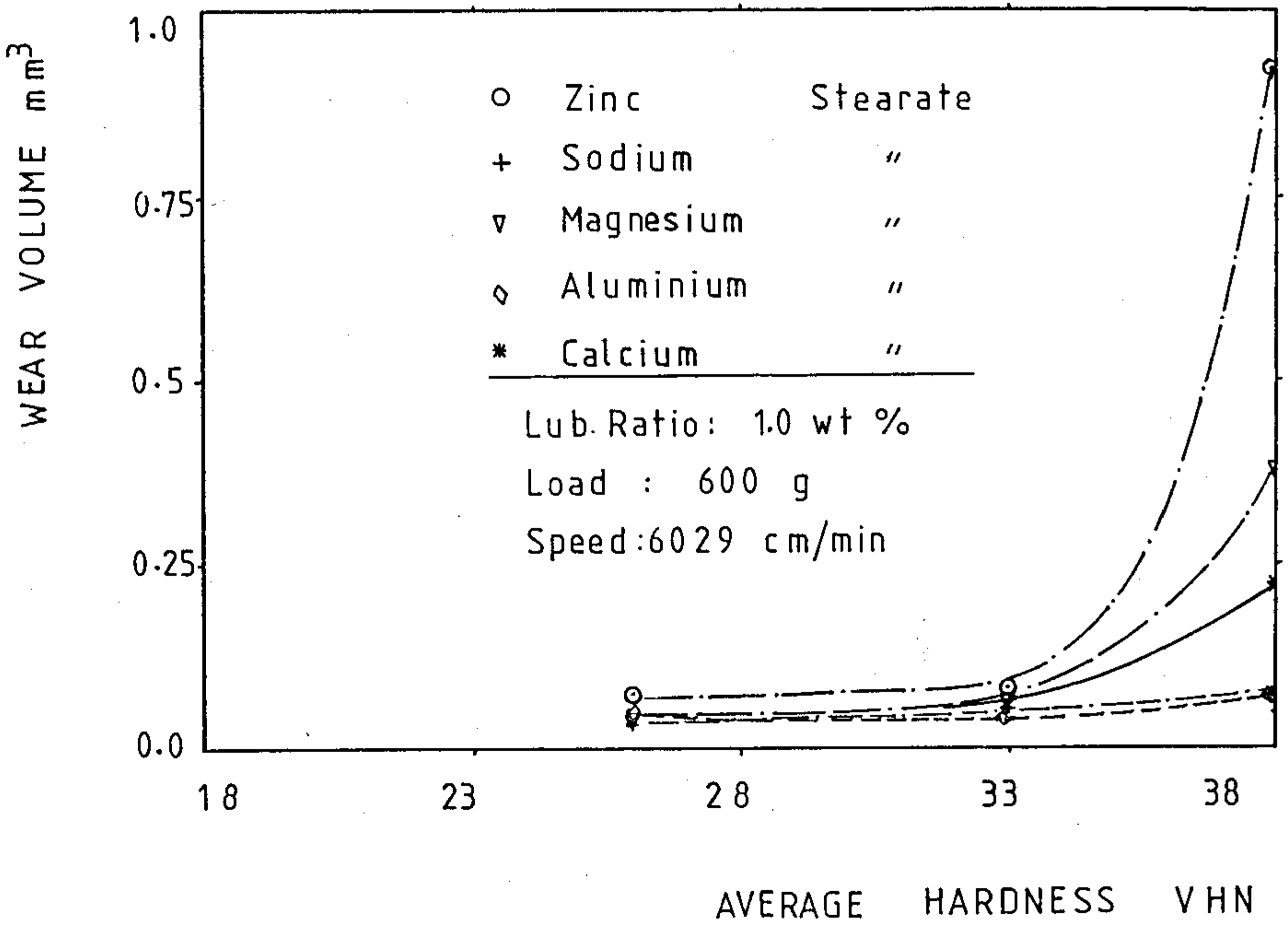

WEAR VOLUME mm³
1.0
0.75
0.5
0.25
0.0
18
23
28
33
38
AVERAGE HARDNESS VHN
○ Zinc Stearate
+ Sodium "
▽ Magnesium "
◇ Aluminium "
* Calcium "
Lub. Ratio: 1.0 wt %
Load : 600 g
Speed: 6029 cm/min

Fig. 92

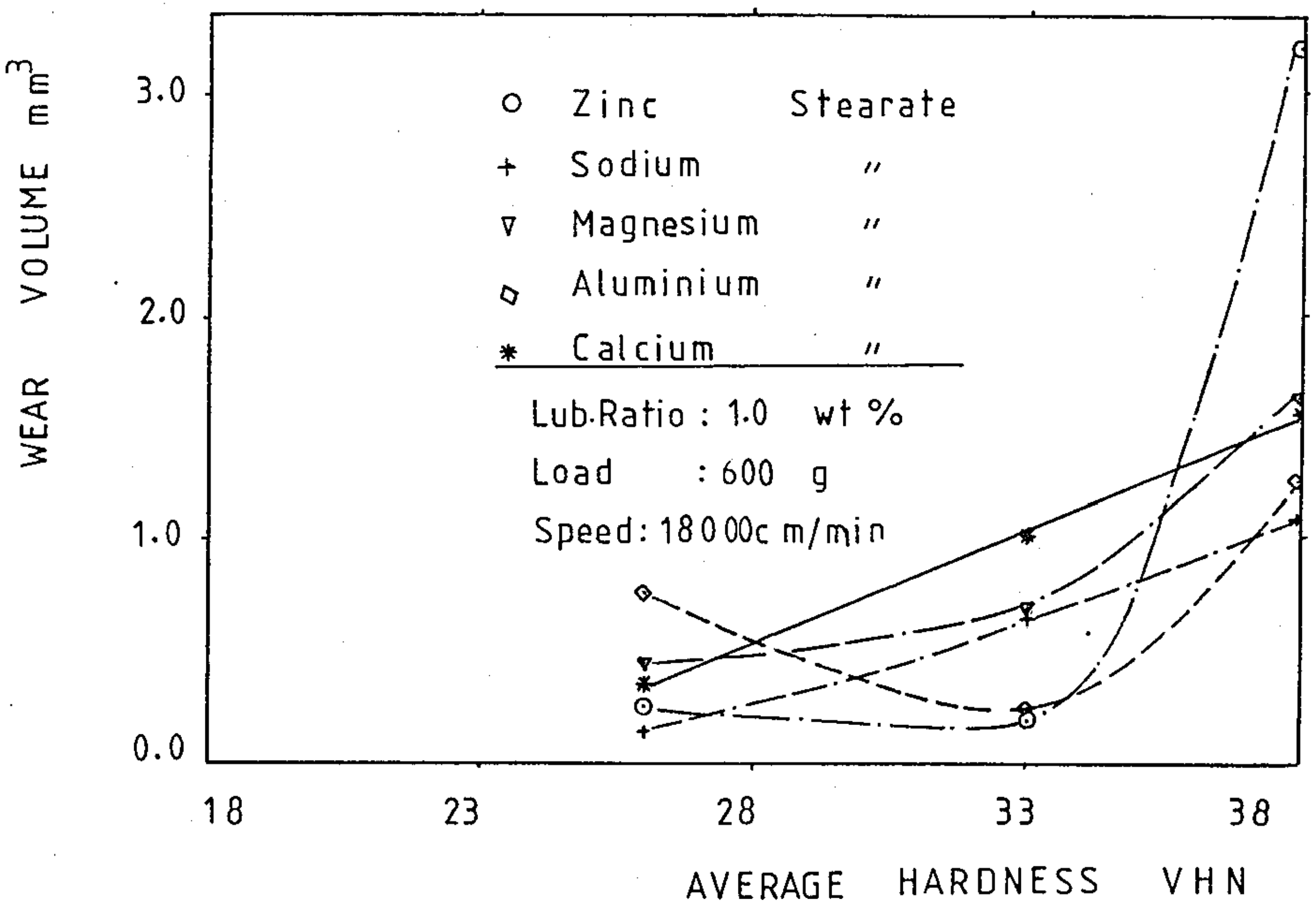

○ Zinc Stearate
+ Sodium "
▽ Magnesium "
◇ Aluminium "
✱ Calcium "
Lub.Ratio : 1.0 wt %
Load : 600 g
Speed: 18000c m/min
WEAR VOLUME $mm^3$
3.0
2.0
1.0
0.0
18
23
28
33
38
AVERAGE HARDNESS VHN

Fig. 93

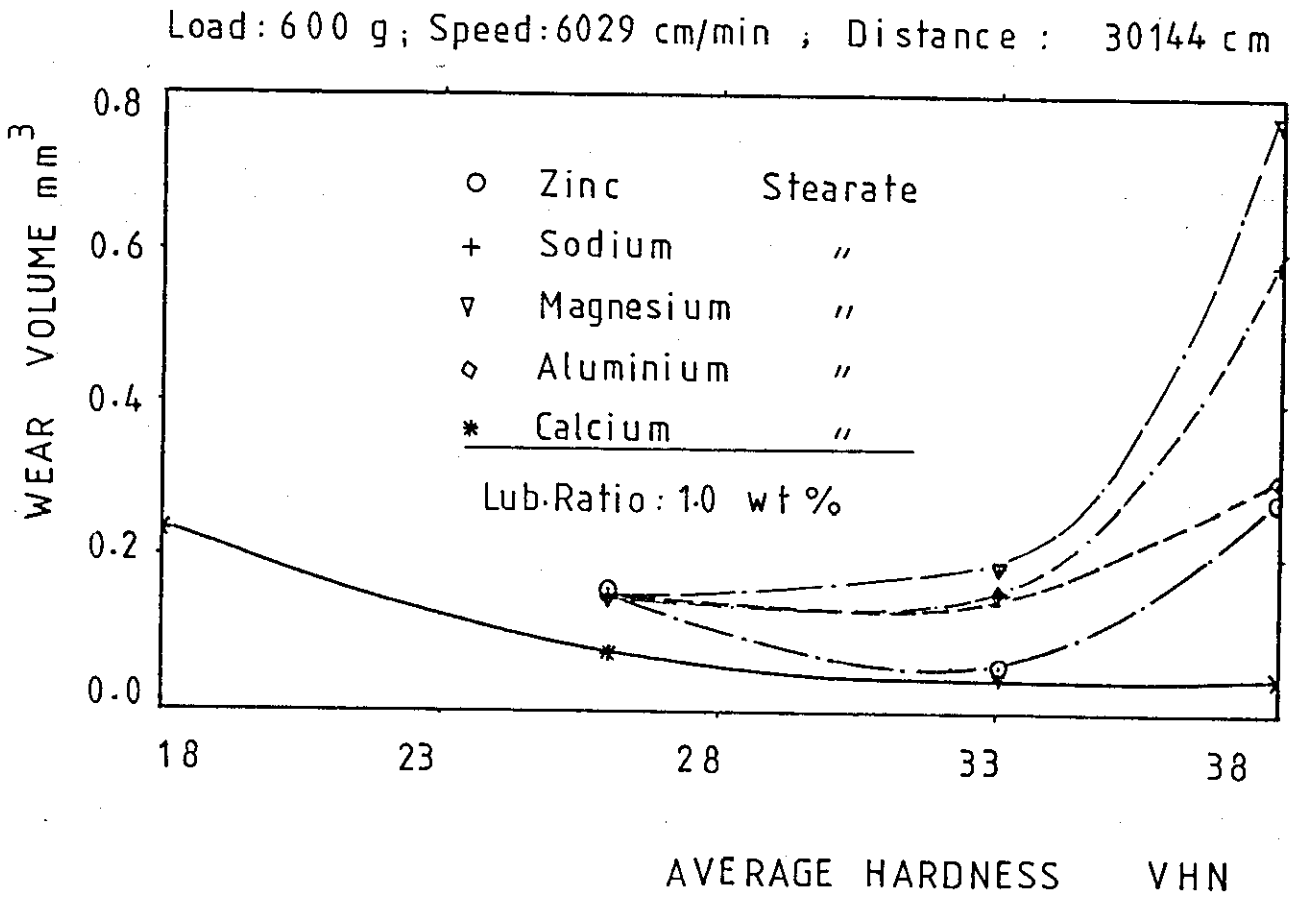
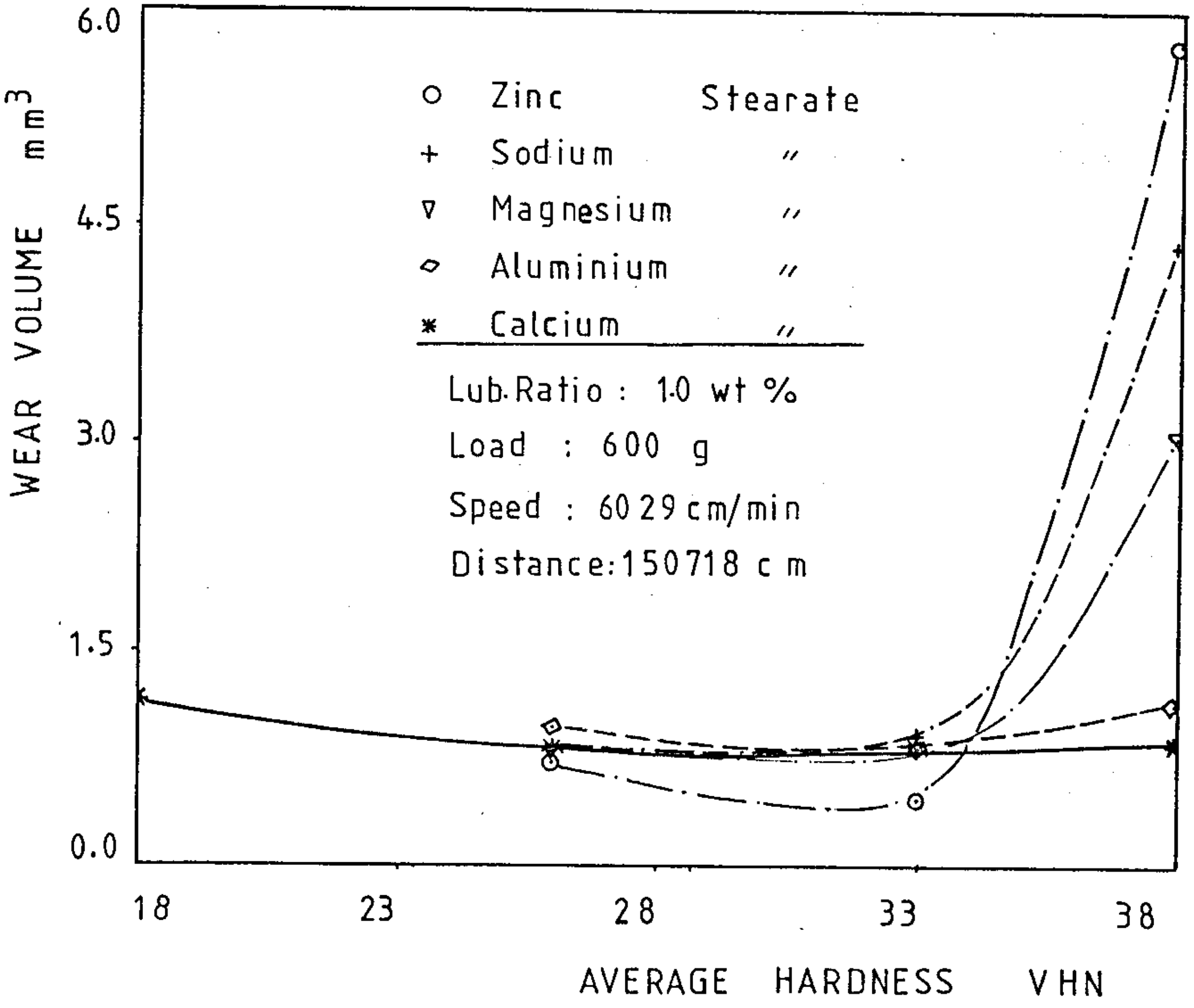
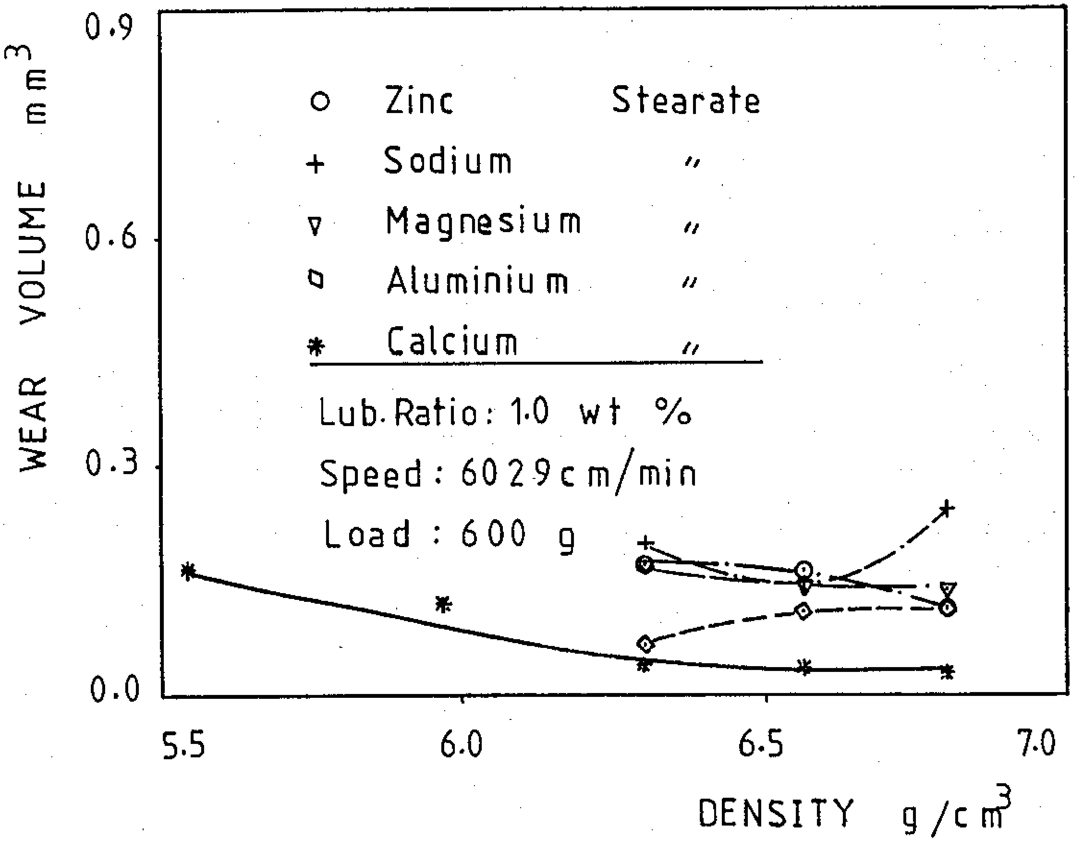

Load: 600 g; Speed: 6029 cm/min ; Distance : 30144 cm
WEAR VOLUME $mm^3$
0.8
0.6
0.4
0.2
0.0
○ Zinc Stearate
+ Sodium 〃
▽ Magnesium 〃
◇ Aluminium 〃
✱ Calcium 〃
Lub.Ratio : 1.0 wt %
18
23
28
33
38
AVERAGE HARDNESS VHN

Fig. 94



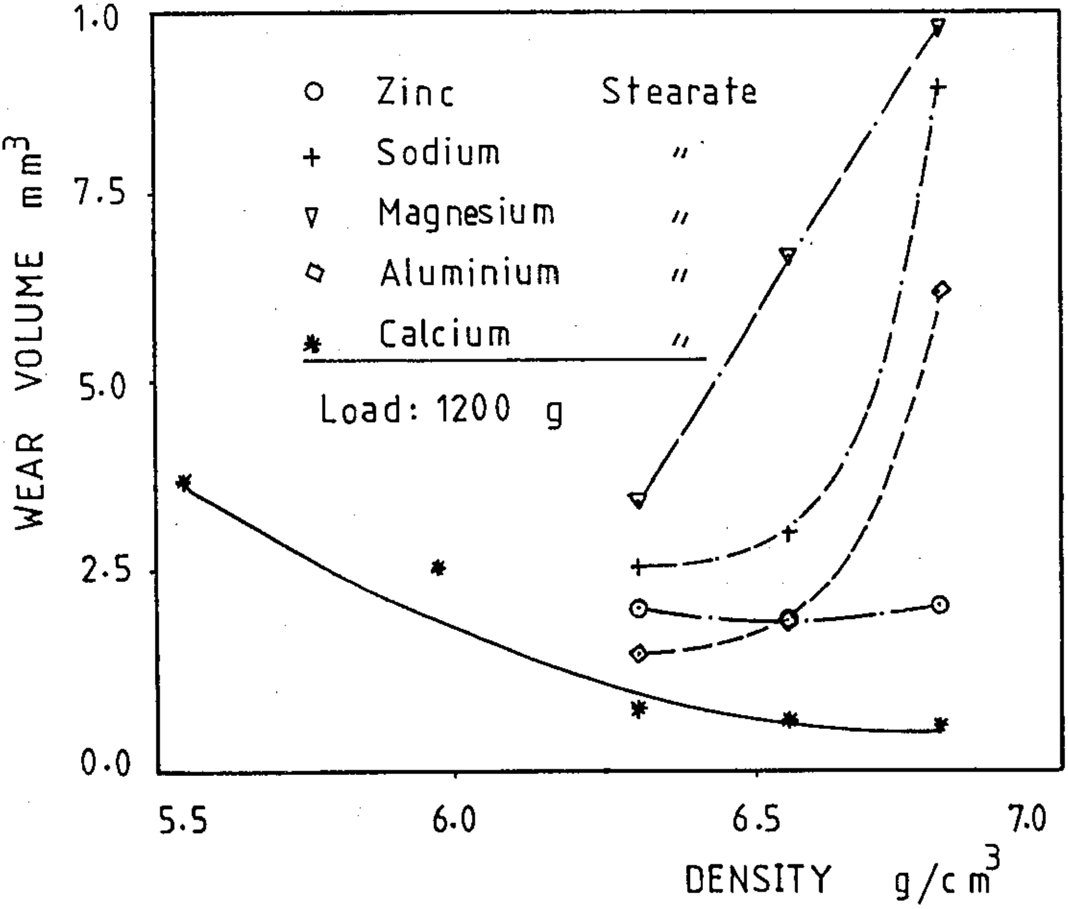
6.0
4.5
3.0
1.5
0.0
WEAR VOLUME mm$^3$
○ Zinc Stearate
+ Sodium "
▽ Magnesium "
◇ Aluminium "
✱ Calcium "
Lub.Ratio : 1.0 wt %
Load : 600 g
Speed : 6029 cm/min
Distance:150718 c m
18
23
28
33
38
AVERAGE HARDNESS VHN

Fig. 95



WEAR VOLUME mm$^3$
0.9
0.6
0.3
0.0
○ Zinc Stearate
+ Sodium "
▽ Magnesium "
◇ Aluminium "
✱ Calcium "
Lub. Ratio: 1.0 wt %
Speed: 6029 cm/min
Load: 600 g
5.5
6.0
6.5
7.0
DENSITY g/cm$^3$

Fig. 96



WEAR VOLUME mm$^3$
1.0
7.5
5.0
2.5
0.0
○ Zinc Stearate
+ Sodium "
▽ Magnesium "
◇ Aluminium "
✱ Calcium "
Load: 1200 g
5.5
6.0
6.5
7.0
DENSITY g/cm$^3$

Fig. 97

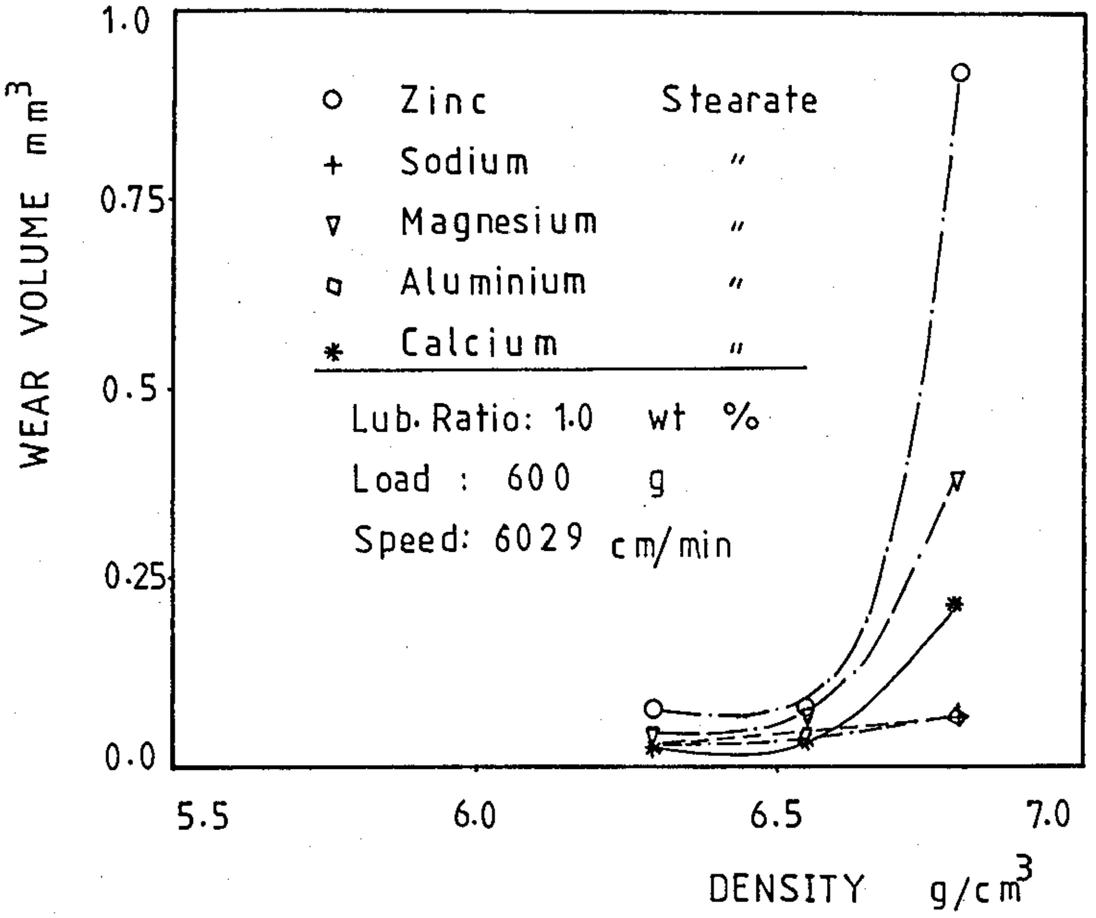

WEAR VOLUME mm$^3$
1.0
0.75
0.5
0.25
0.0
5.5
6.0
6.5
7.0
DENSITY g/cm$^3$
○ Zinc Stearate
+ Sodium "
▽ Magnesium "
◇ Aluminium "
✱ Calcium "
Lub. Ratio: 1.0 wt %
Load : 600 g
Speed: 6029 cm/min

Fig. 98

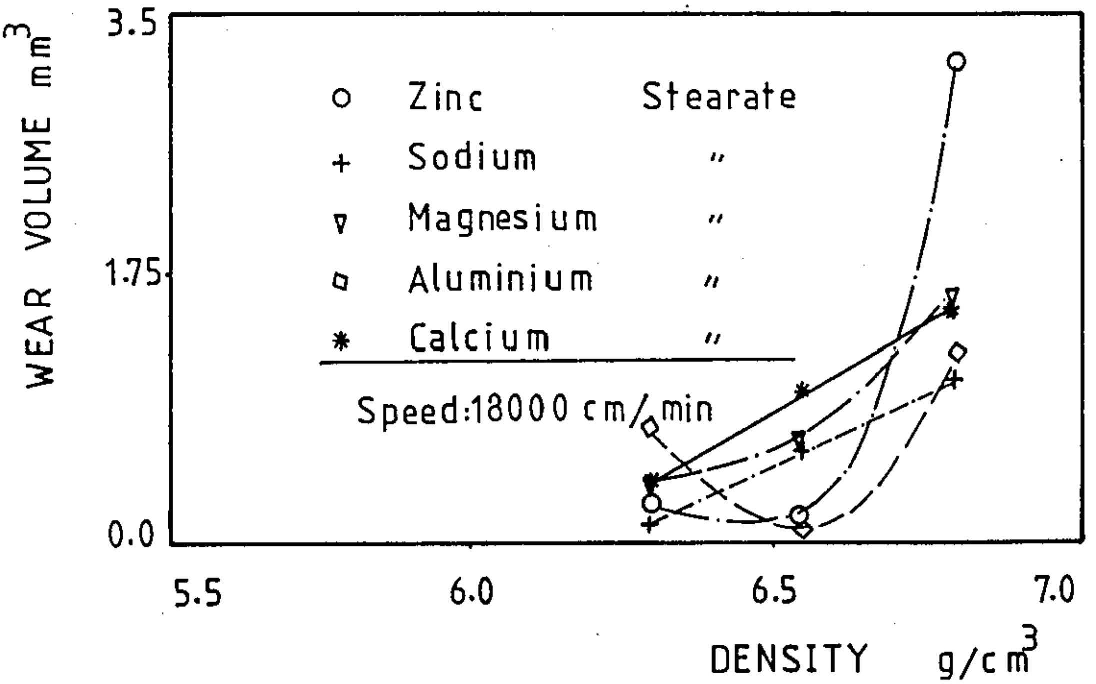

WEAR VOLUME mm$^3$
3.5
1.75
0.0
5.5
6.0
6.5
7.0
DENSITY g/cm$^3$
○ Zinc Stearate
+ Sodium "
▽ Magnesium "
◇ Aluminium "
✱ Calcium "
Speed:18000 cm/min

Fig.99

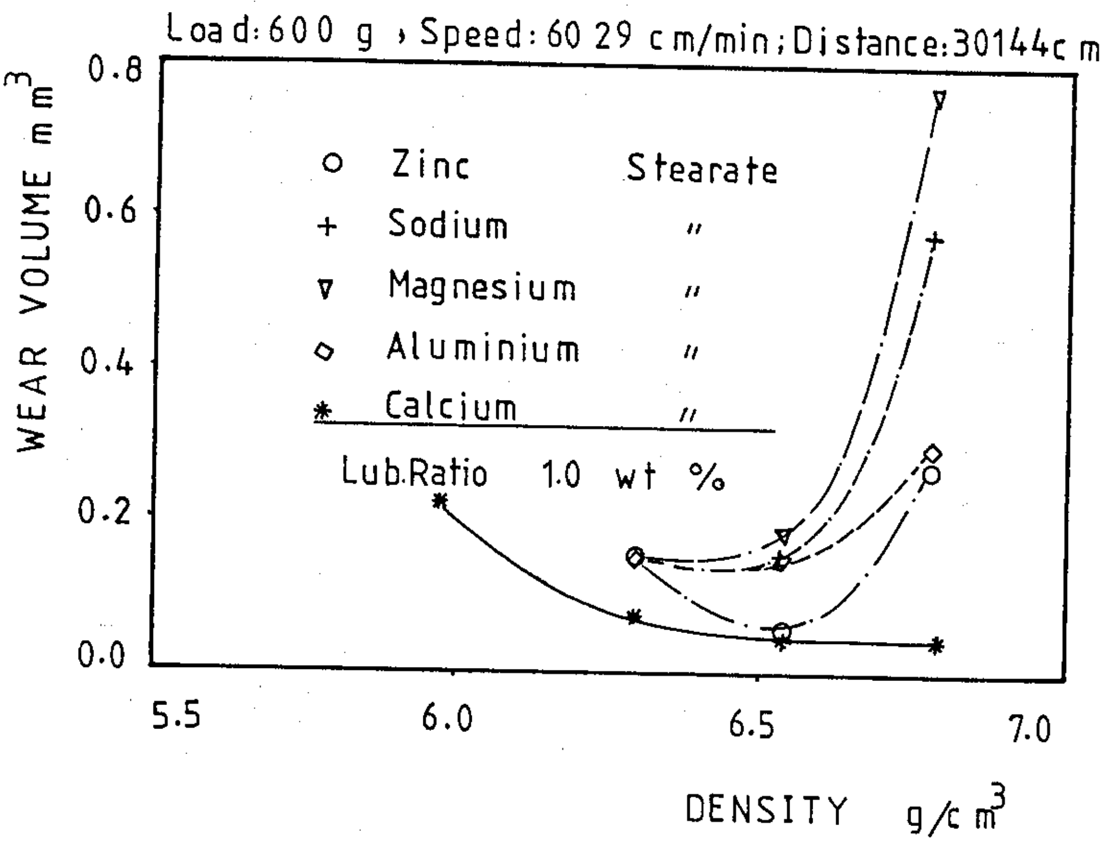


Fig. 100

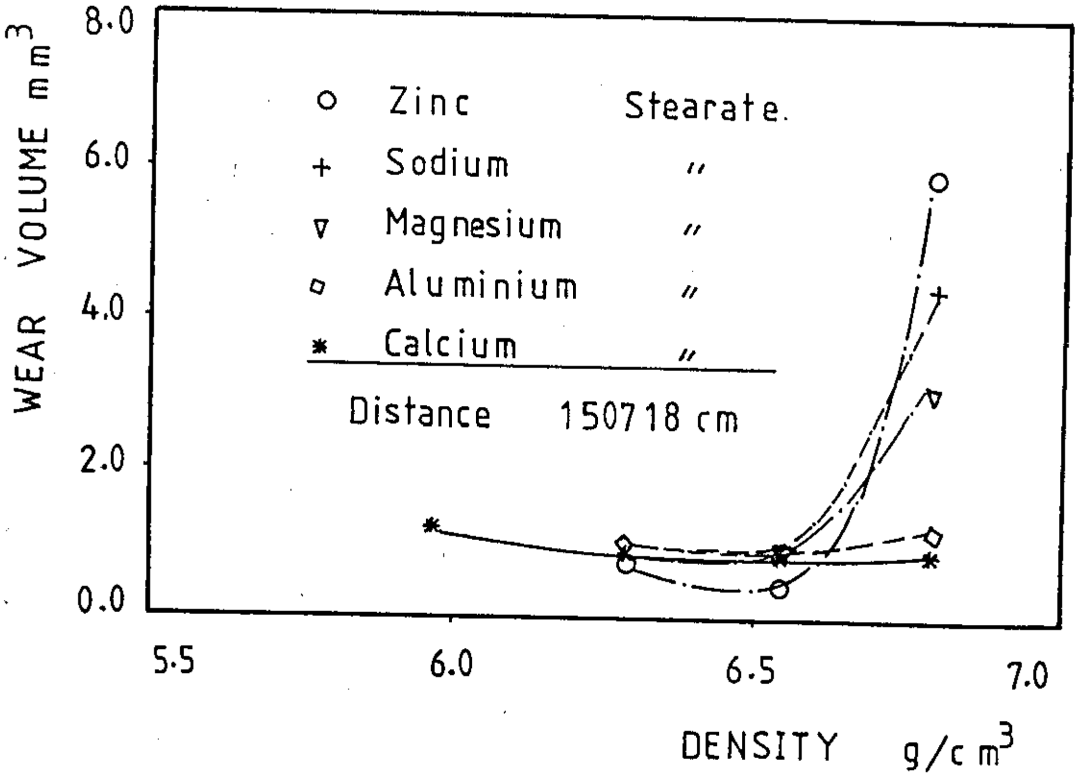


Fig.101

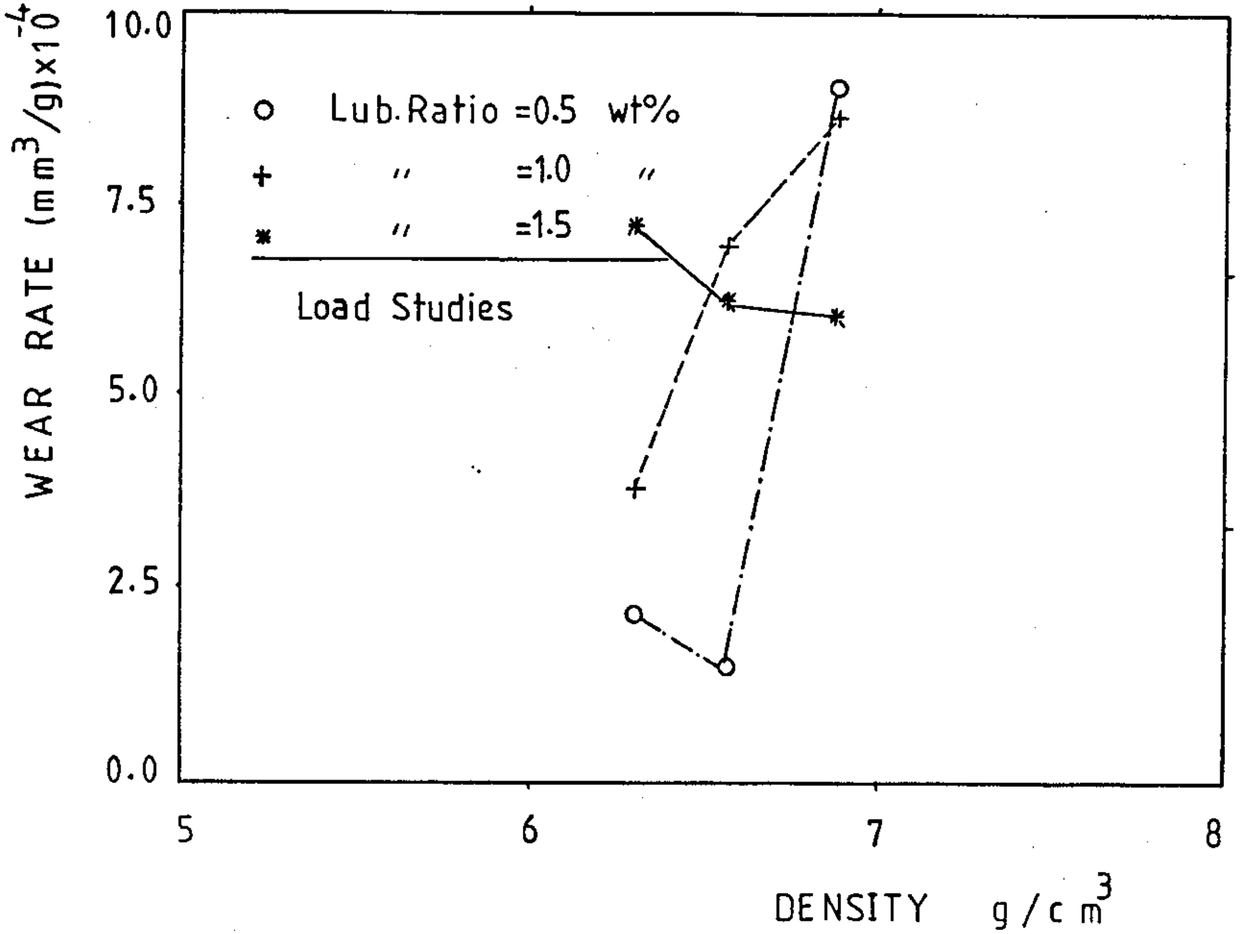

WEAR RATE $(mm^3/g)\times10^{-4}$
10.0
7.5
5.0
2.5
0.0
5
6
7
8
DENSITY $g/cm^3$
○ Lub.Ratio =0.5 wt%
+ " =1.0 "
* " =1.5 "
Load Studies

Fig.102

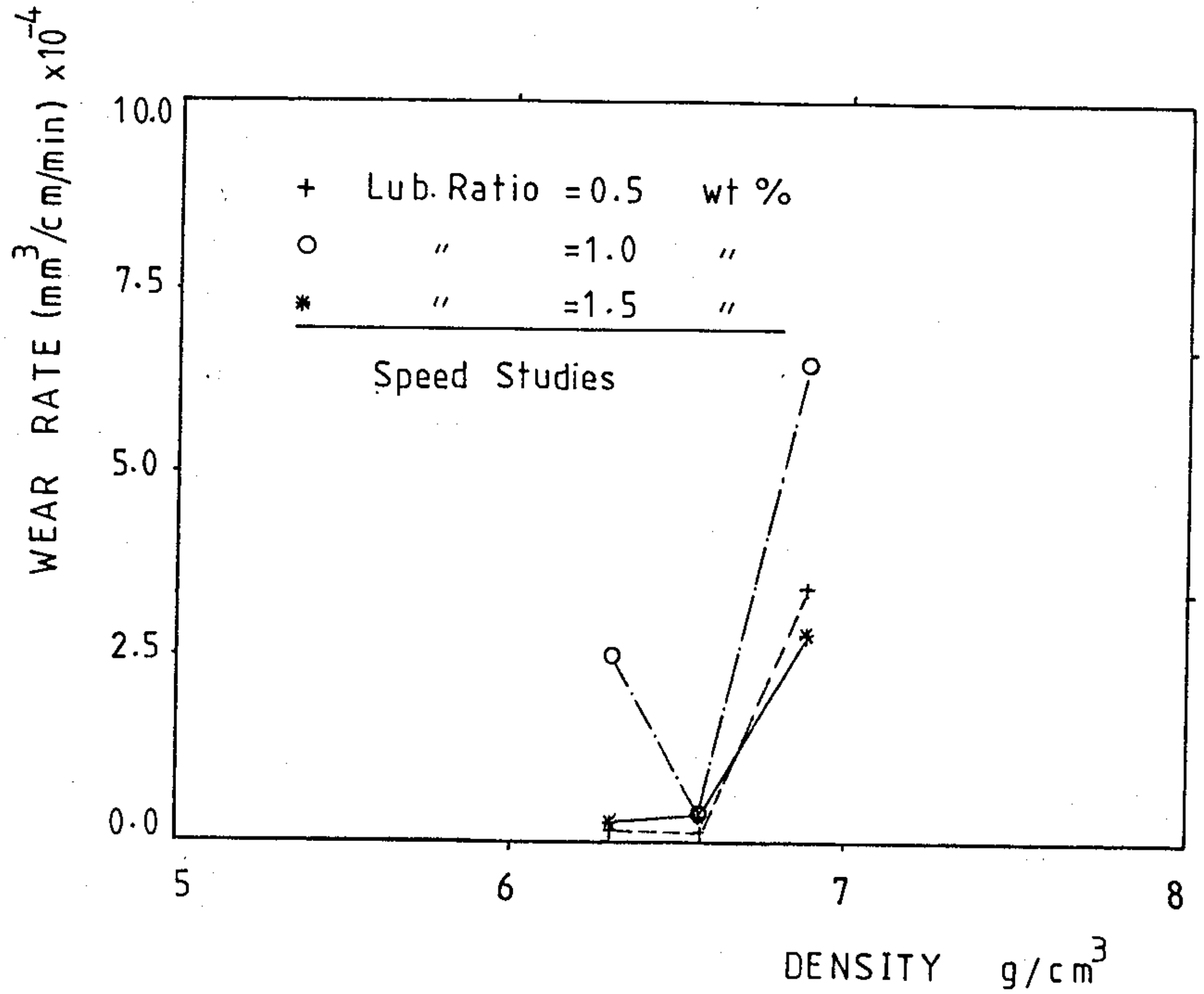

WEAR RATE (mm$^3$/cm/min) x10$^{-4}$
10.0
7.5
5.0
2.5
0.0
5
6
7
8
DENSITY g/cm$^3$
+ Lub. Ratio = 0.5 wt %
○ " = 1.0 "
✱ " = 1.5 "
Speed Studies

Fig.103

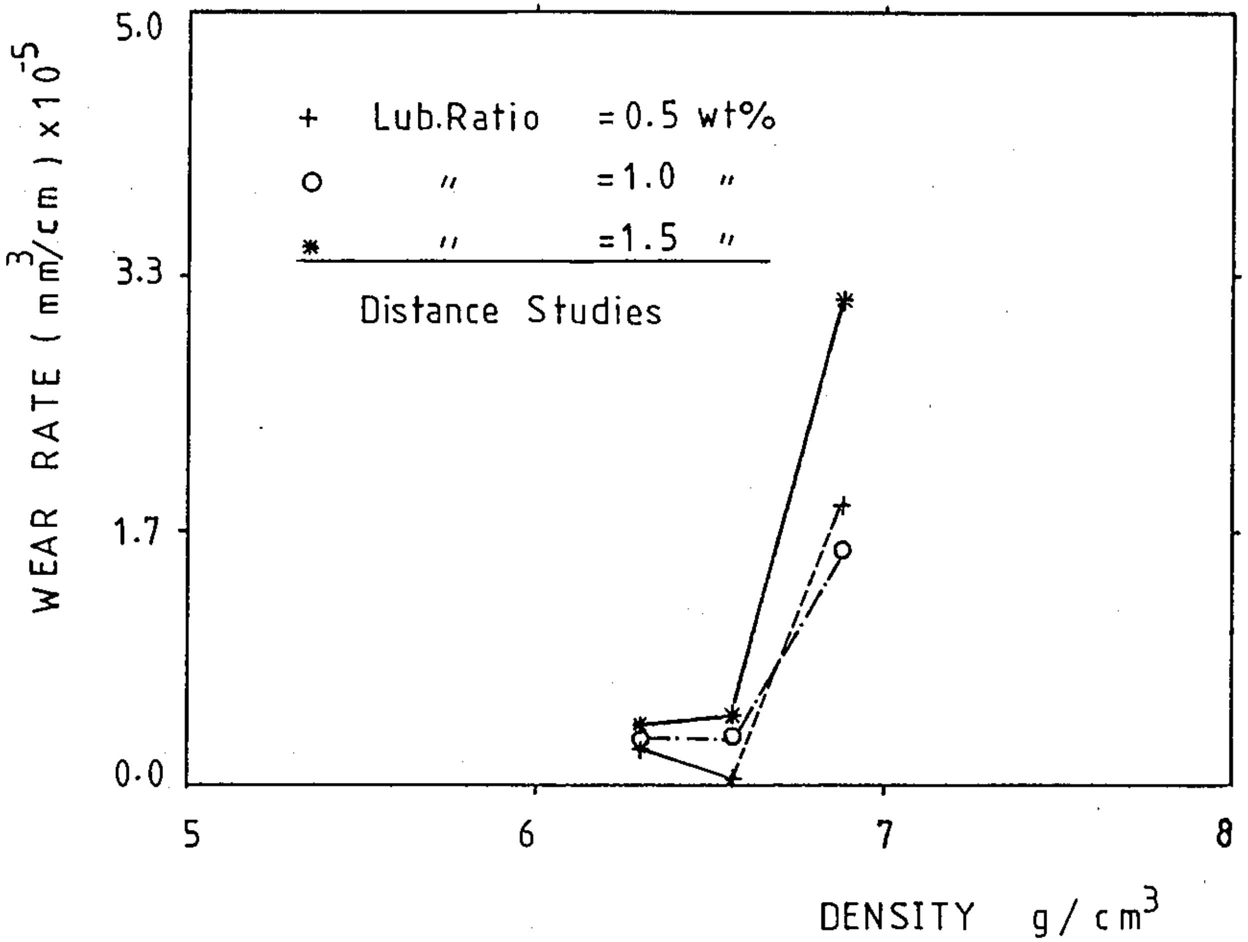

WEAR RATE ( $mm^3/cm$ ) x $10^{-5}$
5.0
3.3
1.7
0.0
5
6
7
8
DENSITY g / $cm^3$
+ Lub.Ratio = 0.5 wt%
○ 〃 = 1.0 〃
* 〃 = 1.5 〃
Distance Studies

Fig. 104

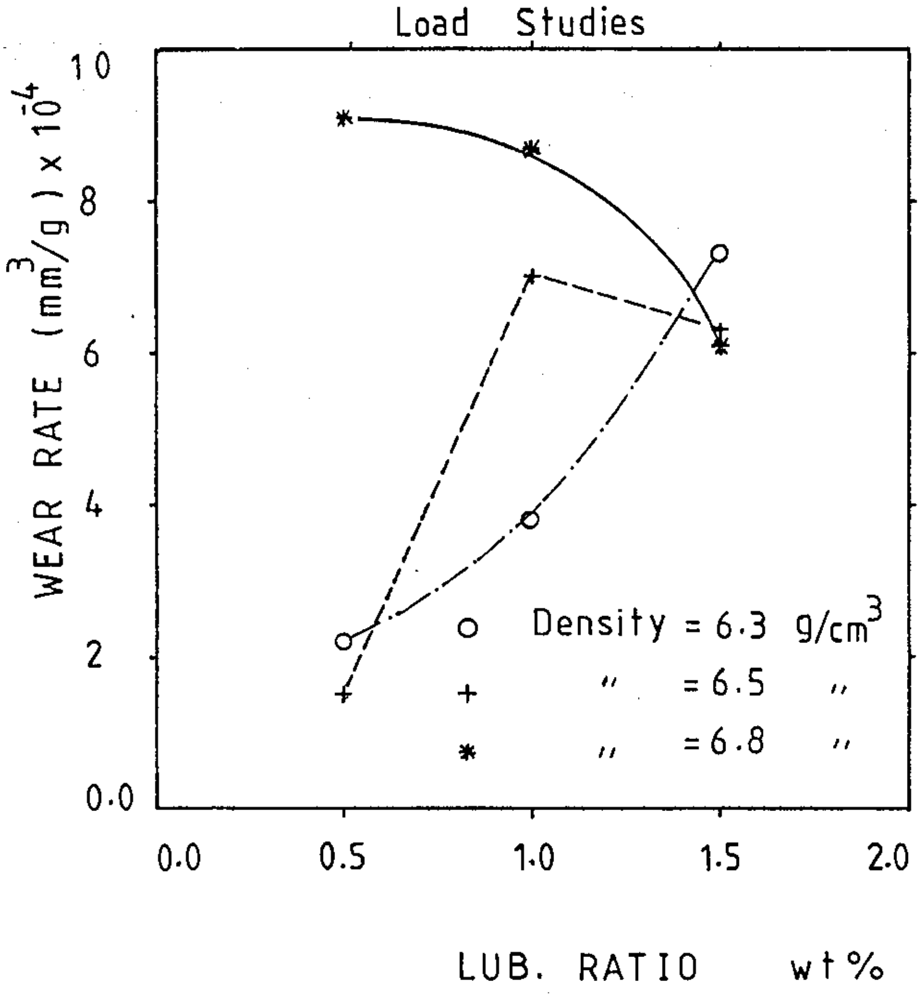

Load Studies
WEAR RATE (mm$^3$/g) x 10$^{-4}$
1 0
8
6
4
2
0.0
0.0
0.5
1.0
1.5
2.0
LUB. RATIO wt%
○ Density = 6.3 g/cm$^3$
+ " = 6.5 "
* " = 6.8 "

Fig. 105

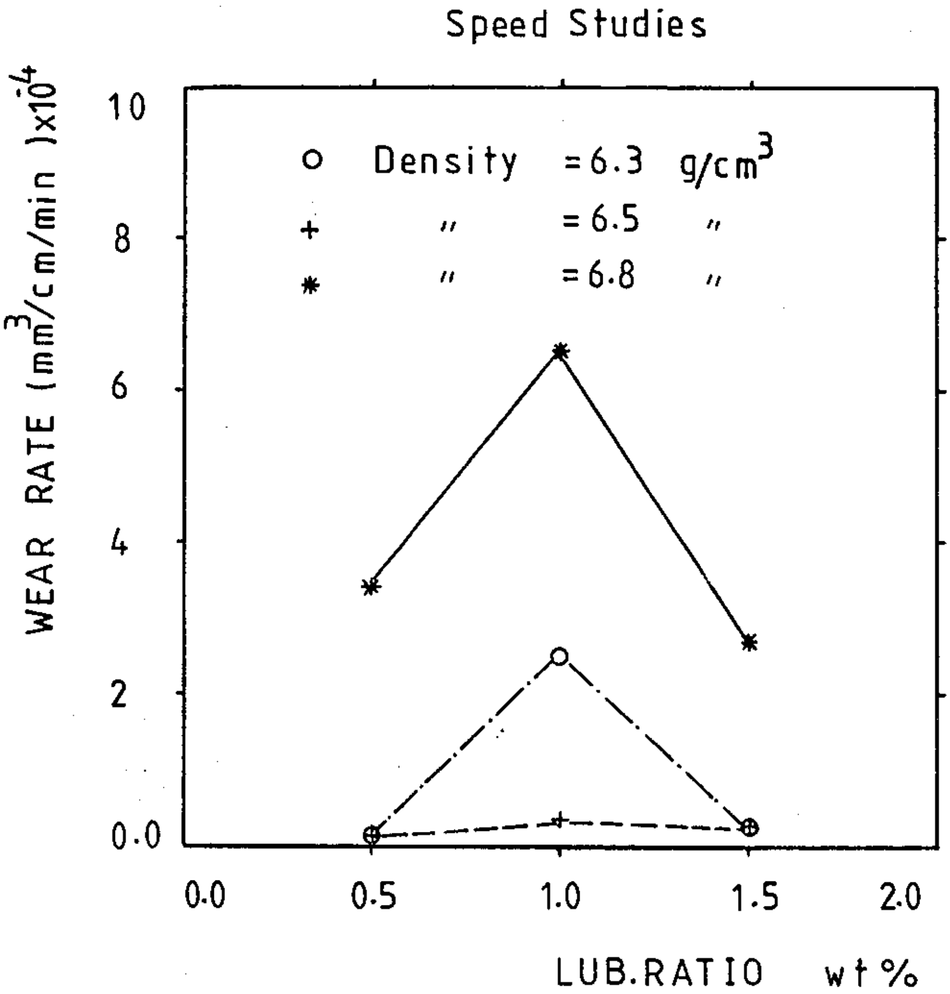

Speed Studies
WEAR RATE (mm$^3$/cm/min )x10$^{-4}$
10
8
6
4
2
0.0
0.0
0.5
1.0
1.5
2.0
LUB.RATIO wt %
○ Density = 6.3 g/cm$^3$
+ " = 6.5 "
* " = 6.8 "

Fig. 106

Distance Studies

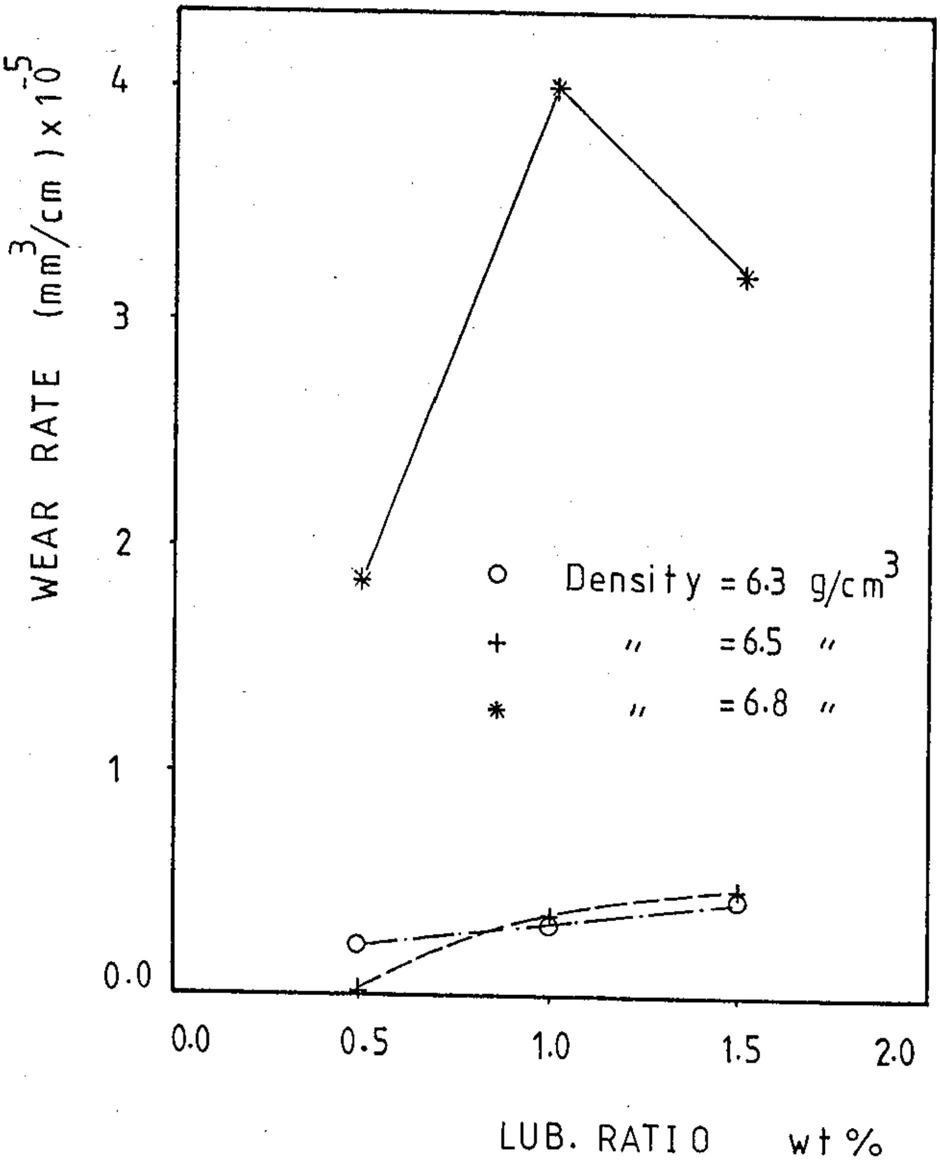


Fig. 107

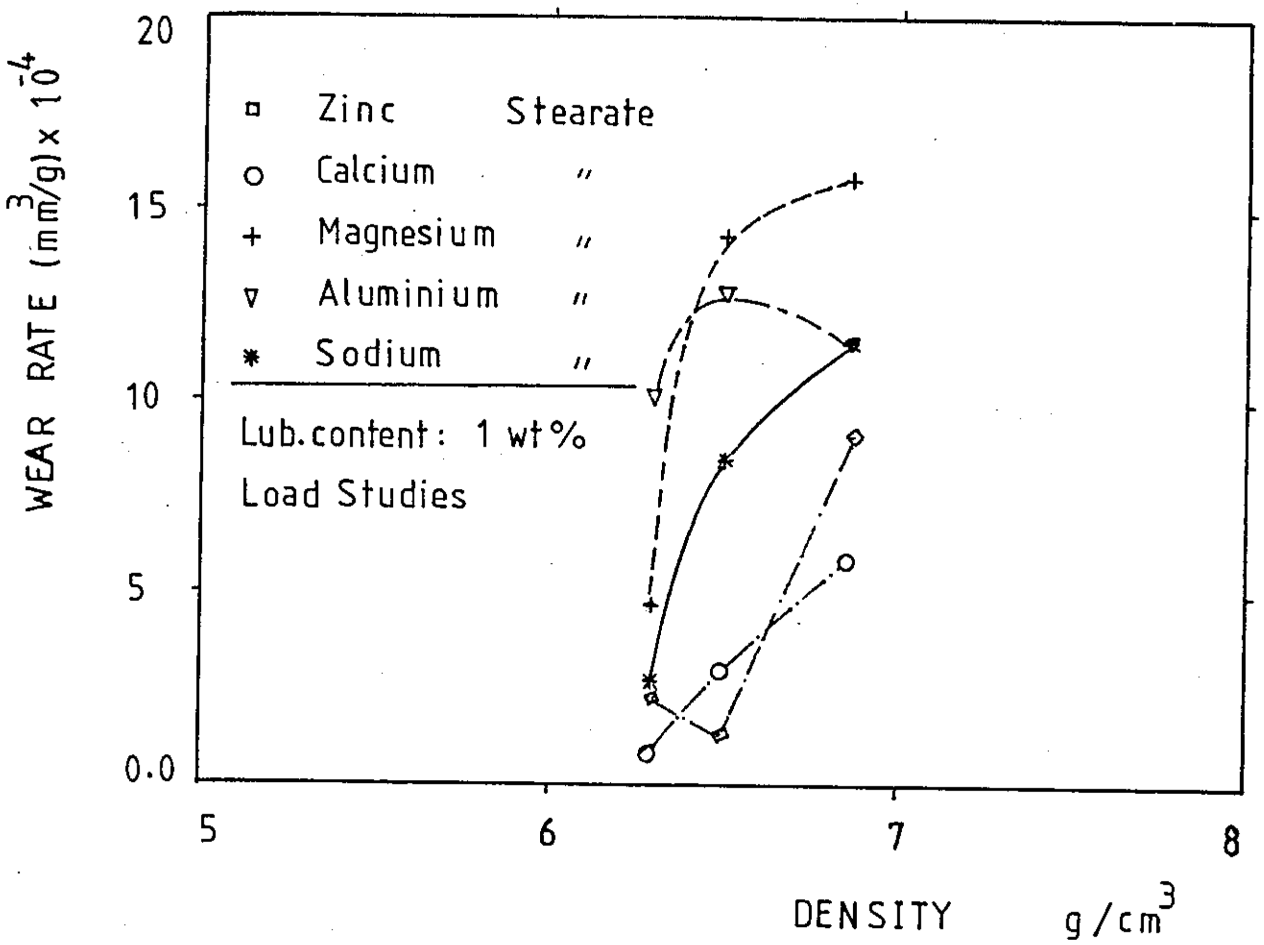

WEAR RATE $(mm^3/g) \times 10^{-4}$
20
15
10
5
0.0
5
6
7
8
DENSITY g/cm³
□ Zinc Stearate
○ Calcium "
+ Magnesium "
▽ Aluminium "
✱ Sodium "
Lub.content: 1 wt%
Load Studies

Fig. 108

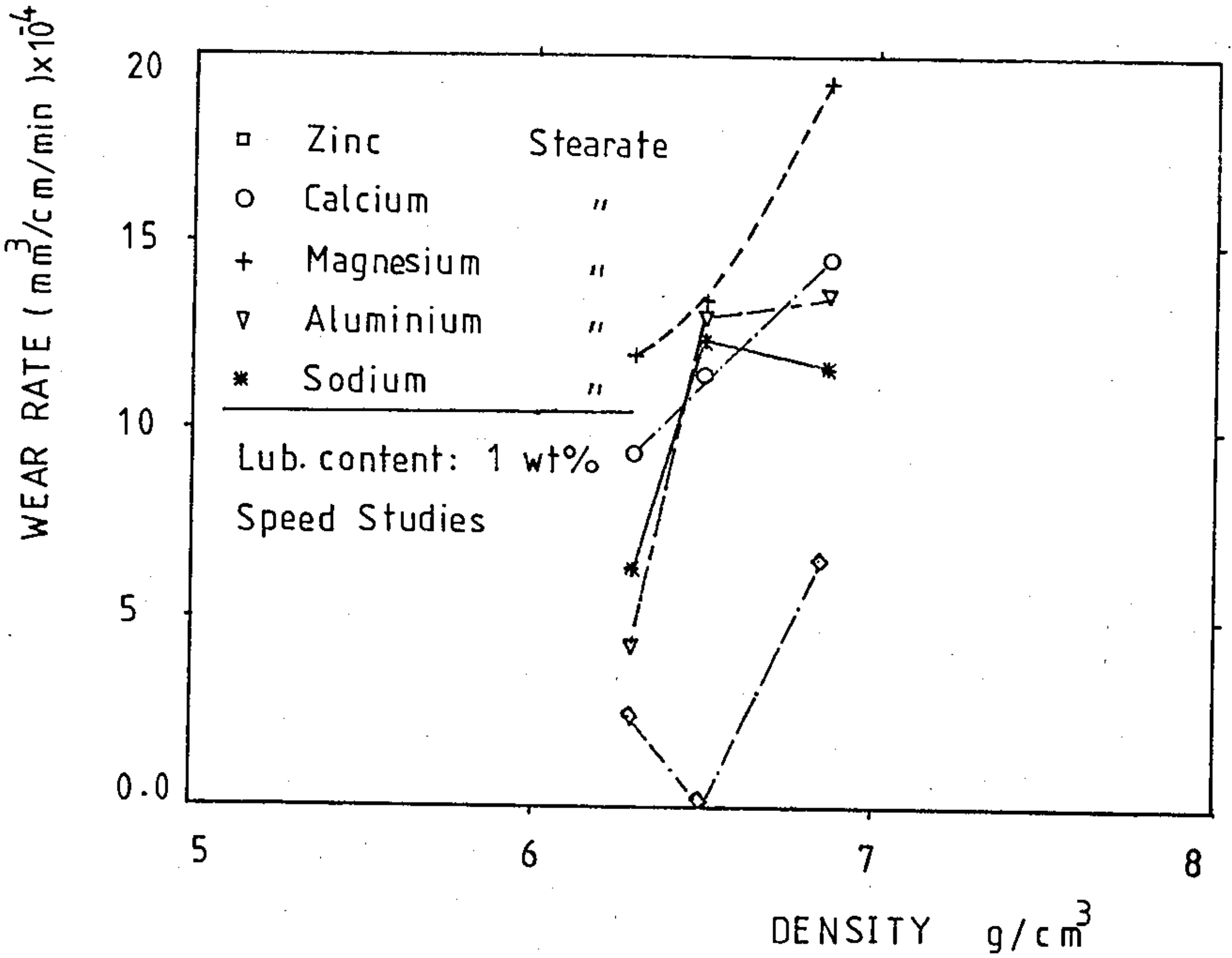

WEAR RATE ( mm$^3$/cm/min )x10$^{-4}$
20
15
10
5
0.0
5
6
7
8
DENSITY g/cm$^3$
□ Zinc Stearate
○ Calcium "
+ Magnesium "
▽ Aluminium "
✱ Sodium "
Lub. content: 1 wt%
Speed Studies

Fig. 109

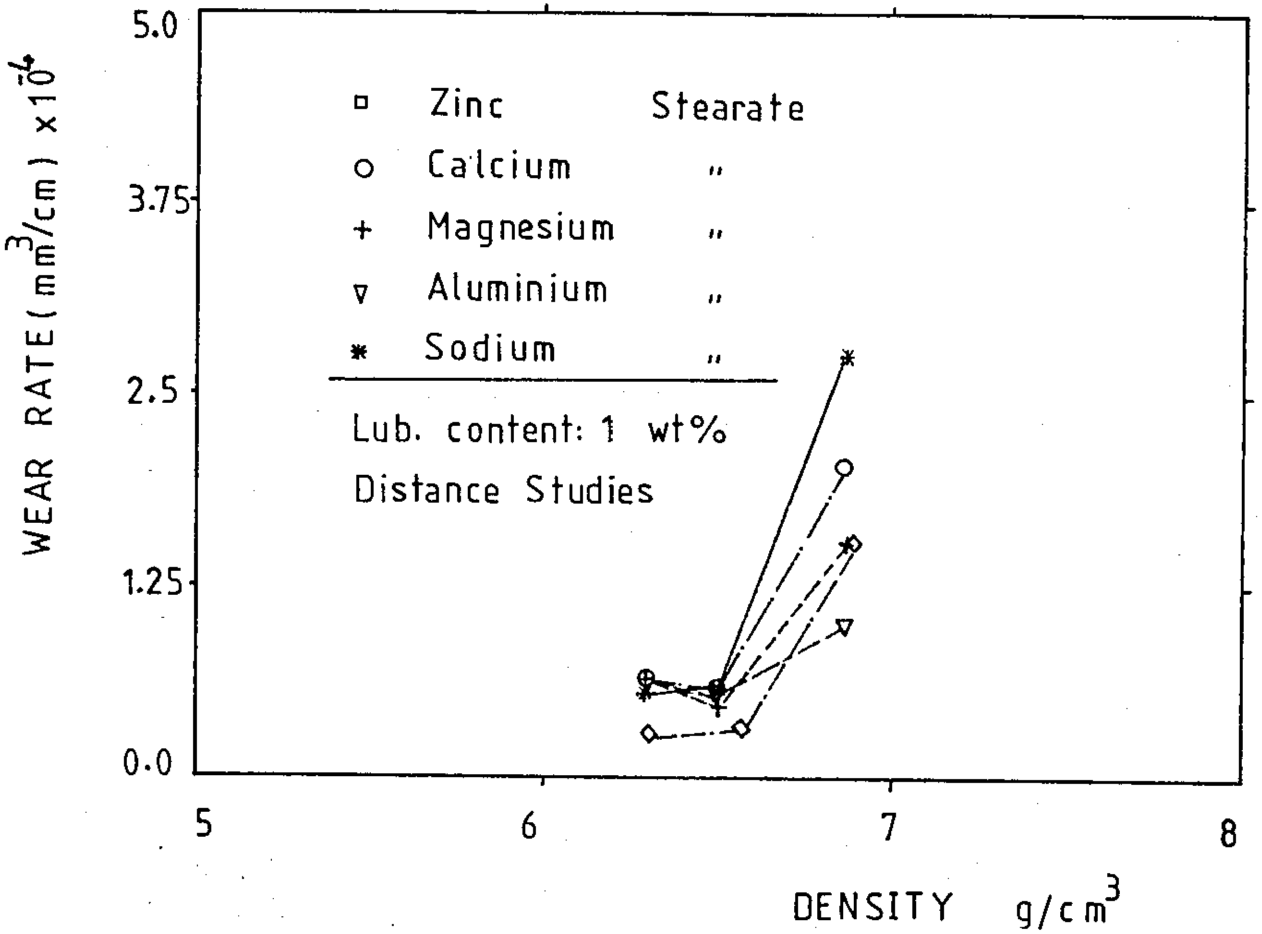

WEAR RATE ( $mm^3$/cm ) x$10^{-4}$
5.0
3.75
2.5
1.25
0.0
5
6
7
8
DENSITY g/c$m^3$
□ Zinc Stearate
○ Calcium "
+ Magnesium "
▽ Aluminium "
* Sodium "
Lub. content: 1 wt%
Distance Studies

Fig. 110

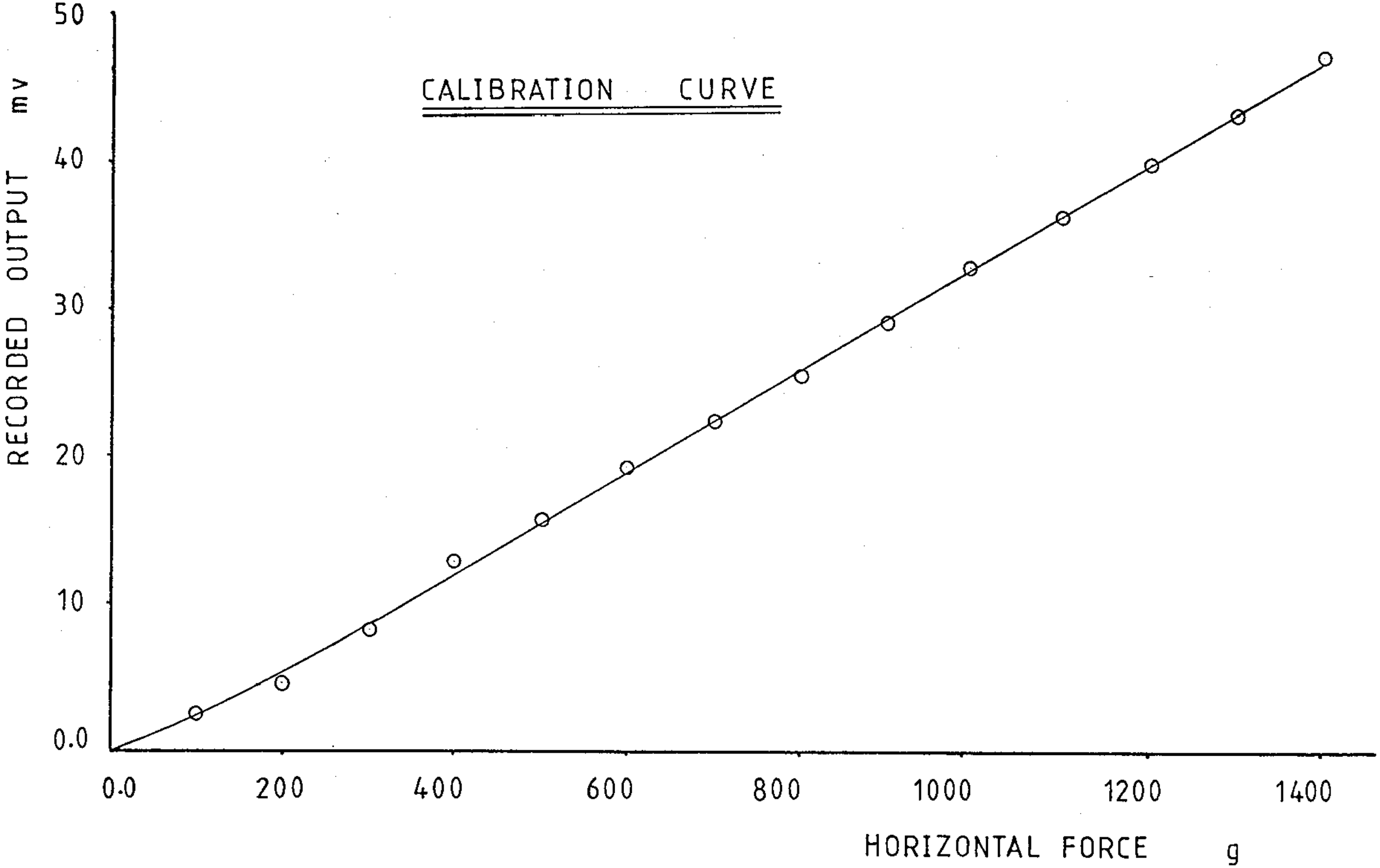

CALIBRATION CURVE
RECORDED OUTPUT mv
50
40
30
20
10
0.0
0.0
200
400
600
800
1000
1200
1400
HORIZONTAL FORCE g

Fig. 111

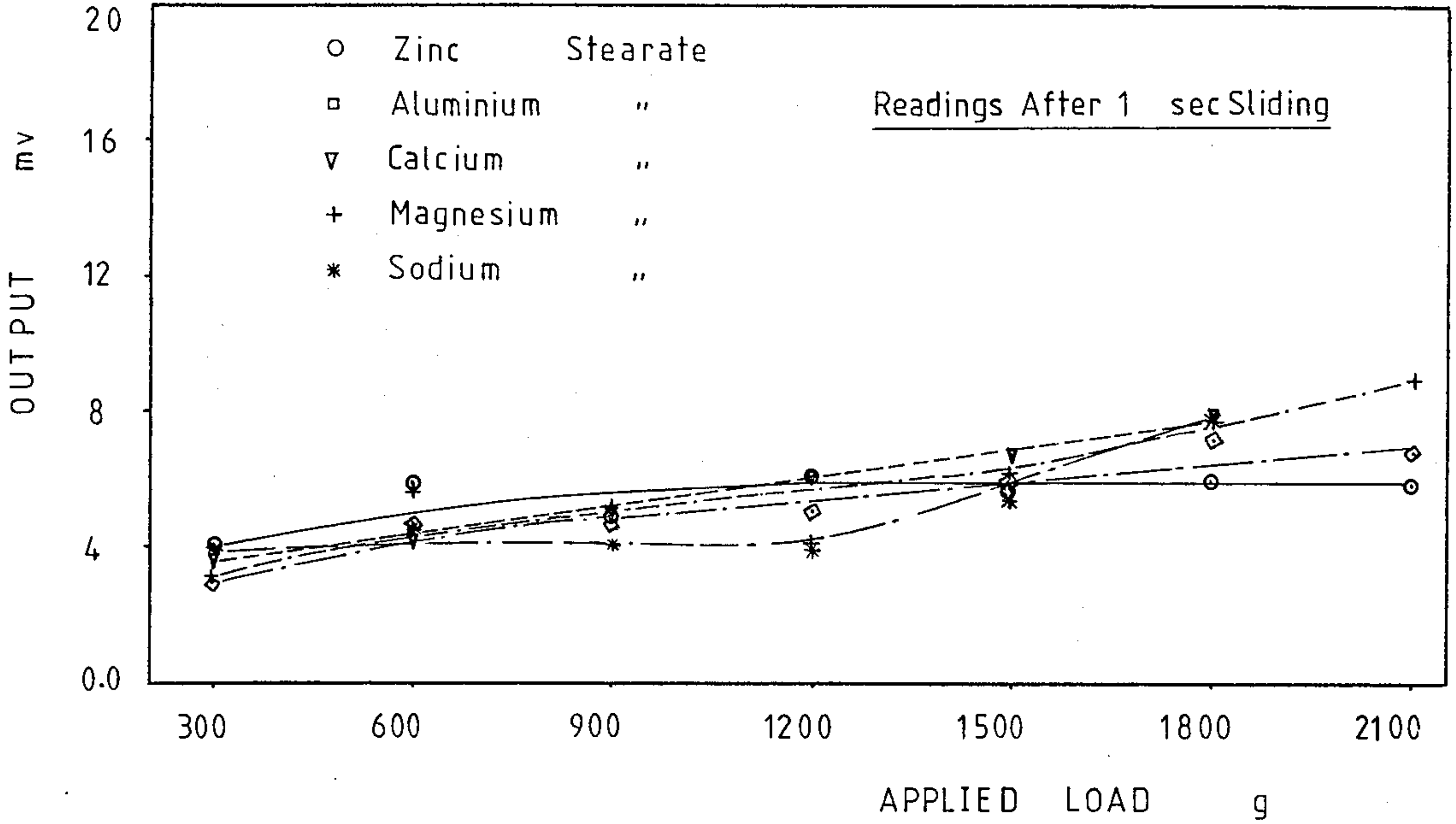

○ Zinc Stearate
□ Aluminium "
∇ Calcium "
+ Magnesium "
* Sodium "
Readings After 1 sec Sliding
OUTPUT mv
20
16
12
8
4
0.0
300
600
900
1200
1500
1800
2100
APPLIED LOAD g

Fig. 112

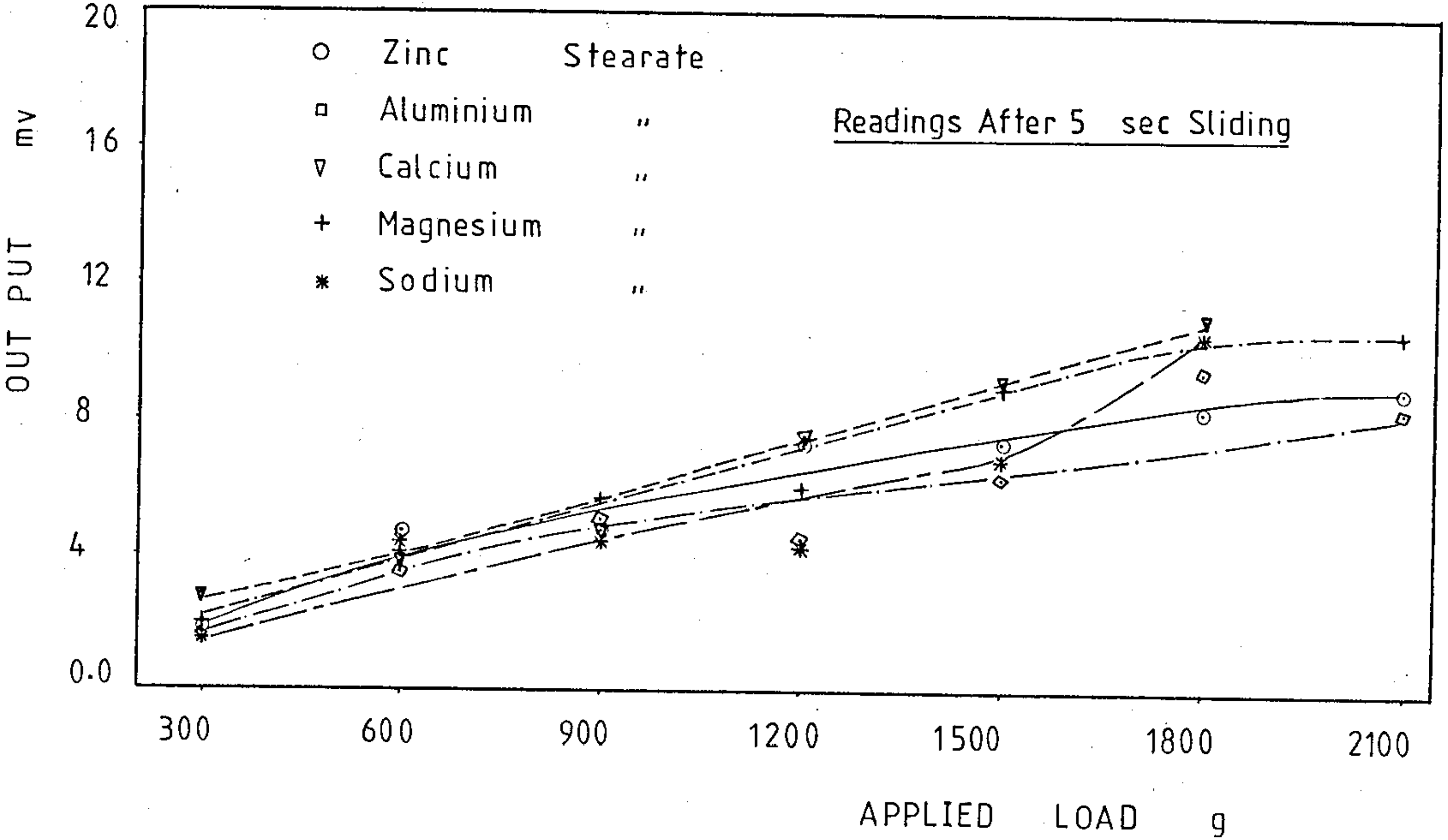

○ Zinc Stearate
□ Aluminium "
▽ Calcium "
+ Magnesium "
✱ Sodium "
Readings After 5 sec Sliding
OUT PUT mv
20
16
12
8
4
0.0
300
600
900
1200
1500
1800
2100
APPLIED LOAD g

Fig. 113

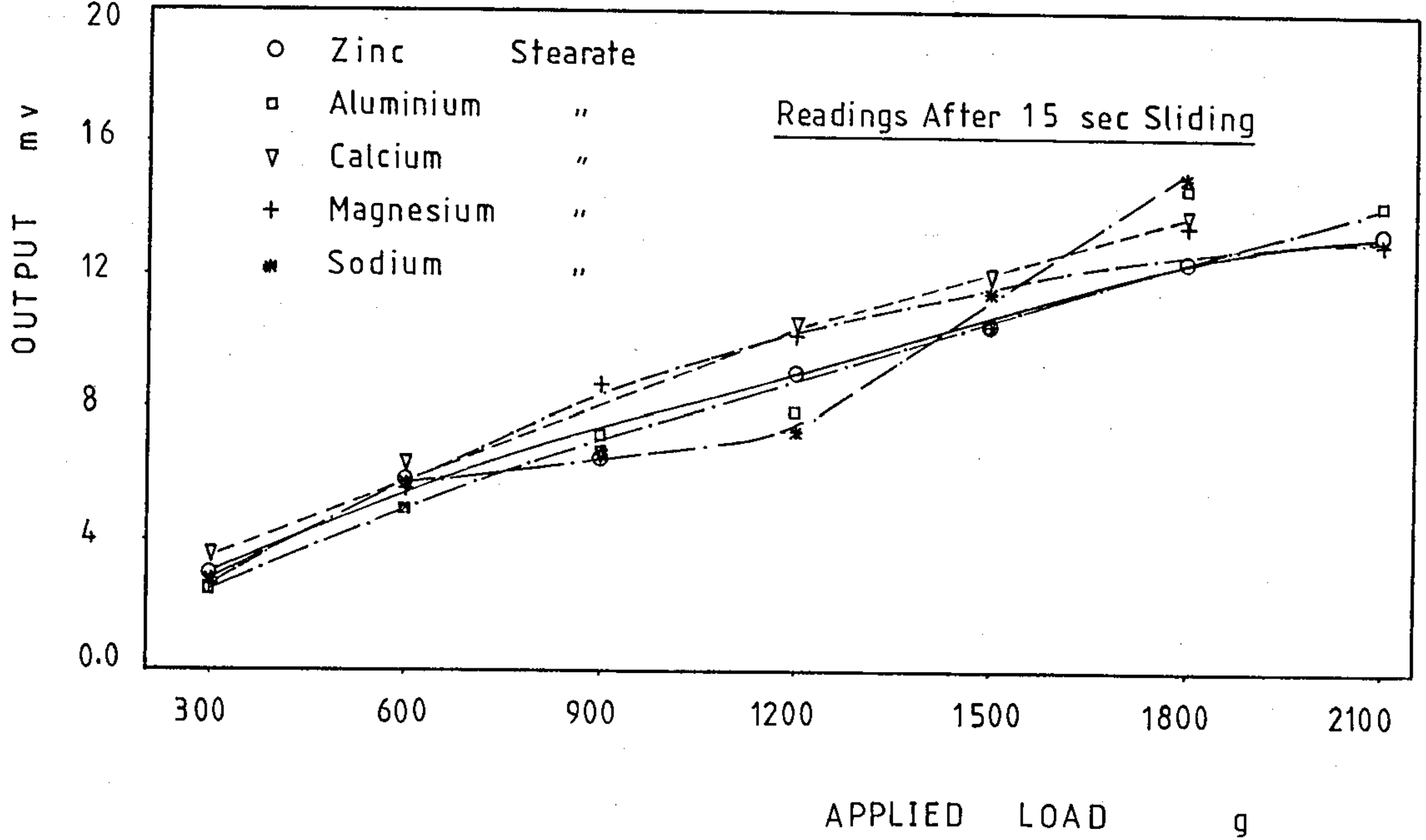

○ Zinc Stearate
□ Aluminium "
▽ Calcium "
+ Magnesium "
✱ Sodium "
Readings After 15 sec Sliding
OUTPUT mv
0.0
4
8
12
16
20
300
600
900
1200
1500
1800
2100
APPLIED LOAD g

Fig. 114

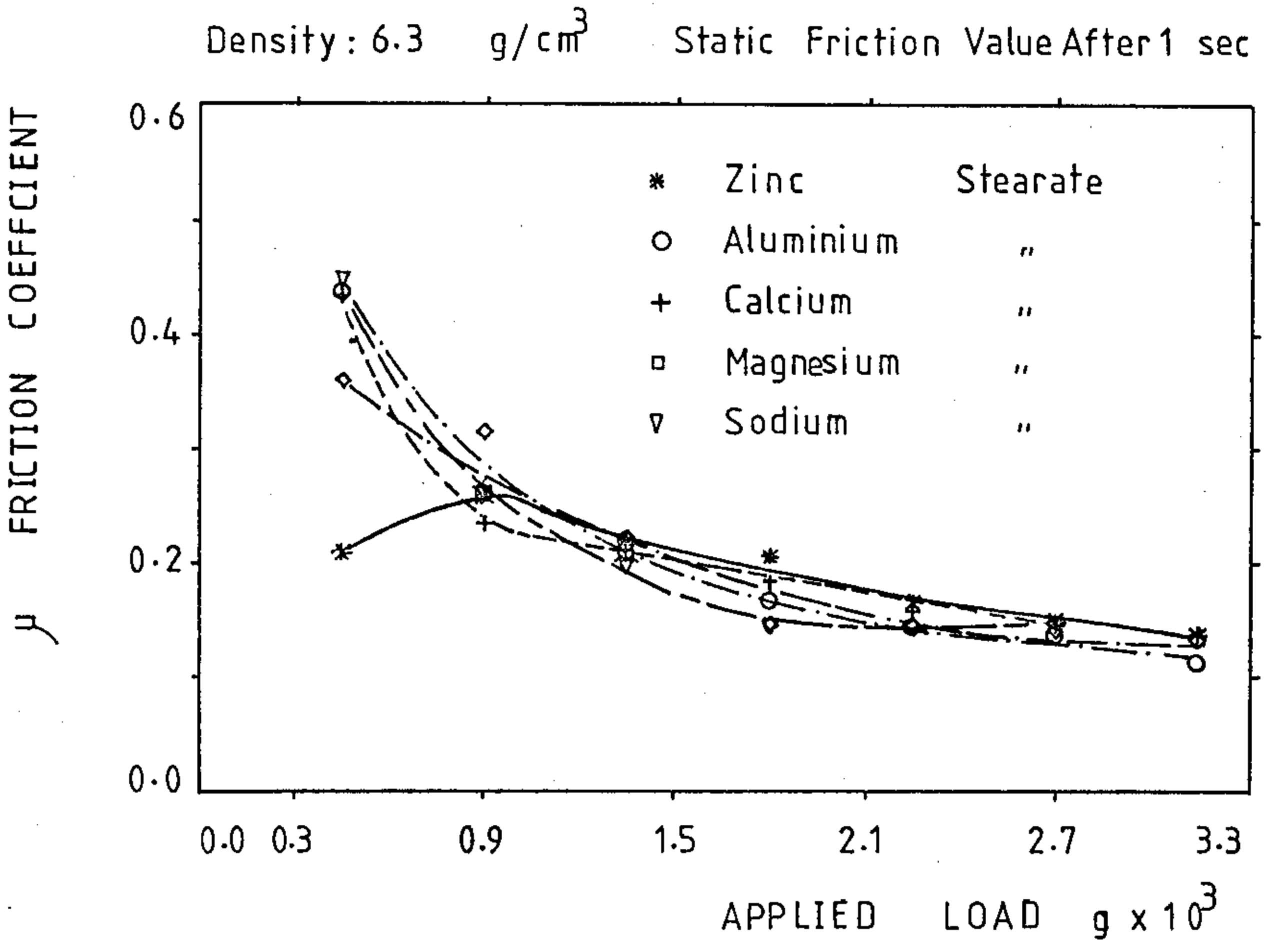

Density : 6.3 g/cm$^3$ Static Friction Value After 1 sec
μ FRICTION COEFFCIENT
0.0
0.2
0.4
0.6
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
✱ Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
∇ Sodium "

Fig. 115

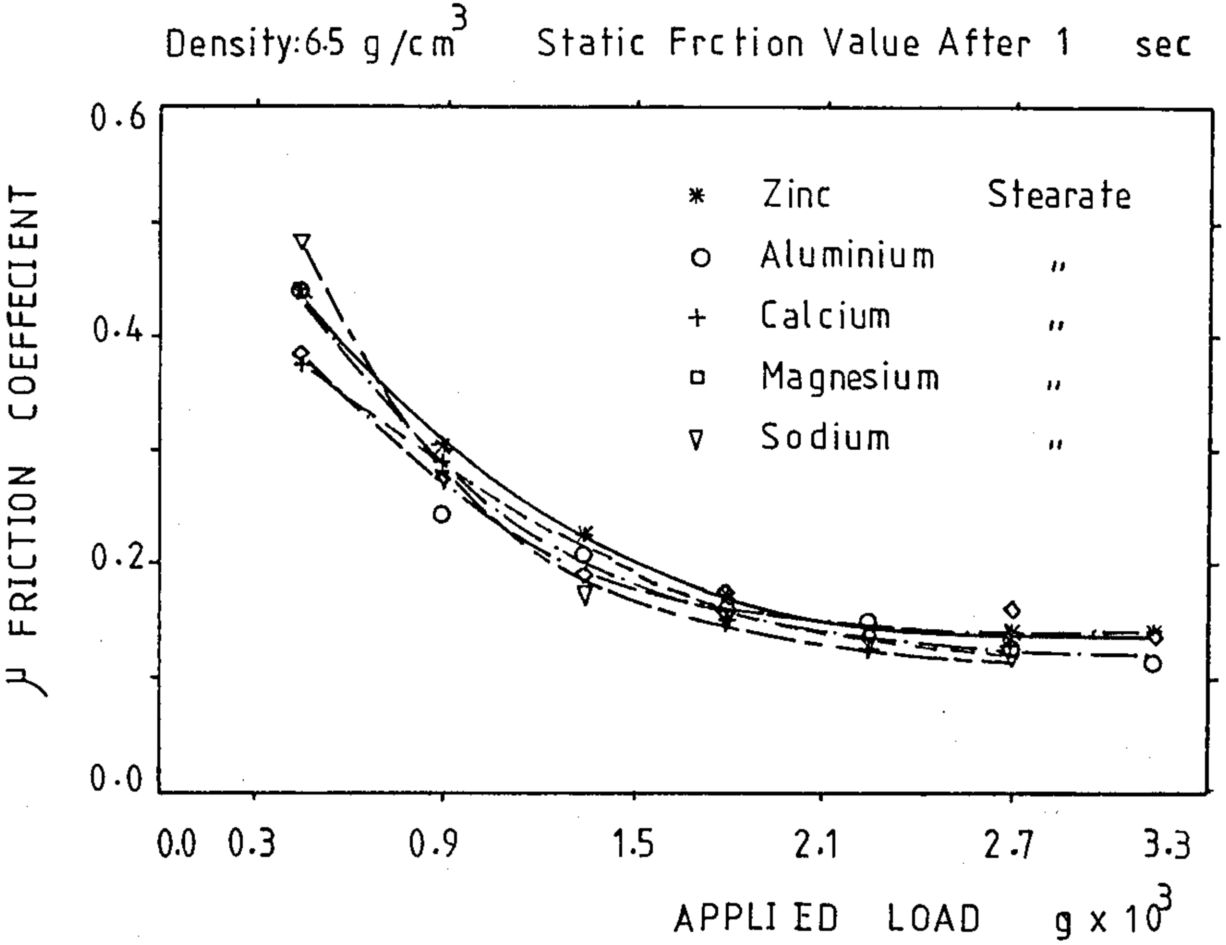

Density:6.5 g/cm$^3$ Static Frction Value After 1 sec
0.6
0.4
0.2
0.0
μ FRICTION COEFFECIENT
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
* Zinc Stearate
○ Aluminium "
+ Calcium "
▫ Magnesium "
▽ Sodium "

Fig. 116

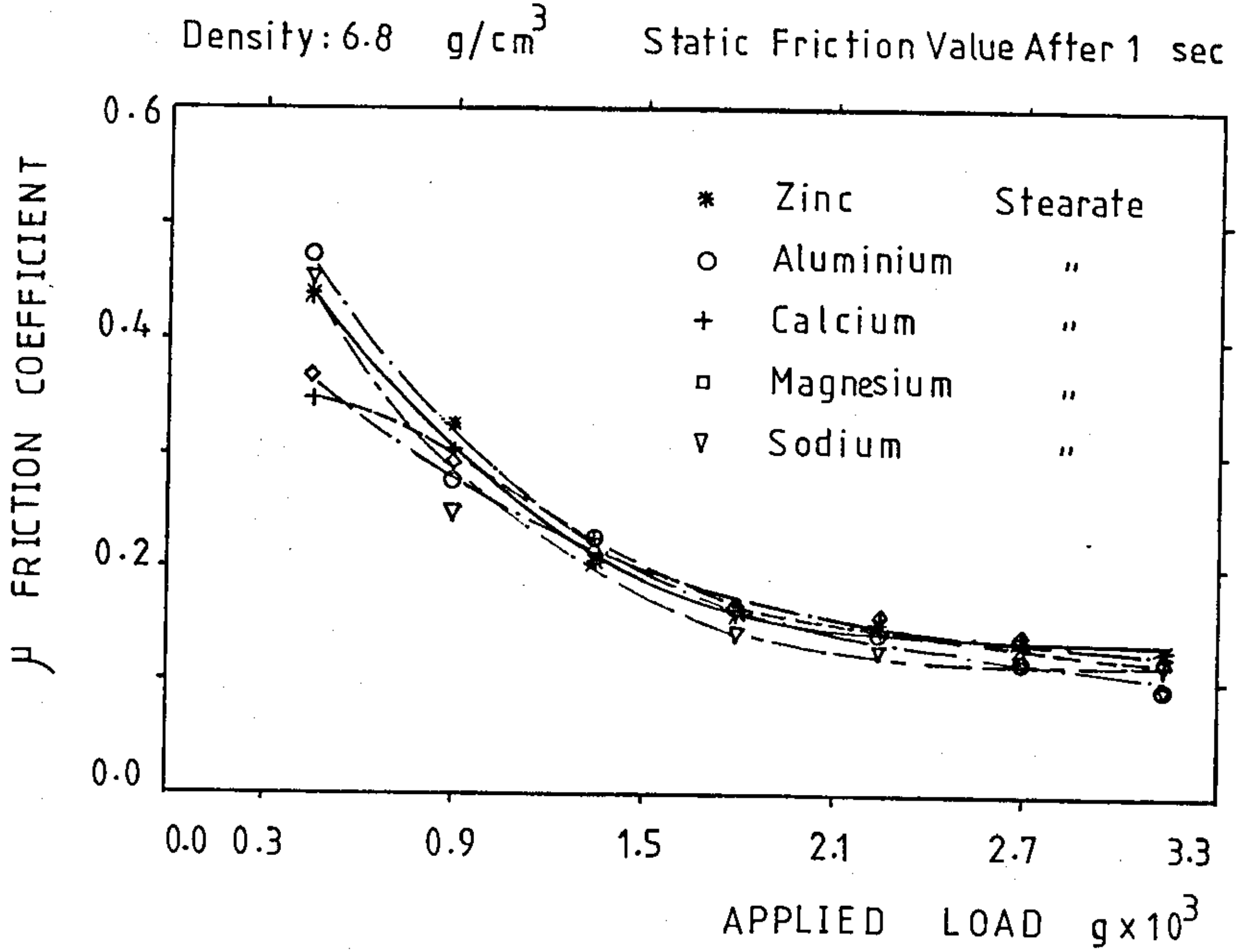

Density: 6.8 g/cm$^3$
Static Friction Value After 1 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
✱ Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 117

Density : 6·3 g/cm$^3$ Sliding Friction After : 5 sec

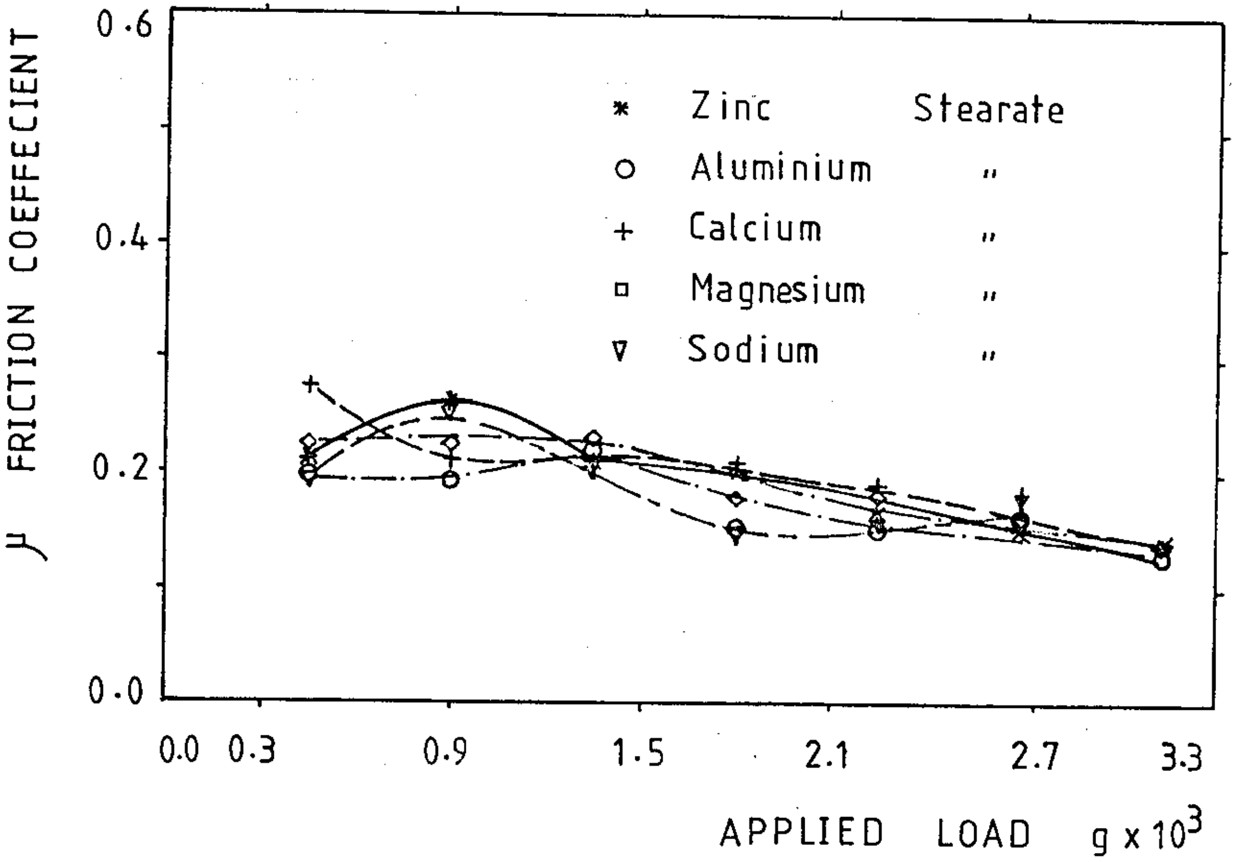


Fig. 118

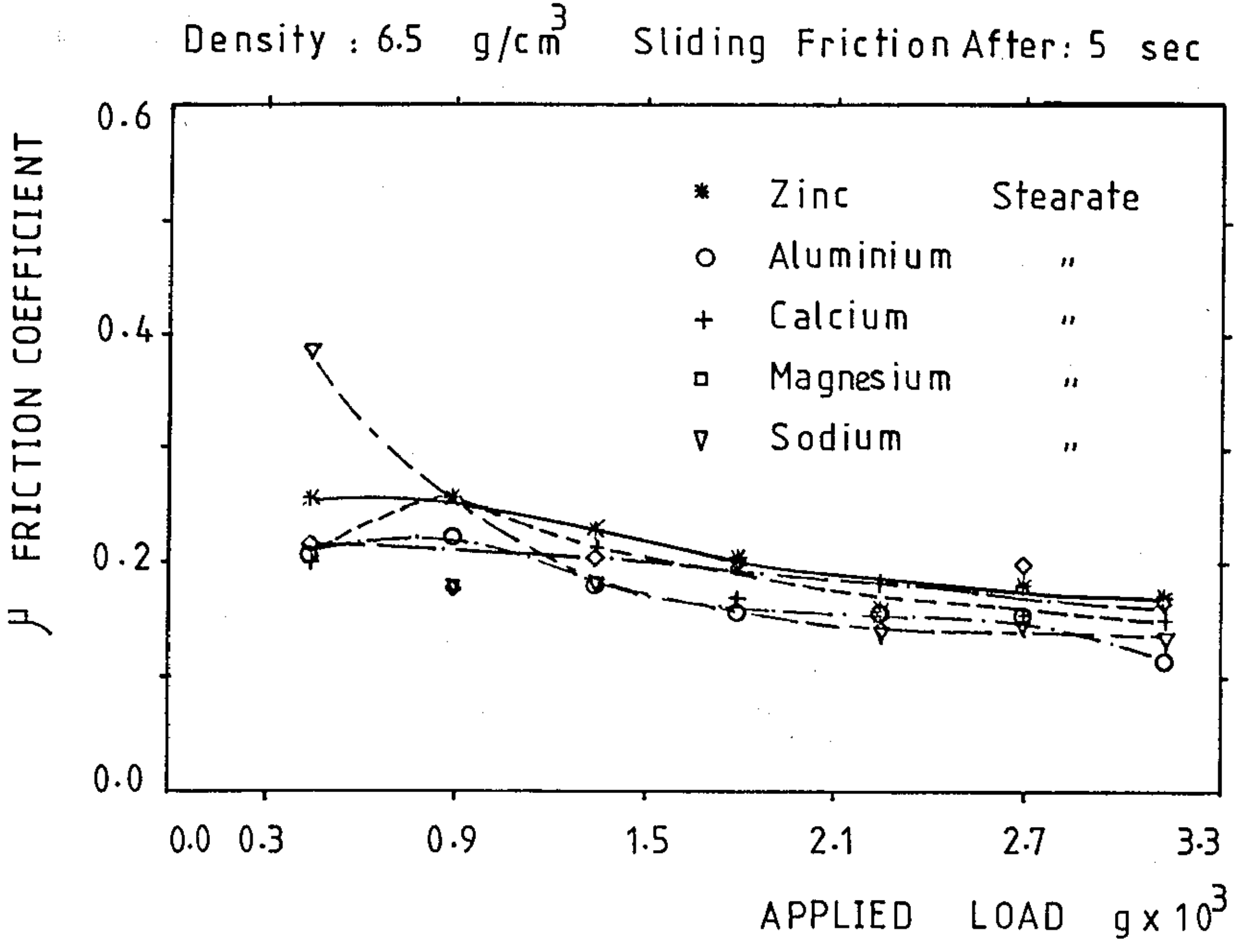

Density : 6.5 g/cm$^3$ Sliding Friction After: 5 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
* Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 119

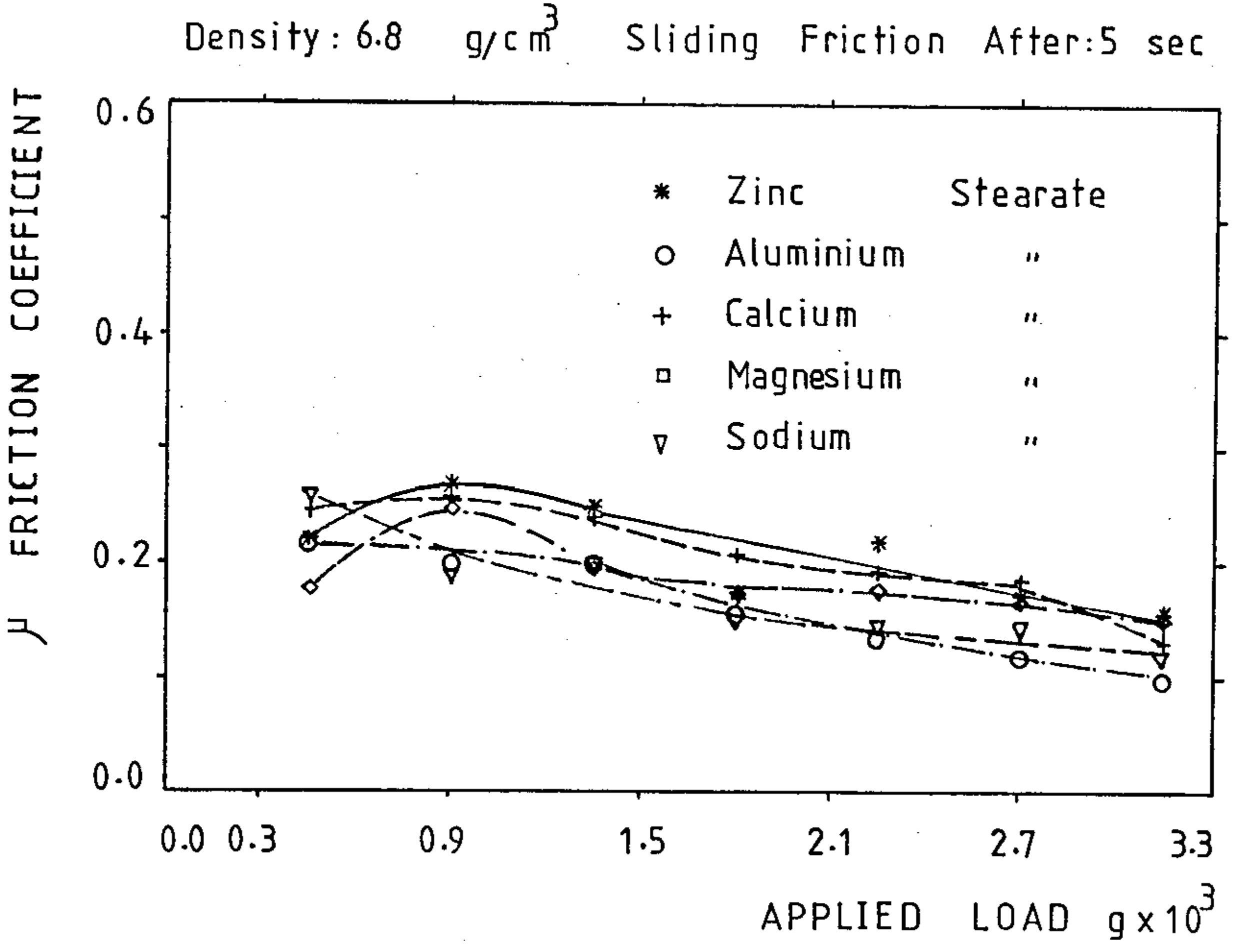

Density : 6.8 g/cm$^3$ Sliding Friction After:5 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
* Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 120

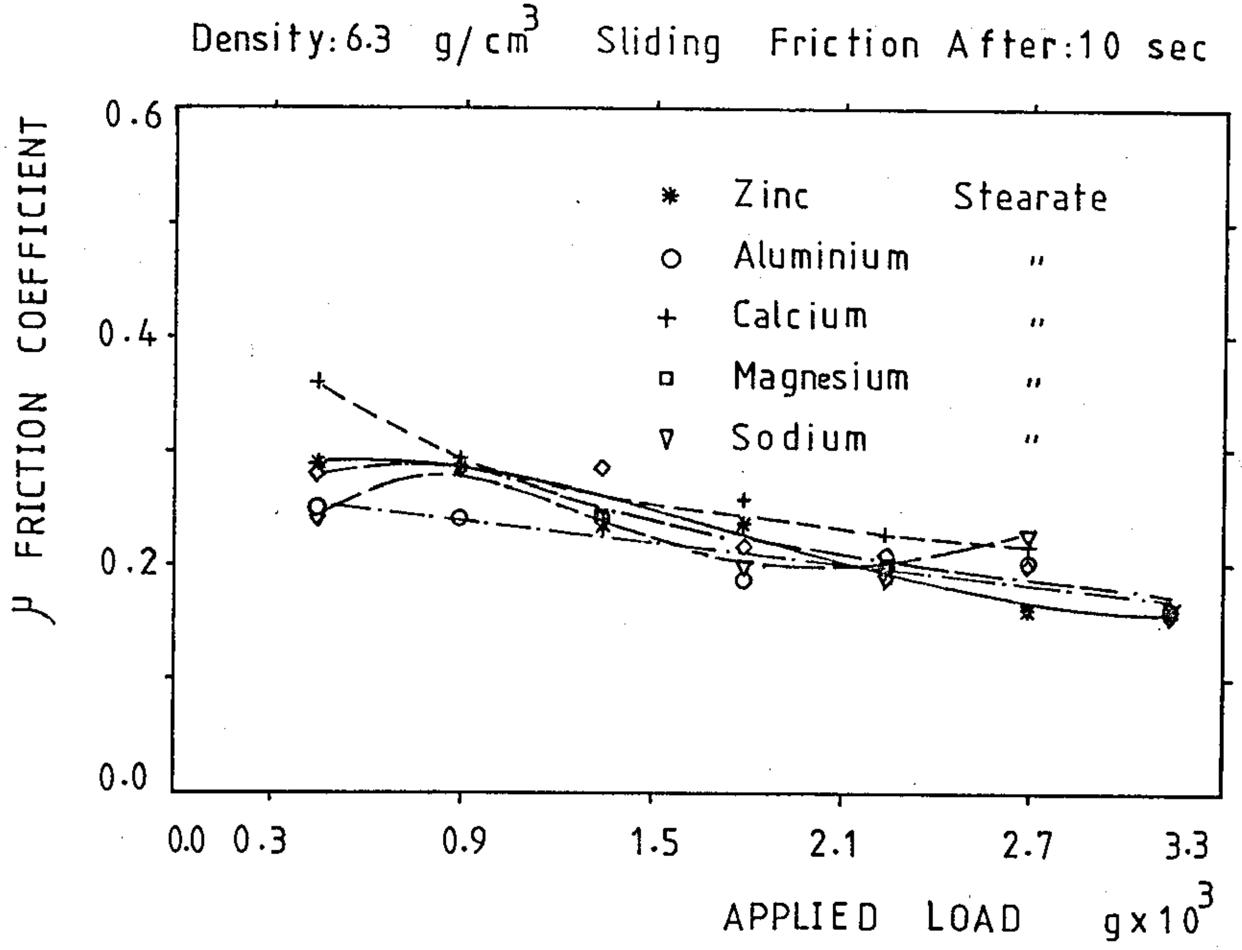

Density: 6.3 g/cm$^3$ Sliding Friction After: 10 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
✱ Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$

Fig. 121

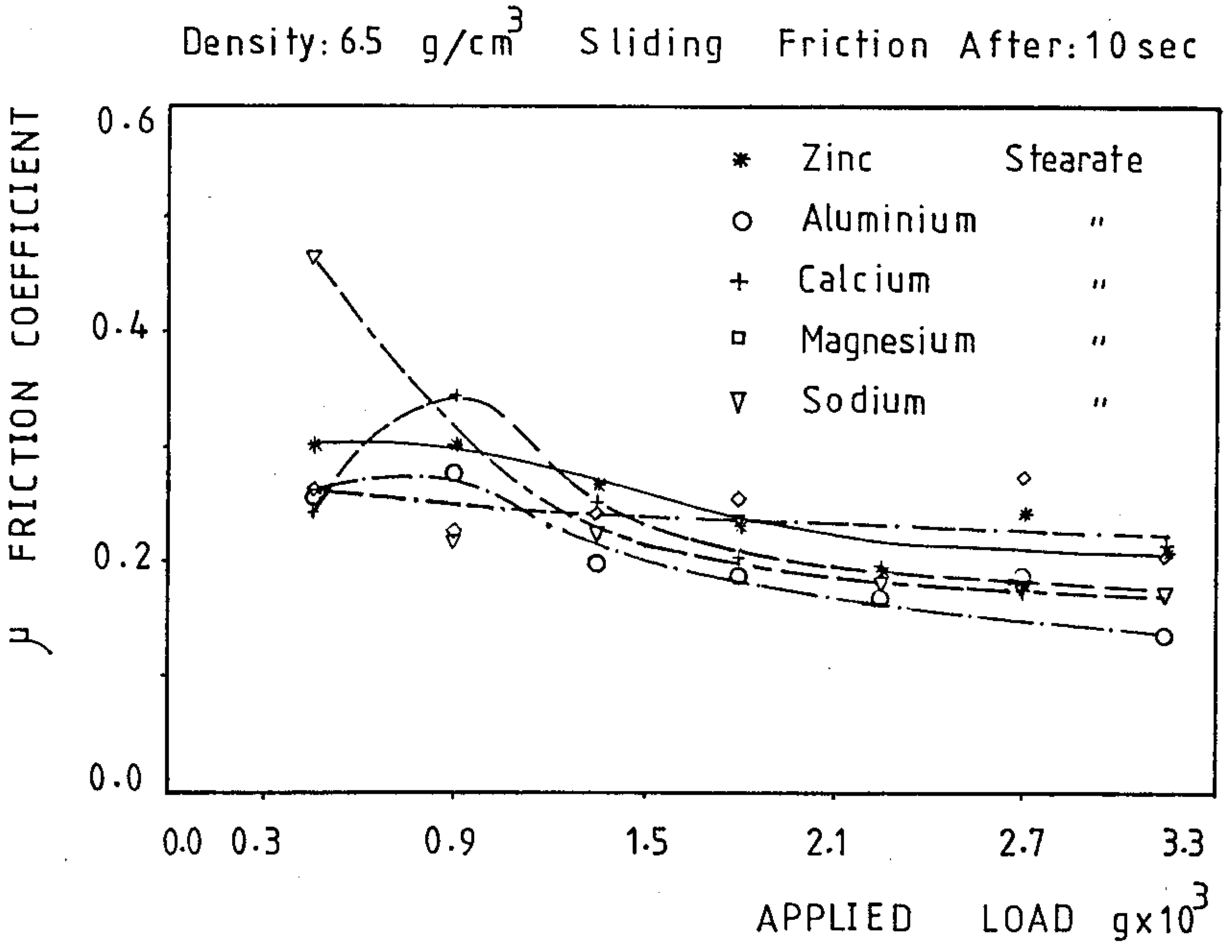

Density: 6.5 g/cm$^3$ Sliding Friction After: 10 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
* Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
∇ Sodium "
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$

Fig. 122

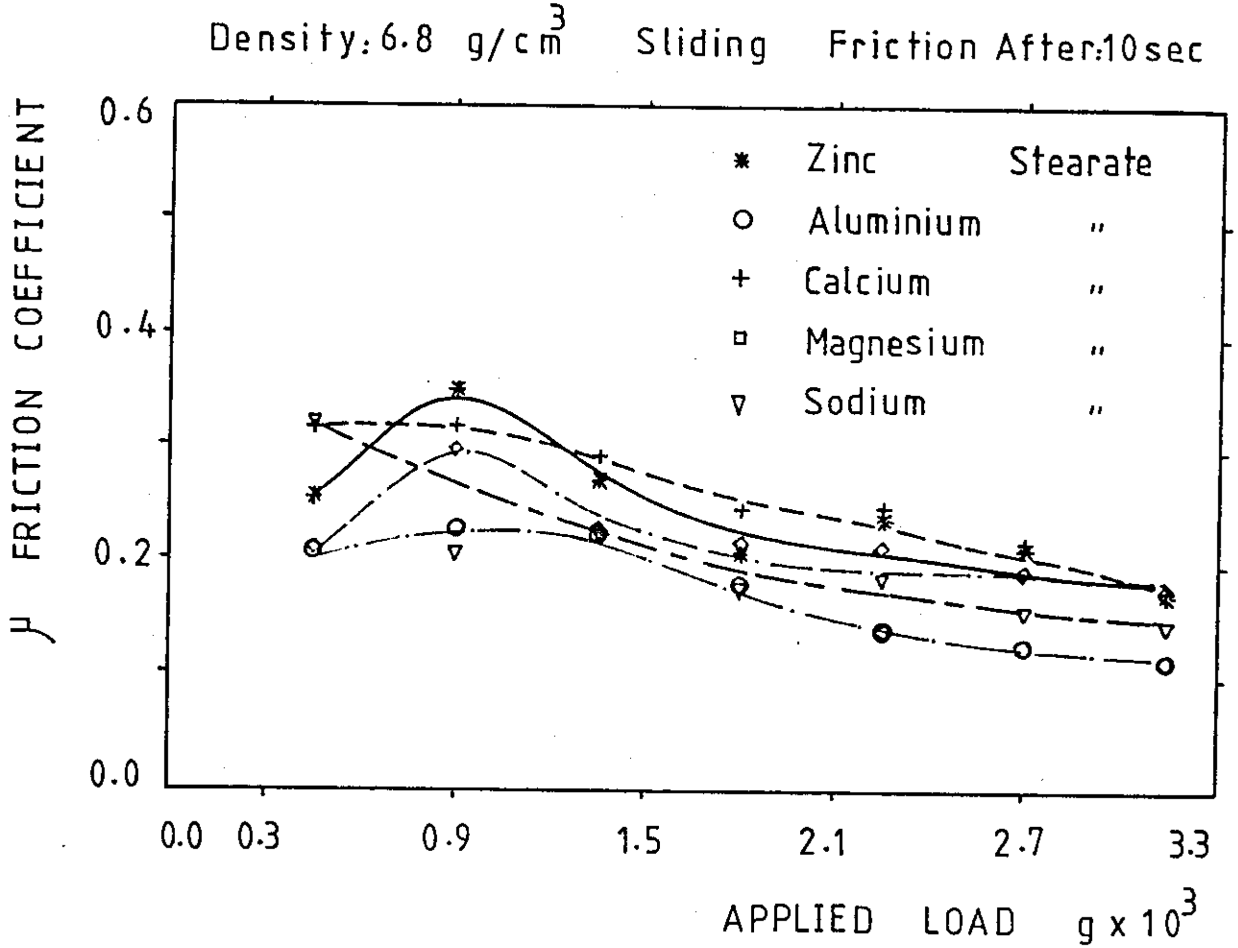

Density: 6.8 g/cm$^3$ Sliding Friction After:10sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
✱ Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 123

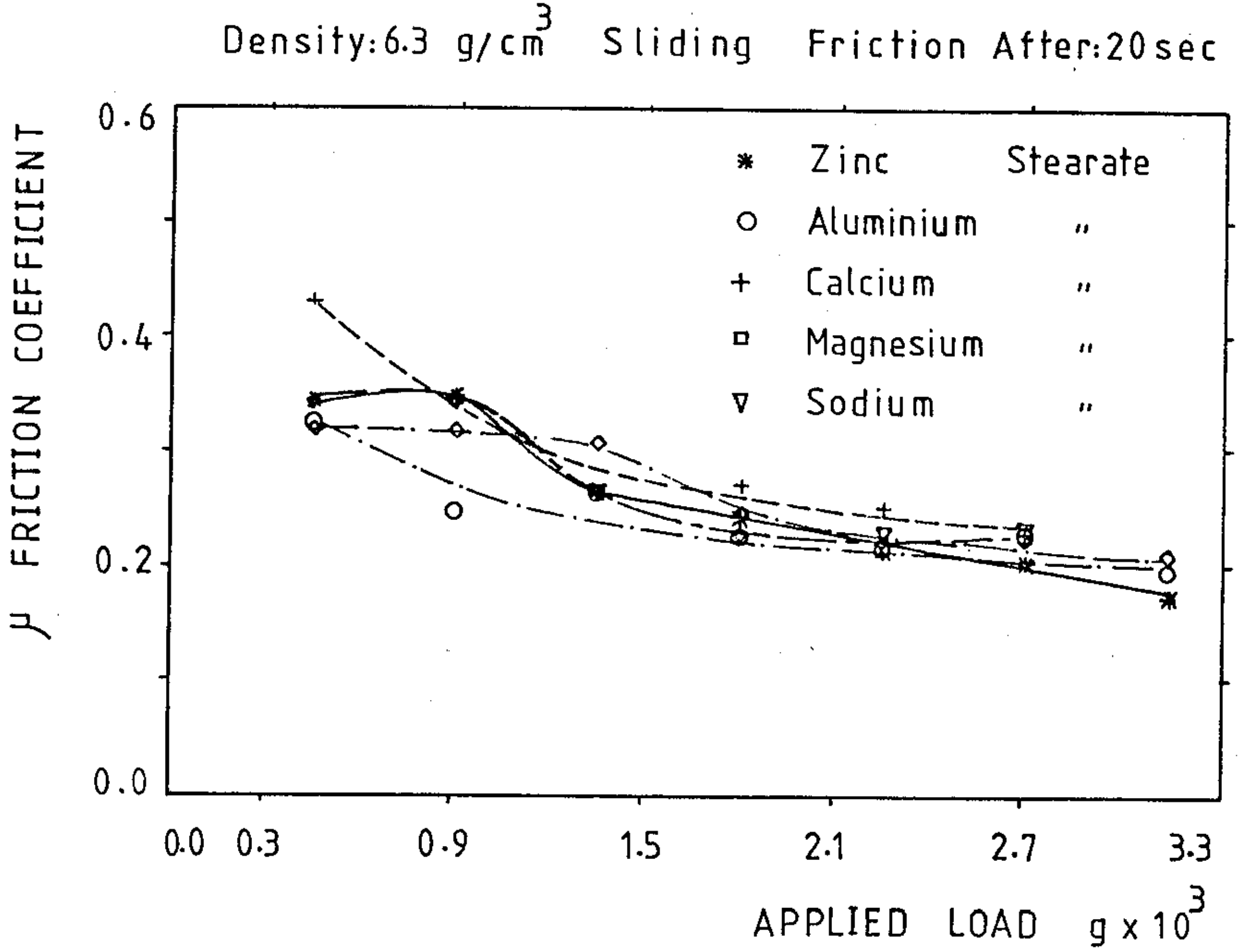
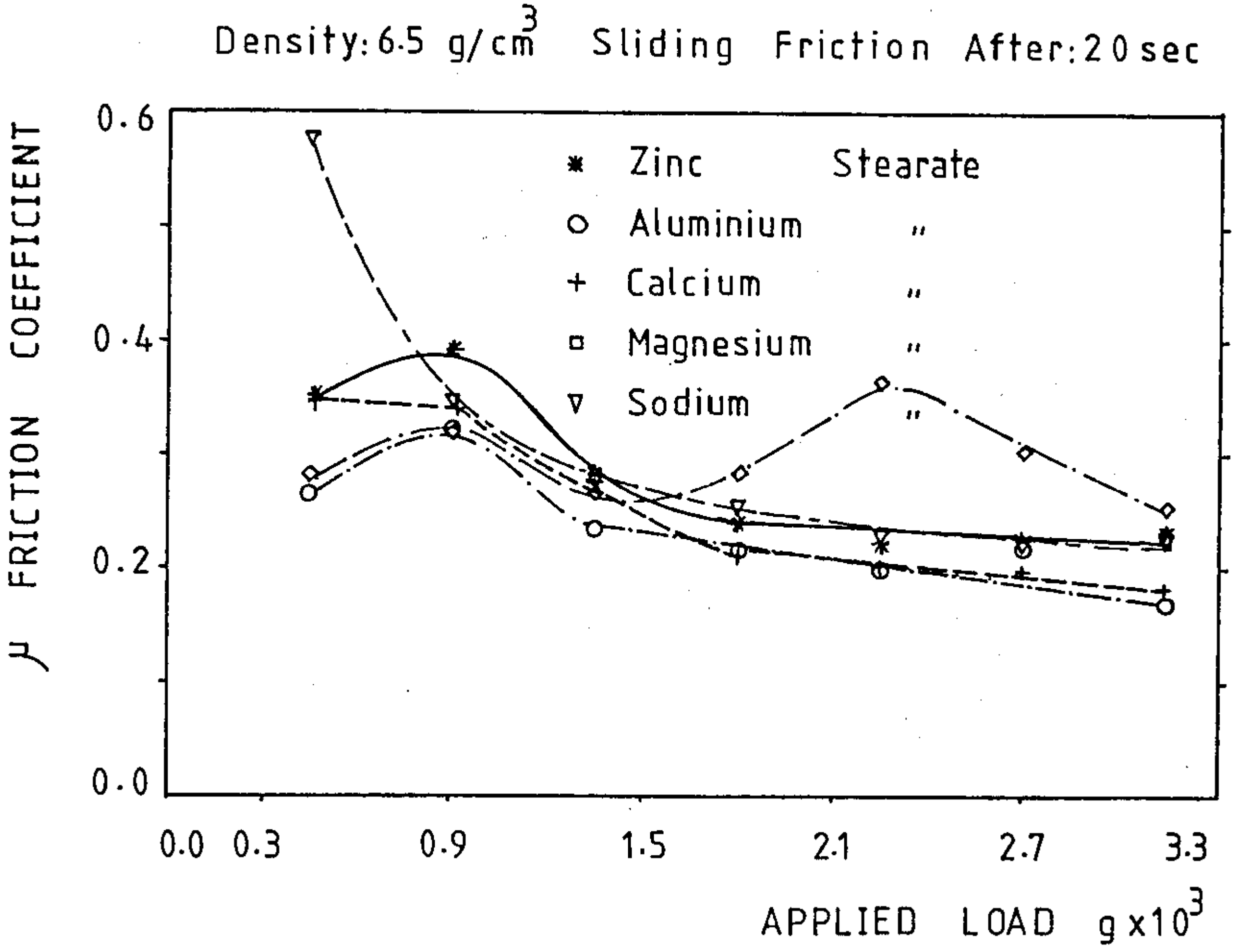

Density:6.3 g/cm$^3$ Sliding Friction After:20sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
✱ Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 124



Density: 6.5 g/cm$^3$ Sliding Friction After: 20 sec

Fig. 125

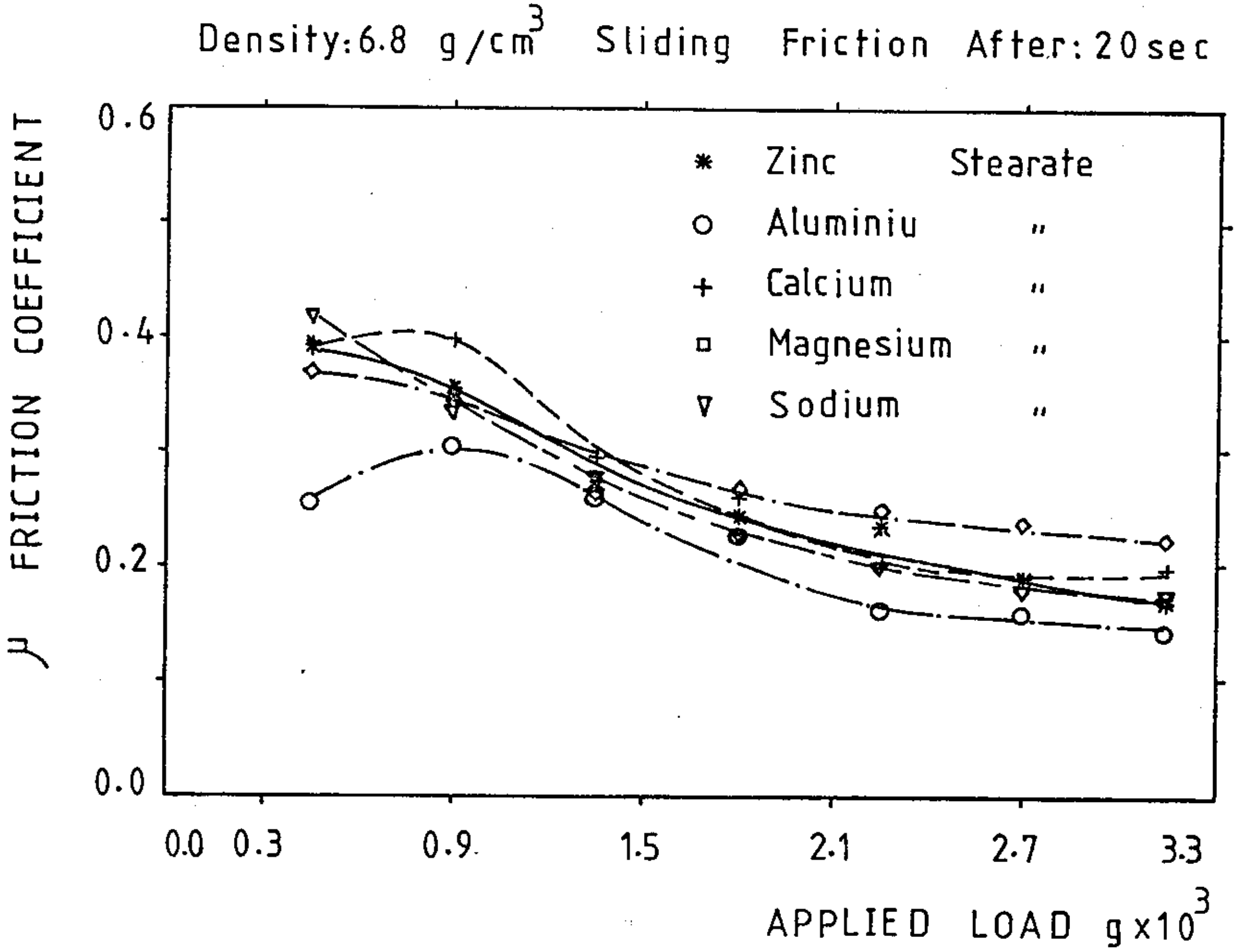

Density: 6.8 g/cm$^3$ Sliding Friction After: 20 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x10$^3$
* Zinc Stearate
○ Aluminiu "
+ Calcium "
□ Magnesium "
∇ Sodium "

Fig. 126

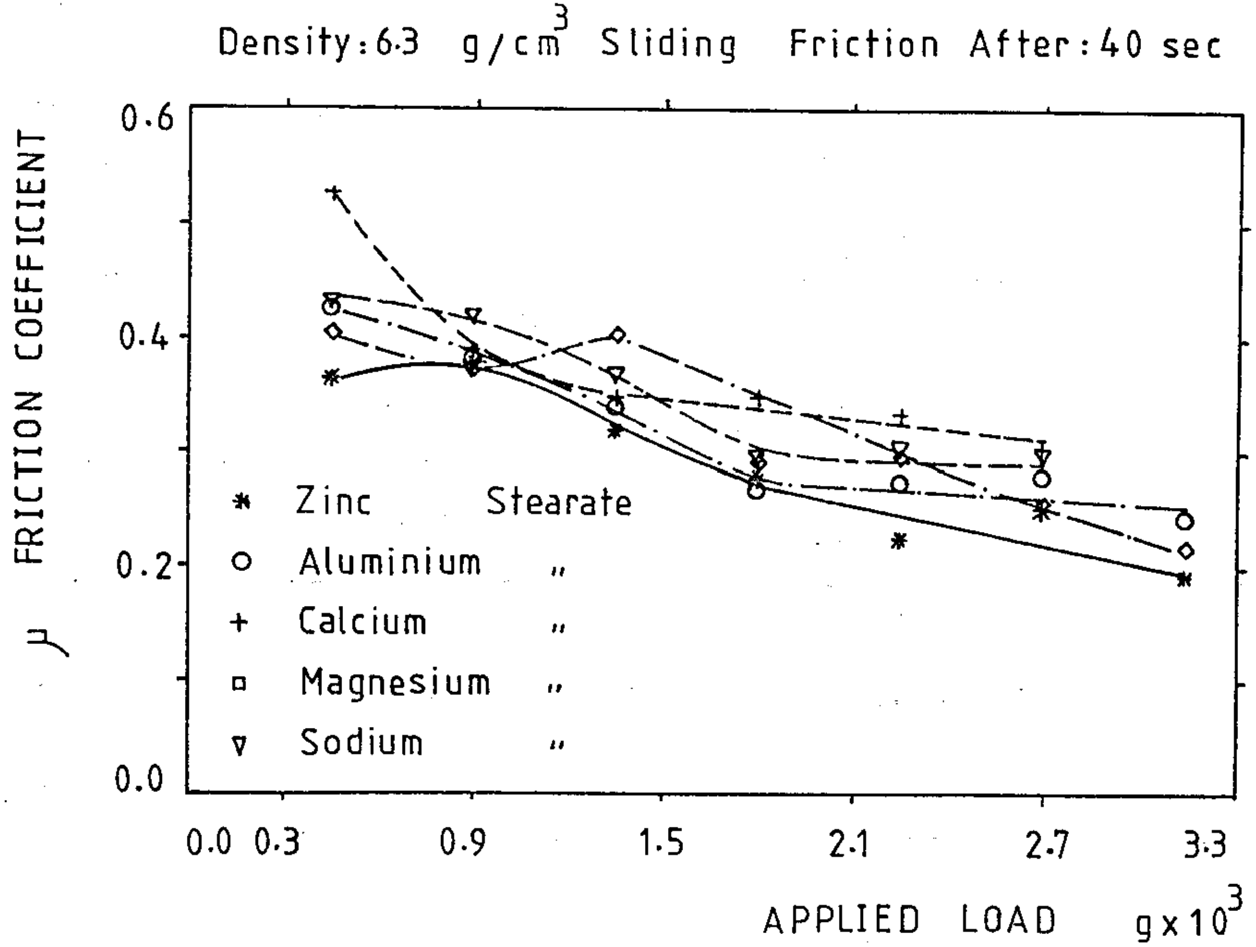

Density: 6.3 g/cm$^3$ Sliding Friction After: 40 sec
FRICTION COEFFICIENT
μ
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
* Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 127

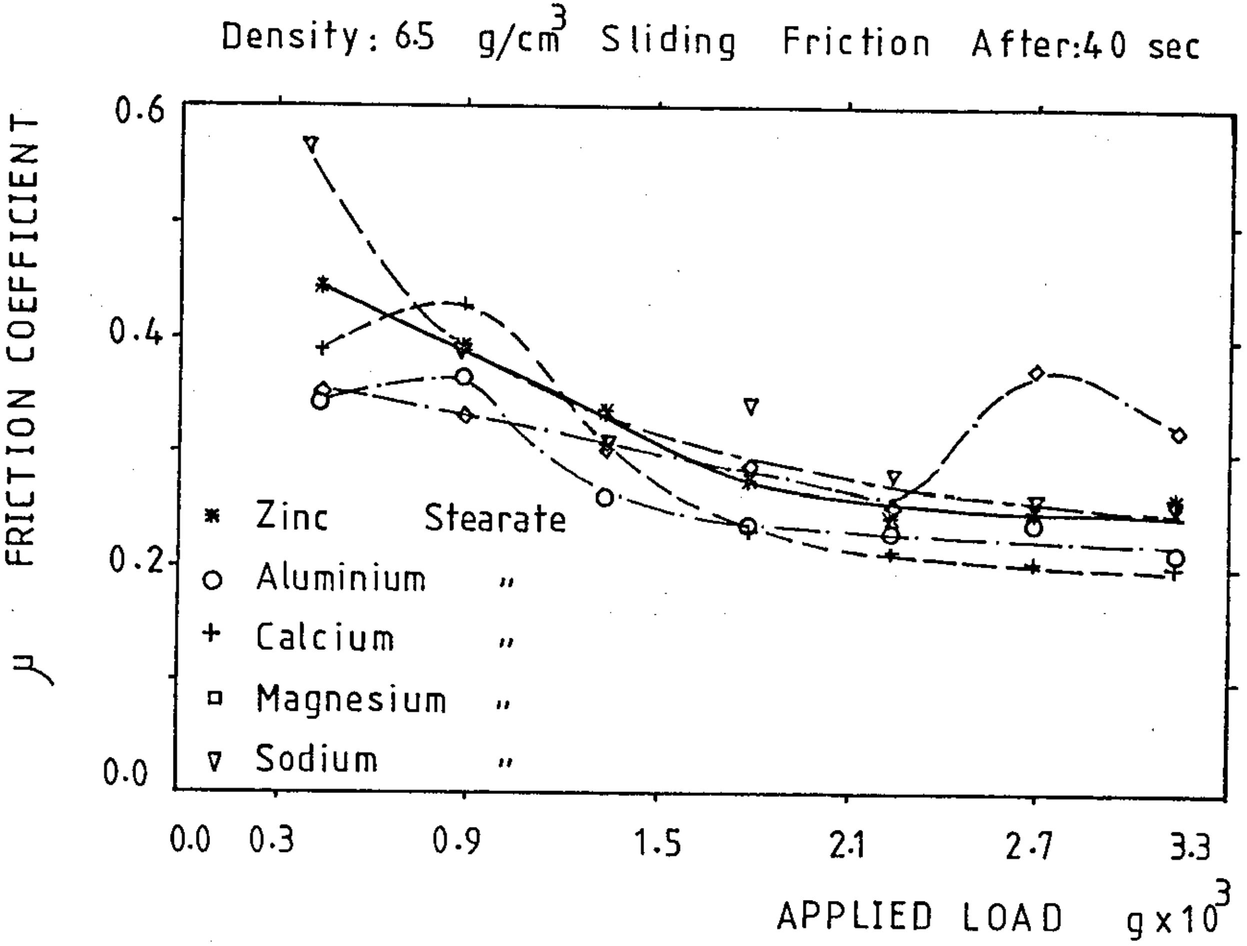

Density: 6.5 g/cm3 Sliding Friction After:40 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10^3
* Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 128

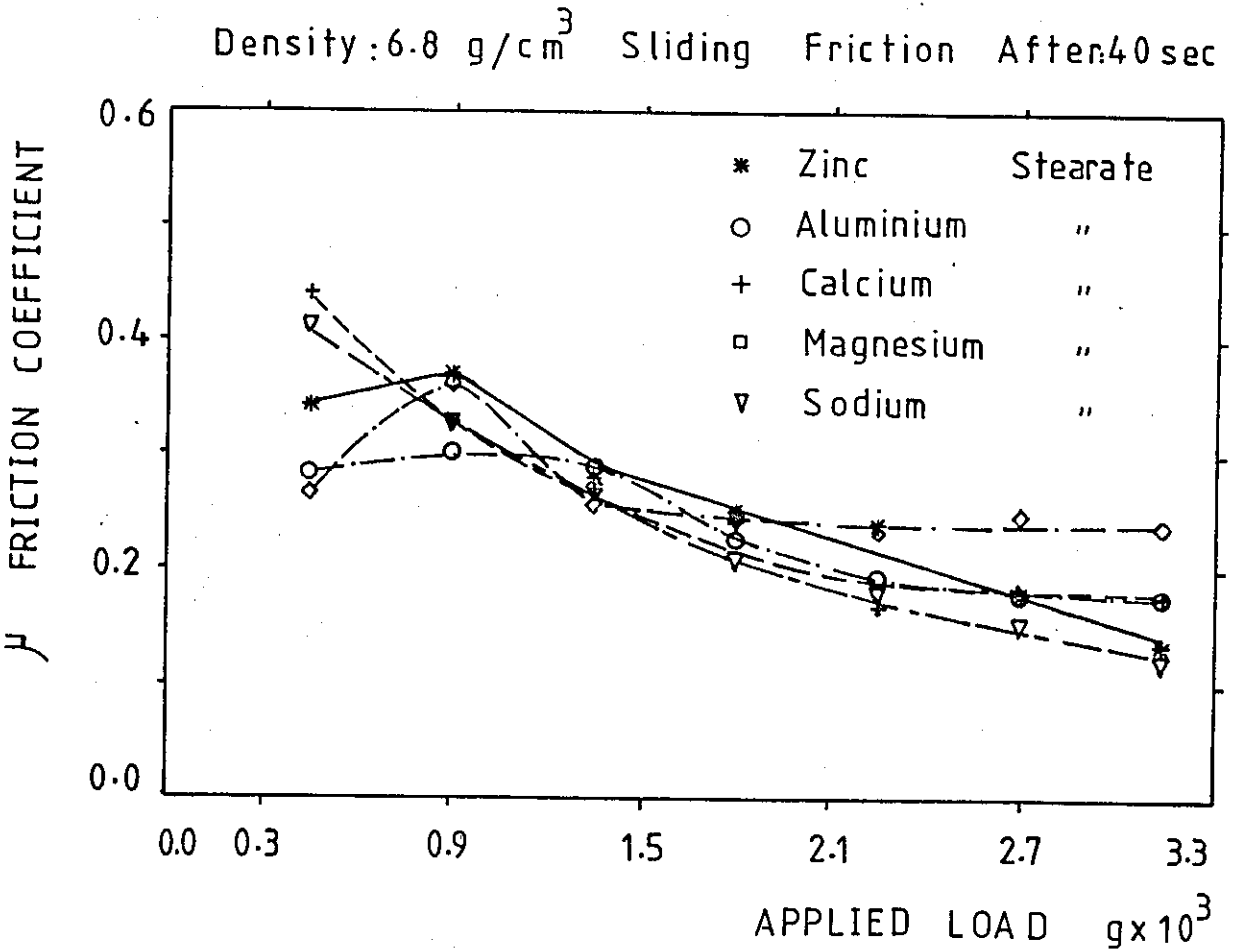

Density : 6.8 g/cm$^3$ Sliding Friction After 40 sec
0.6
0.4
0.2
0.0
μ FRICTION COEFFICIENT
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
✱ Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 129

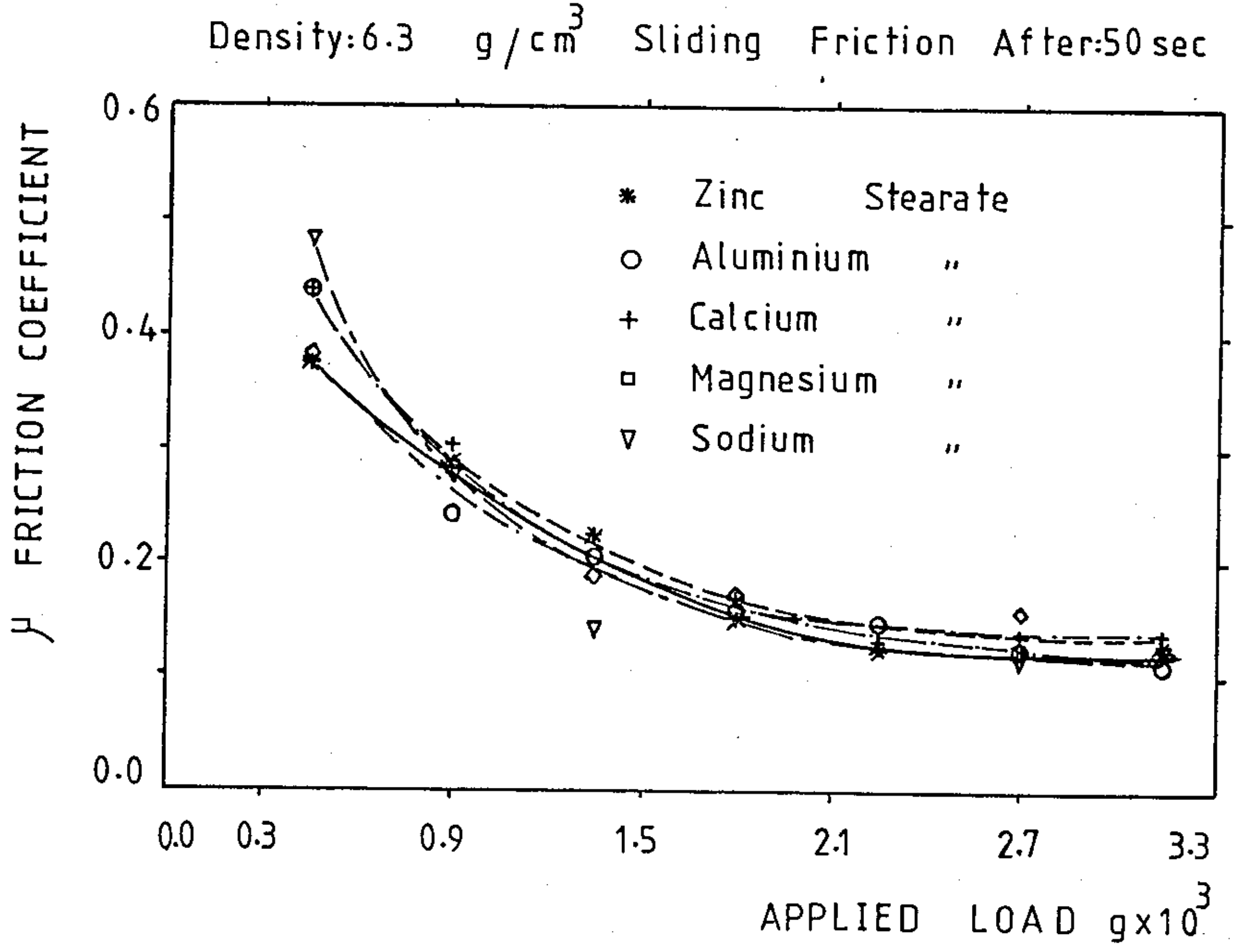

Density: 6.3 g/cm$^3$ Sliding Friction After: 50 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
* Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 130

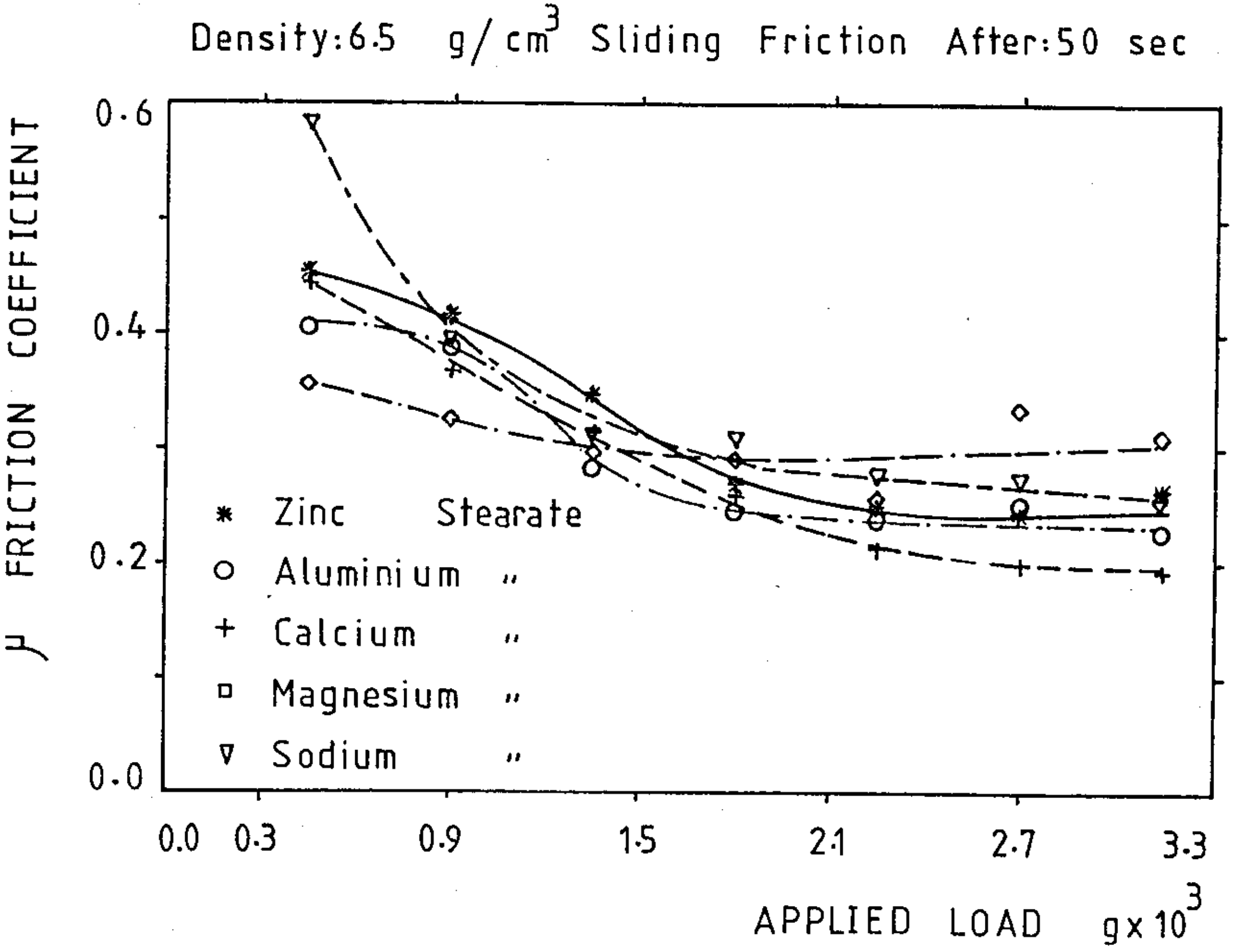

Density:6.5 g/cm$^3$ Sliding Friction After:50 sec
μ FRICTION COEFFICIENT
0·6
0·4
0·2
0·0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
* Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 131

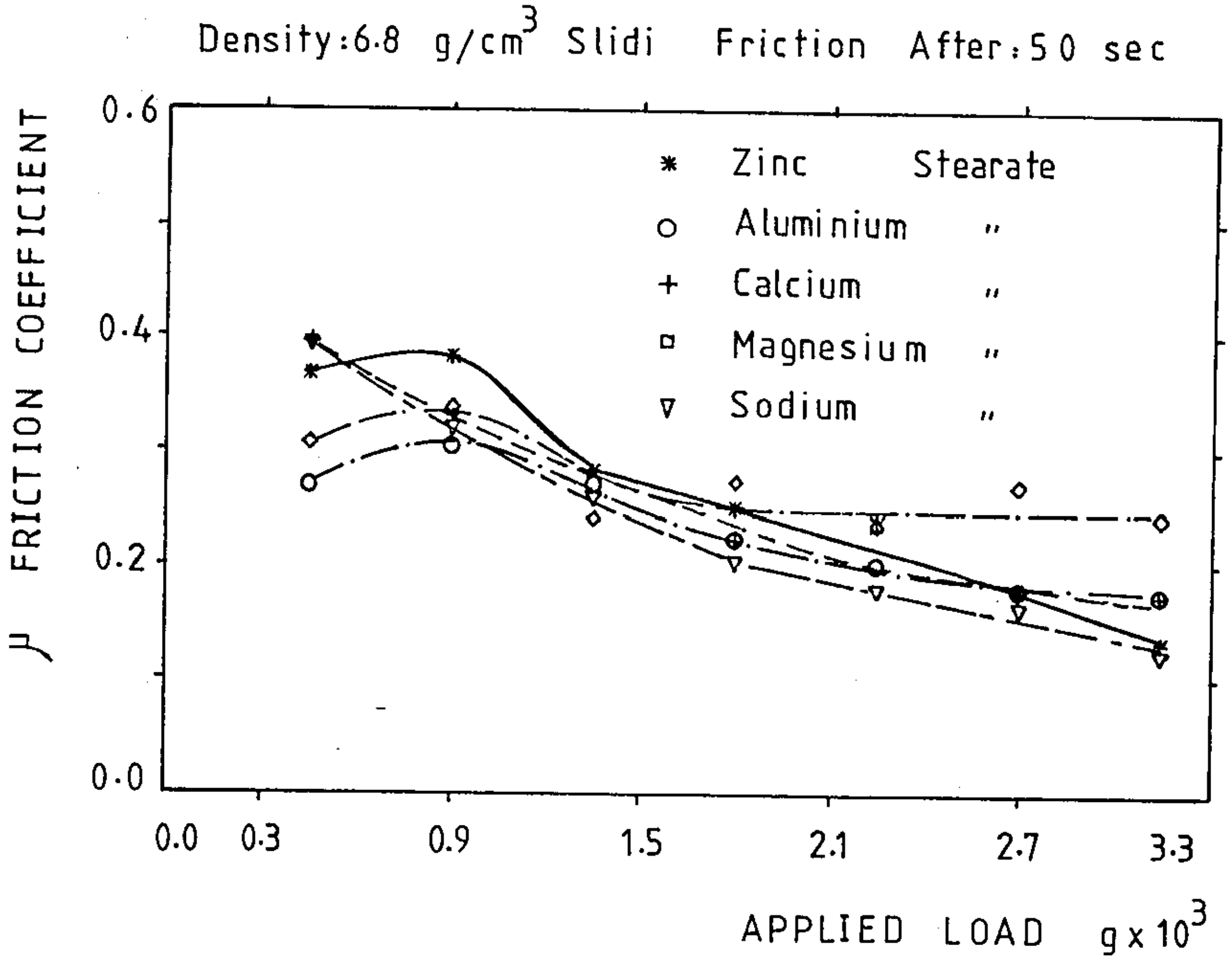

Density:6.8 g/cm3 Slidi Friction After:50 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
* Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
∇ Sodium "
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10^3

Fig. 132

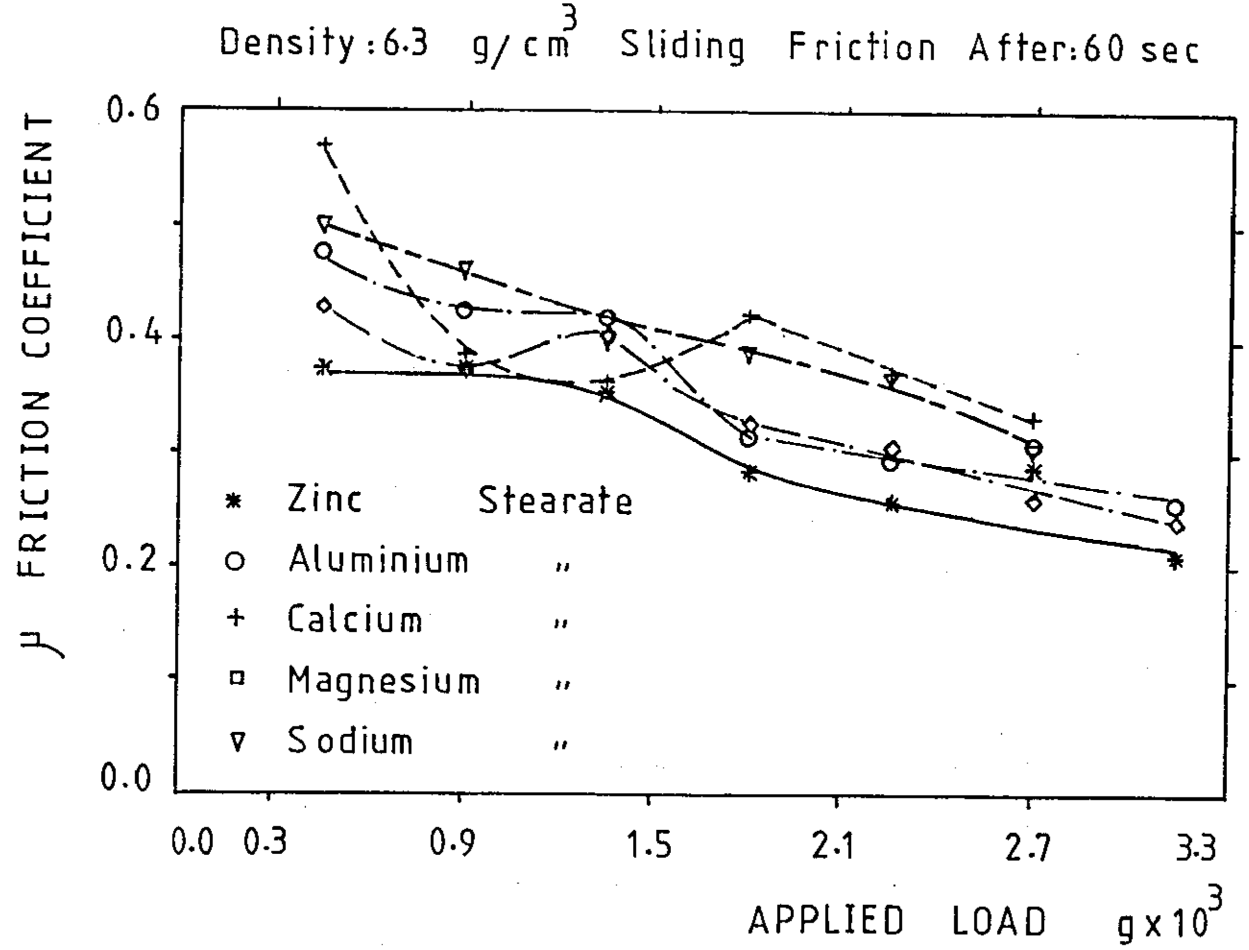
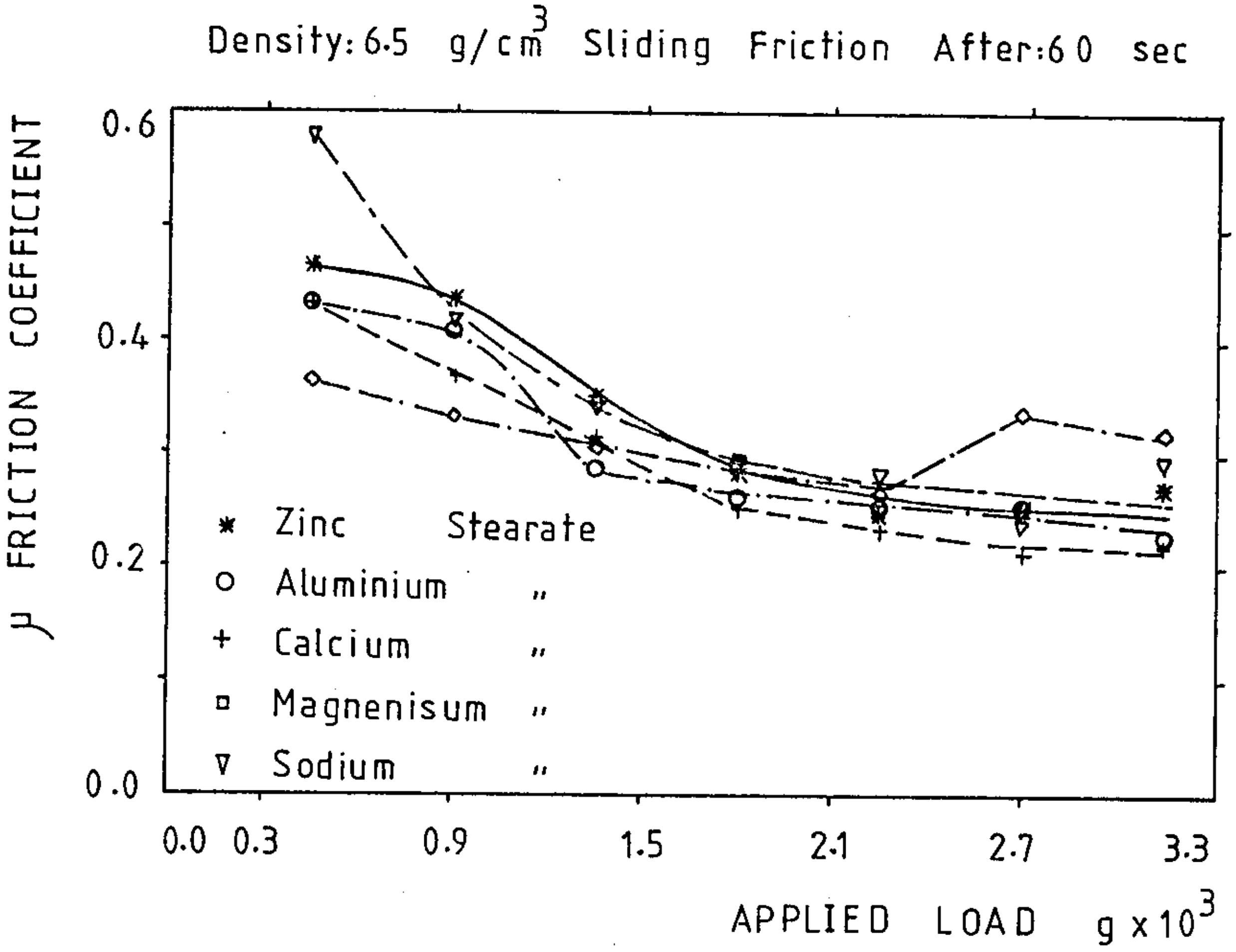

Density: 6.3 g/cm$^3$ Sliding Friction After: 60 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
* Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnesium "
▽ Sodium "

Fig. 133



Density: 6.5 g/cm$^3$ Sliding Friction After: 60 sec
μ FRICTION COEFFICIENT
0.6
0.4
0.2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$
✱ Zinc Stearate
○ Aluminium "
+ Calcium "
□ Magnenisum "
▽ Sodium "

Fig. 134

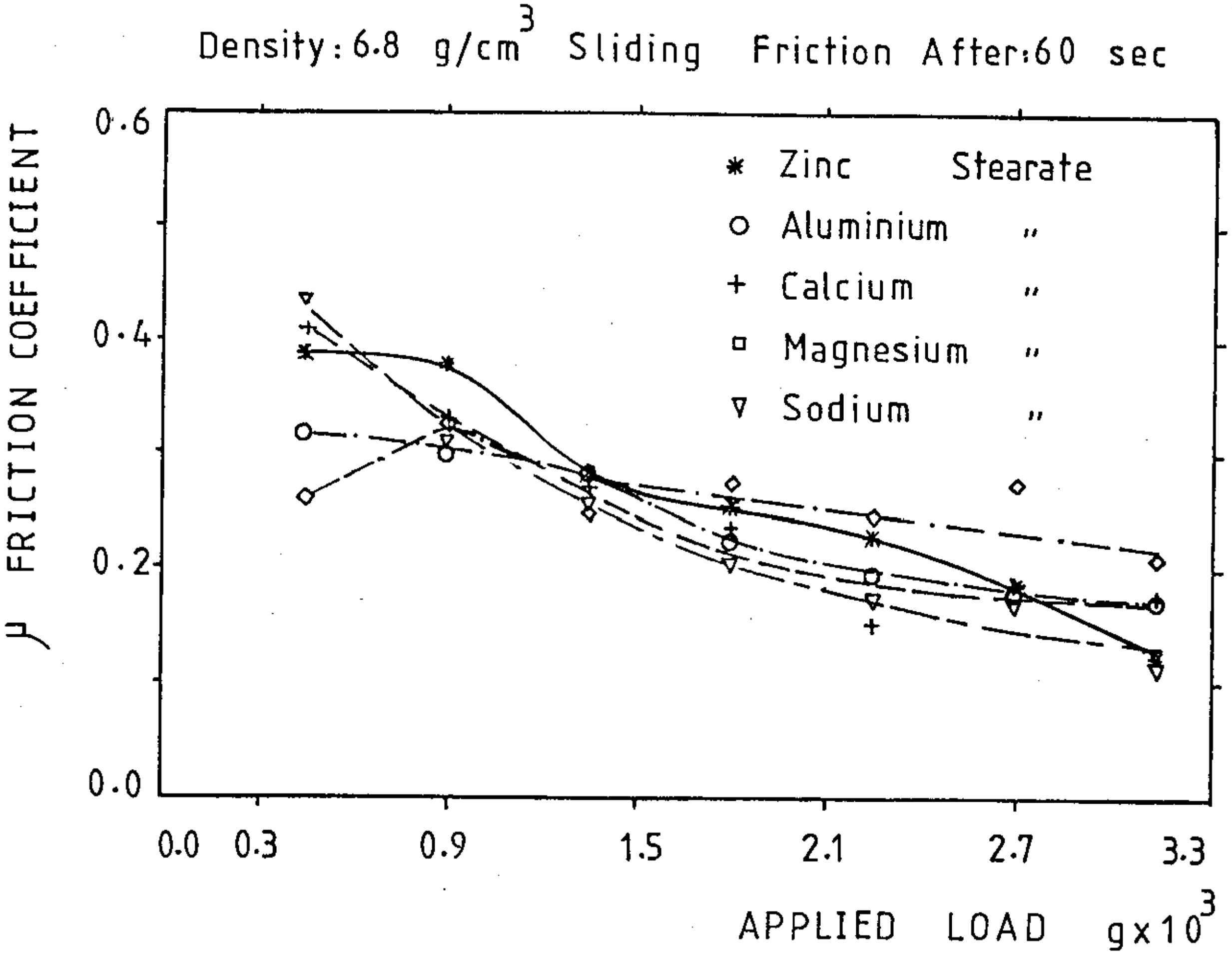

Density: 6.8 g/cm$^3$ Sliding Friction After: 60 sec
✱ Zinc Stearate
○ Aluminium "
+ Calcium "
▫ Magnesium "
▽ Sodium "
$\mu$ FRICTION COEFFICIENT
0·6
0·4
0·2
0.0
0.0
0.3
0.9
1.5
2.1
2.7
3.3
APPLIED LOAD g x 10$^3$

Fig. 135

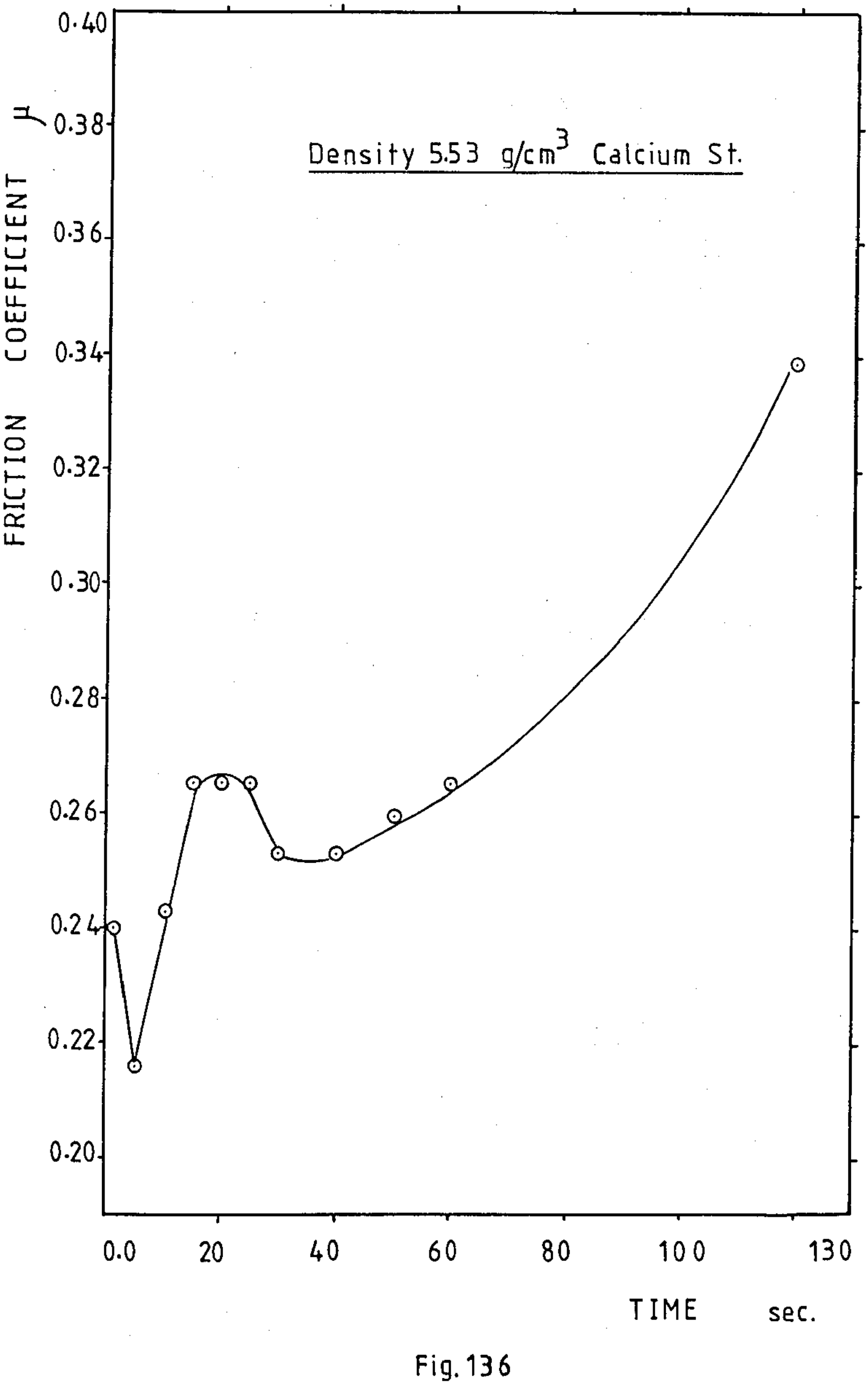

Density 5.53 g/cm$^3$ Calcium St.
FRICTION COEFFICIENT μ
0·40
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.0
20
40
60
80
100
130
TIME sec.

Fig. 136

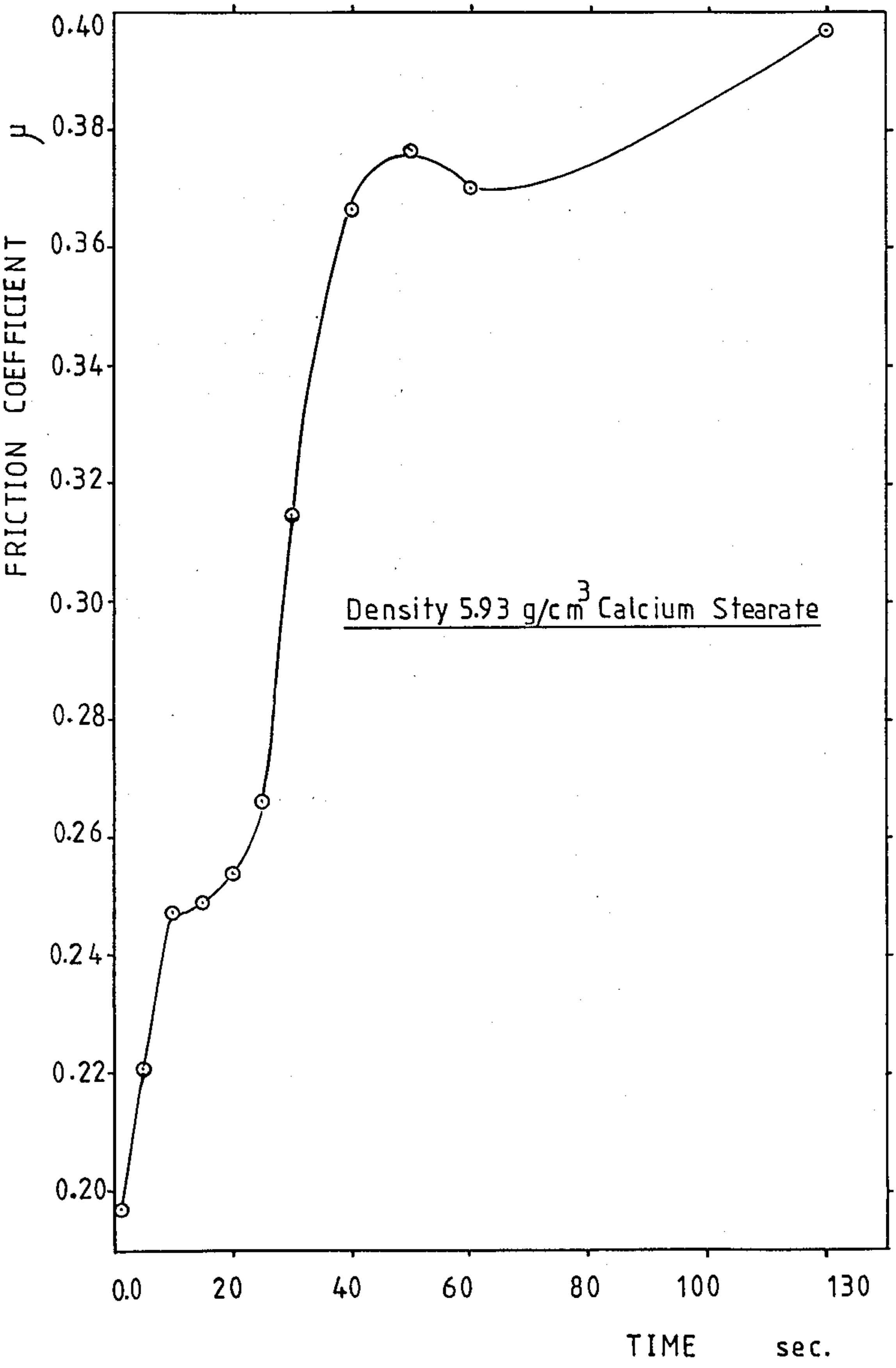

FRICTION COEFFICIENT $\mu$
0.40
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
Density 5.93 g/cm$^3$ Calcium Stearate
0.0
20
40
60
80
100
130
TIME sec.

Fig. 137

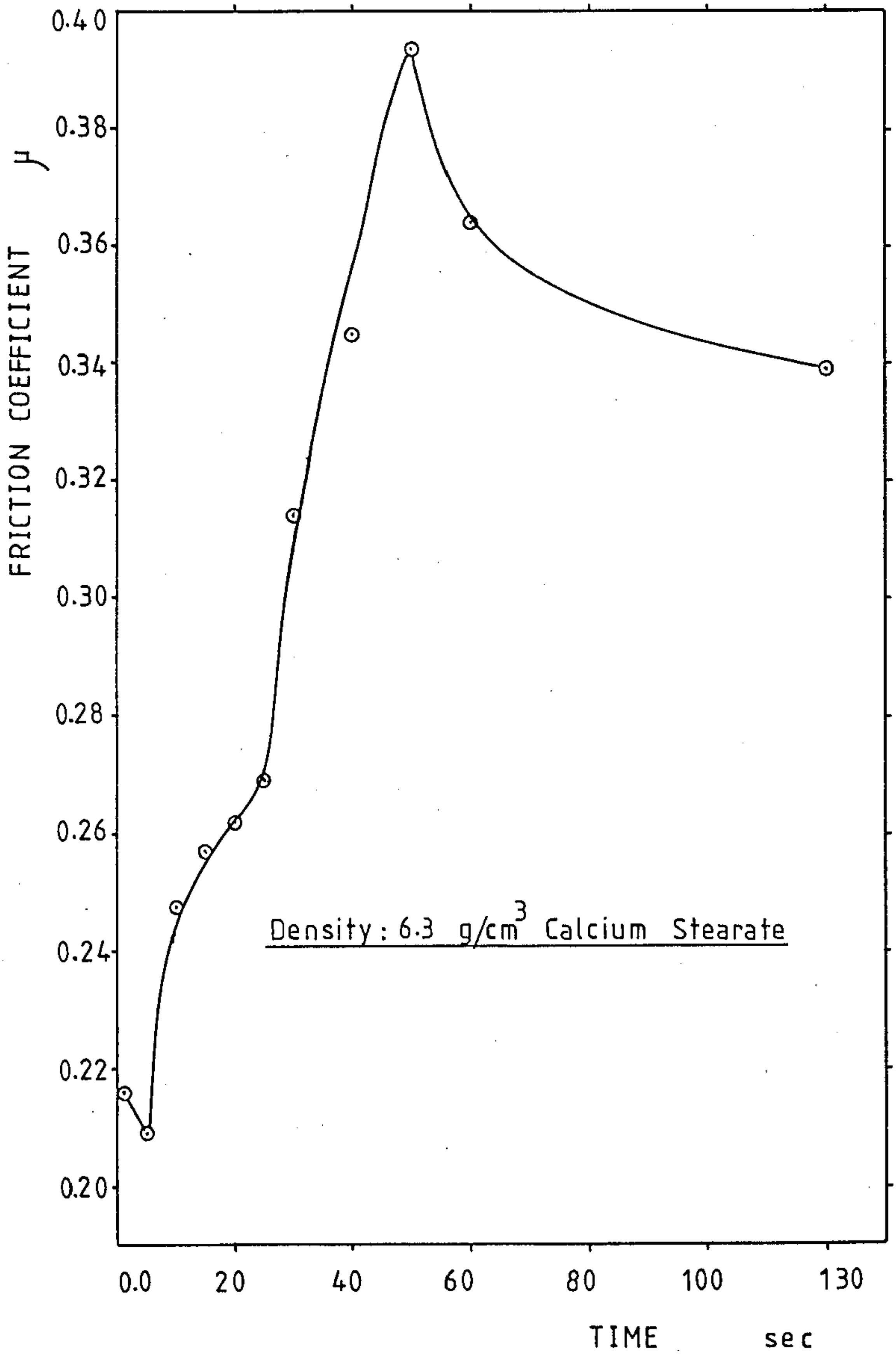

0.40
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
FRICTION COEFFICIENT $\mu$
0.0
20
40
60
80
100
130
TIME sec
Density : 6.3 g/cm$^3$ Calcium Stearate

Fig. 138

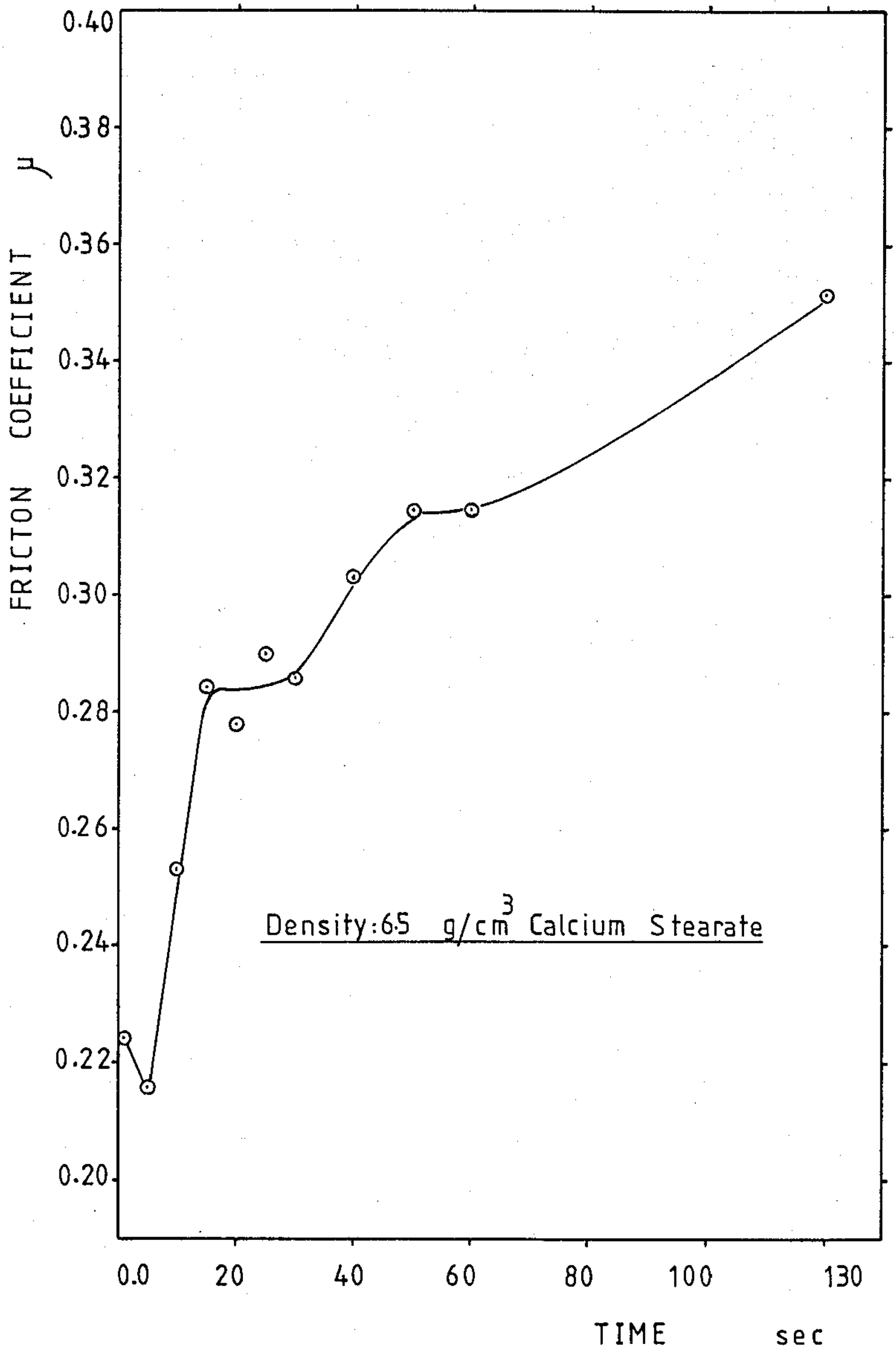

FRICTON COEFFICIENT μ
0.40
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
Density: 6.5 g/cm$^3$ Calcium Stearate
0.0
20
40
60
80
100
130
TIME sec

Fig. 13 9

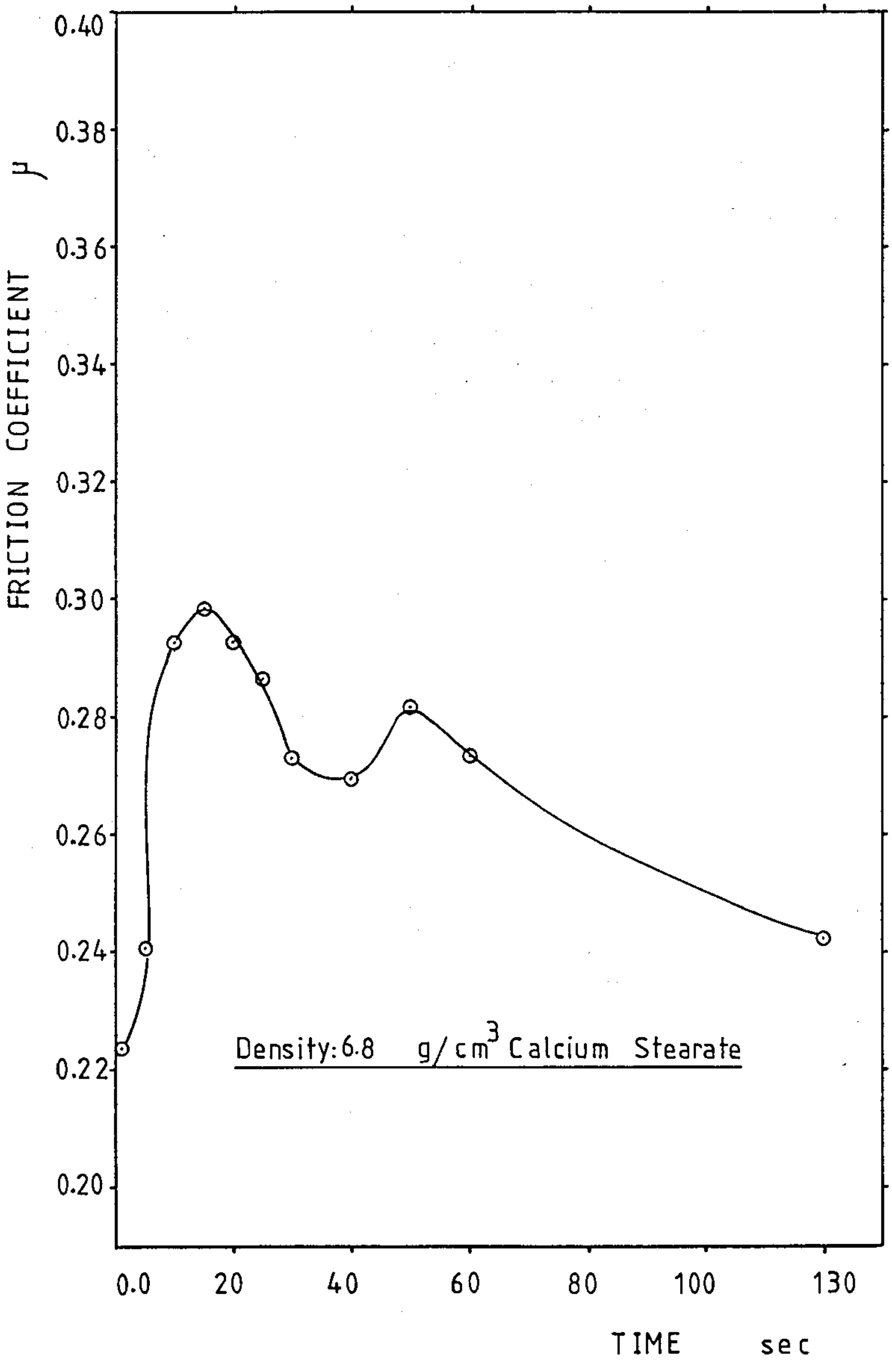

FRICTION COEFFICIENT μ
0.40
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
Density: 6.8 g/cm$^3$ Calcium Stearate
0.0
20
40
60
80
100
130
TIME sec

Fig. 140

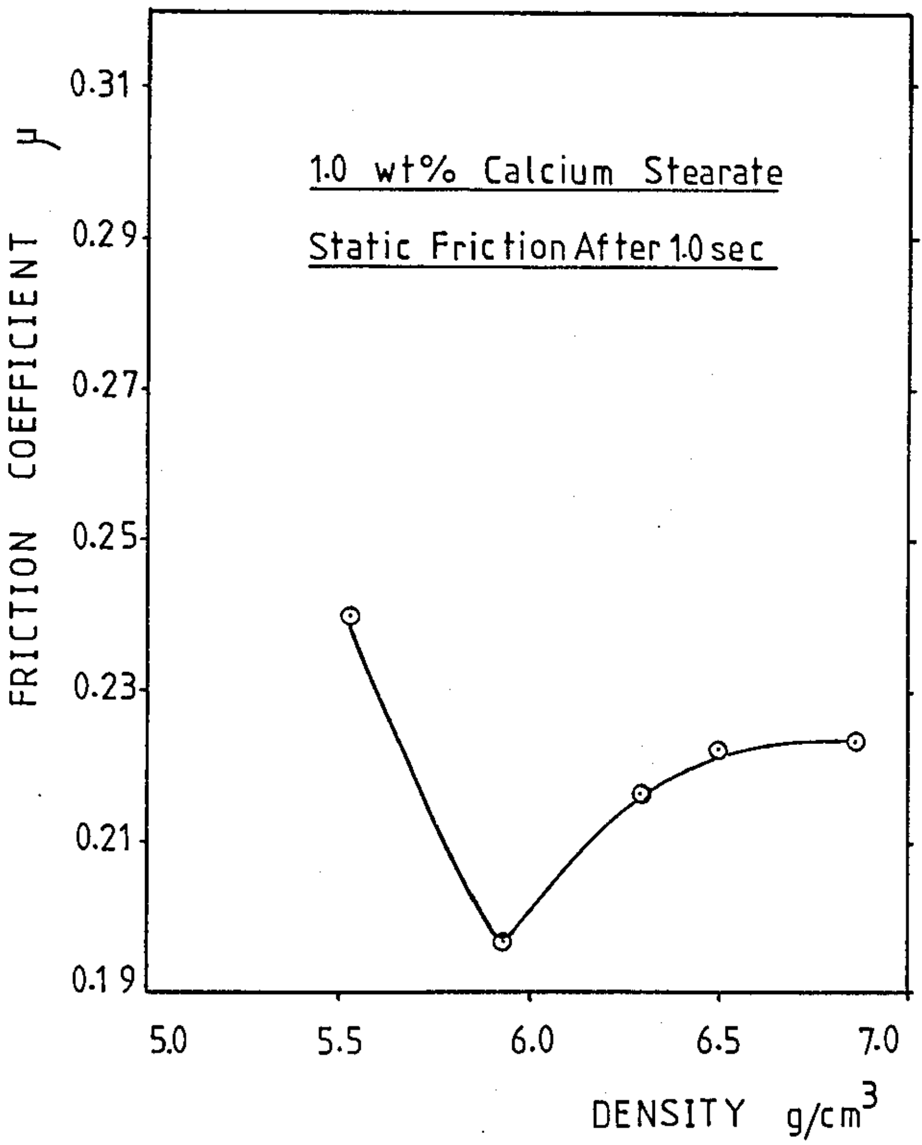

1.0 wt% Calcium Stearate
Static Friction After 1.0 sec
FRICTION COEFFICIENT μ
0.31
0.29
0.27
0.25
0.23
0.21
0.19
5.0
5.5
6.0
6.5
7.0
DENSITY g/cm3

Fig. 141

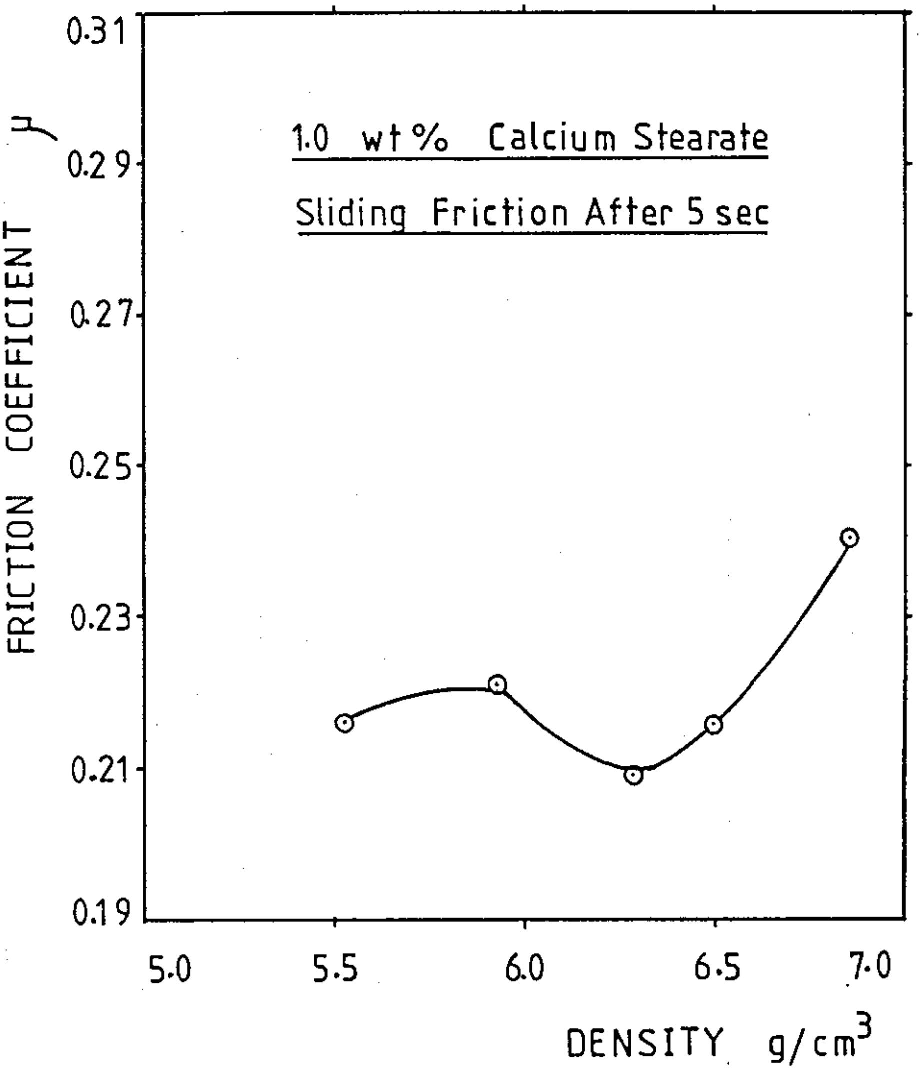

1.0 wt% Calcium Stearate
Sliding Friction After 5 sec
FRICTION COEFFICIENT μ
0.31
0.29
0.27
0.25
0.23
0.21
0.19
5.0
5.5
6.0
6.5
7.0
DENSITY g/cm³

Fig. 142

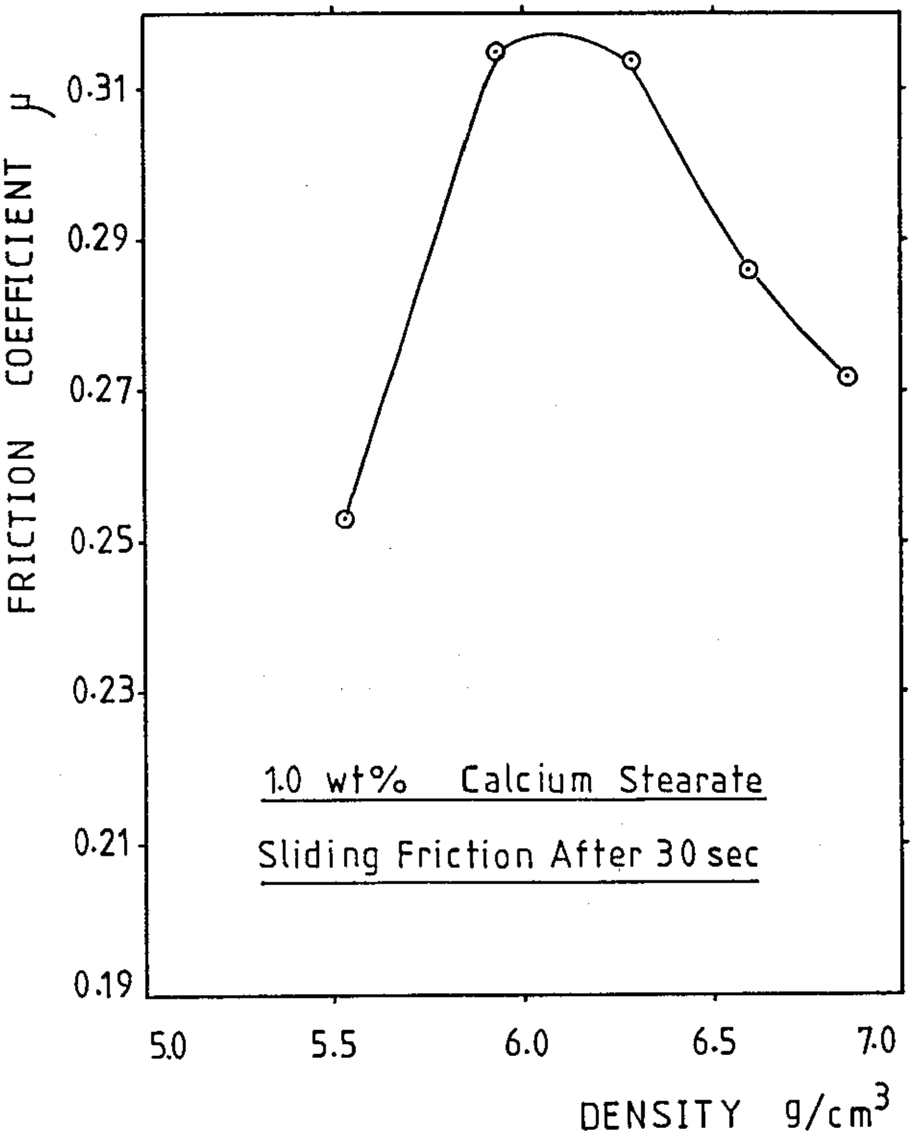

FRICTION COEFFICIENT μ
0.31
0.29
0.27
0.25
0.23
0.21
0.19
5.0
5.5
6.0
6.5
7.0
DENSITY g/cm³
1.0 wt% Calcium Stearate
Sliding Friction After 30 sec

Fig. 143

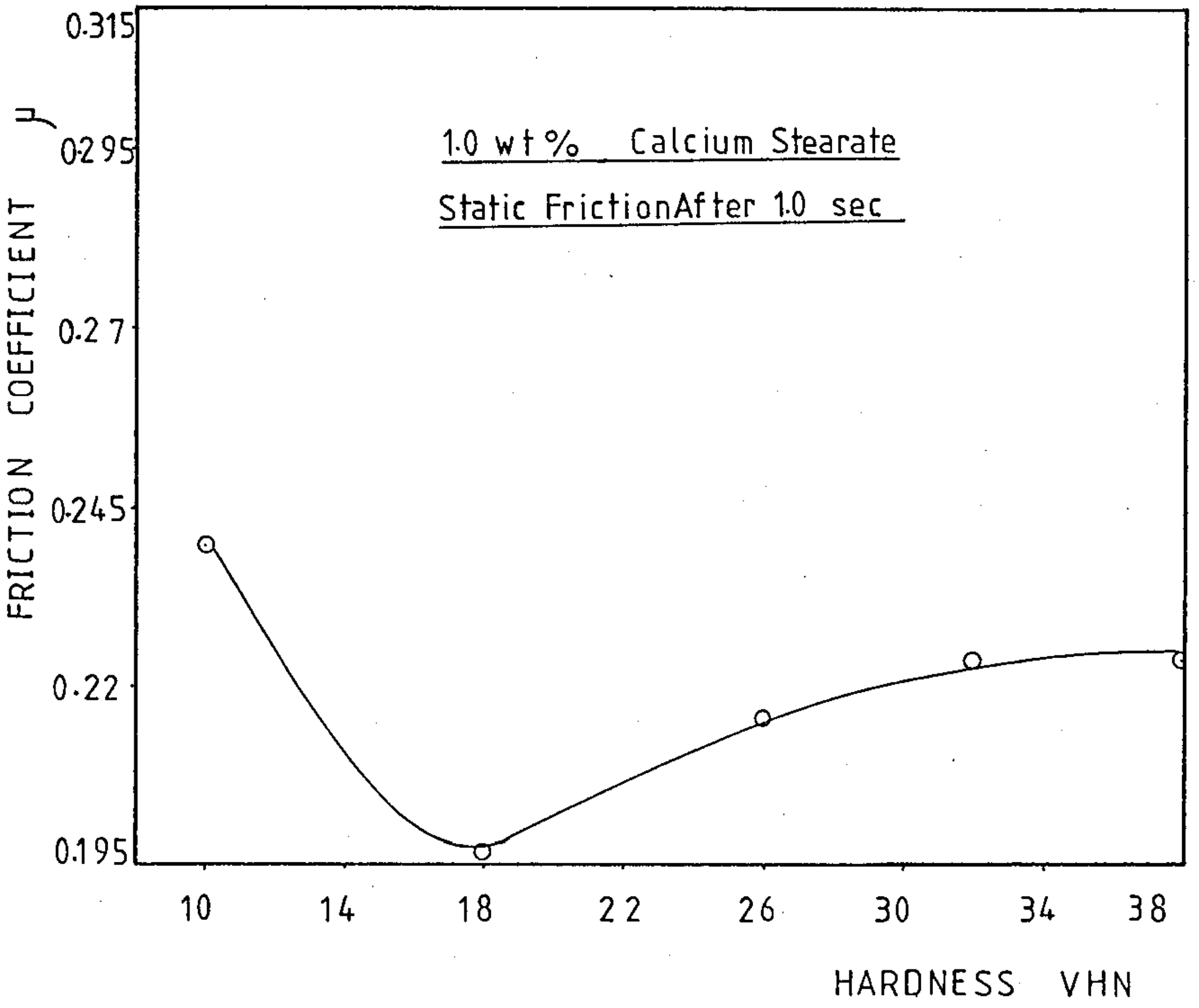

0.315
0.295
0.27
0.245
0.22
0.195
FRICTION COEFFICIENT μ
1.0 wt % Calcium Stearate
Static Friction After 1.0 sec
10
14
18
22
26
30
34
38
HARDNESS VHN

Fig. 144

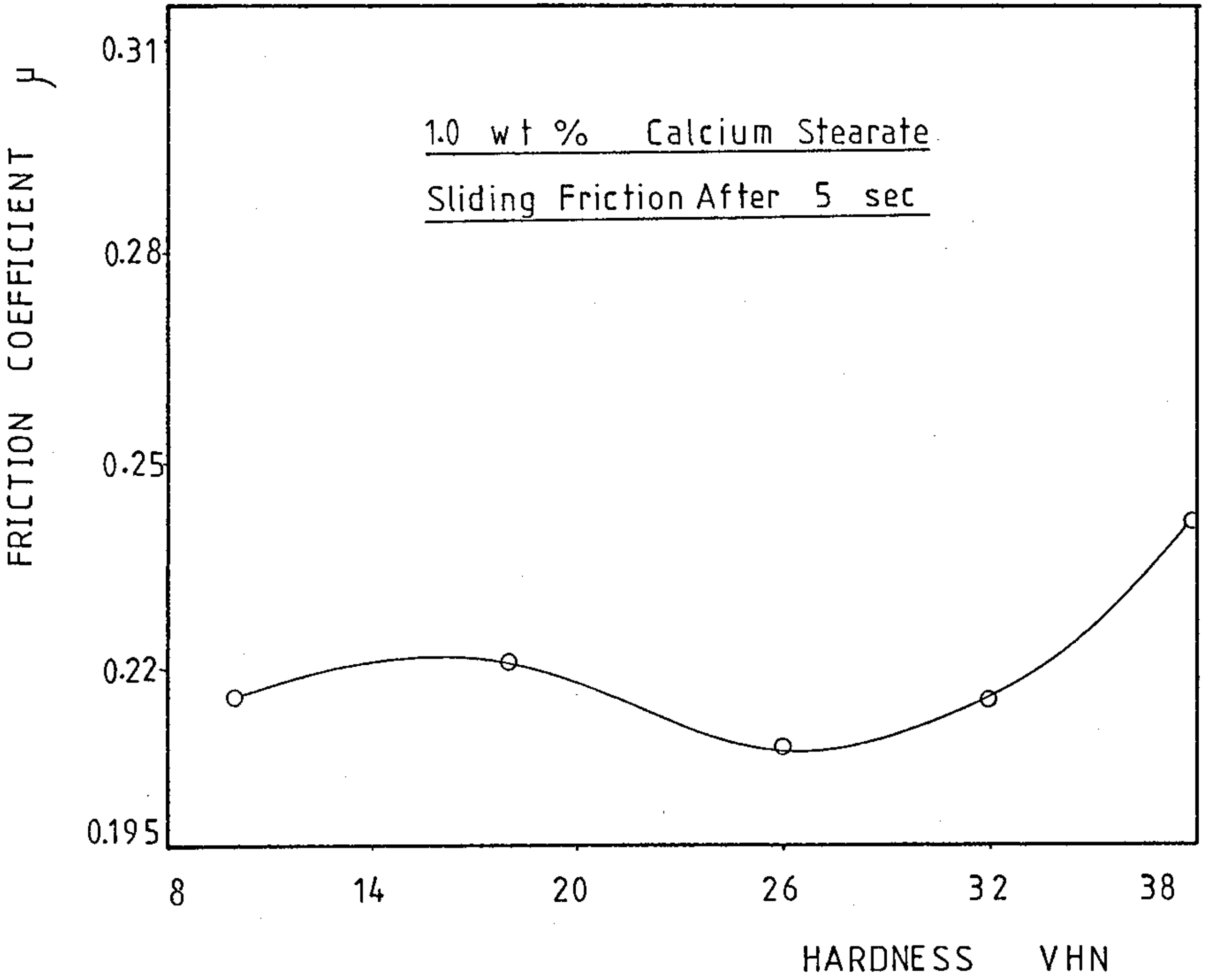

1.0 wt % Calcium Stearate
Sliding Friction After 5 sec
FRICTION COEFFICIENT μ
0.31
0.28
0.25
0.22
0.195
8
14
20
26
32
38
HARDNESS VHN

Fig. 145

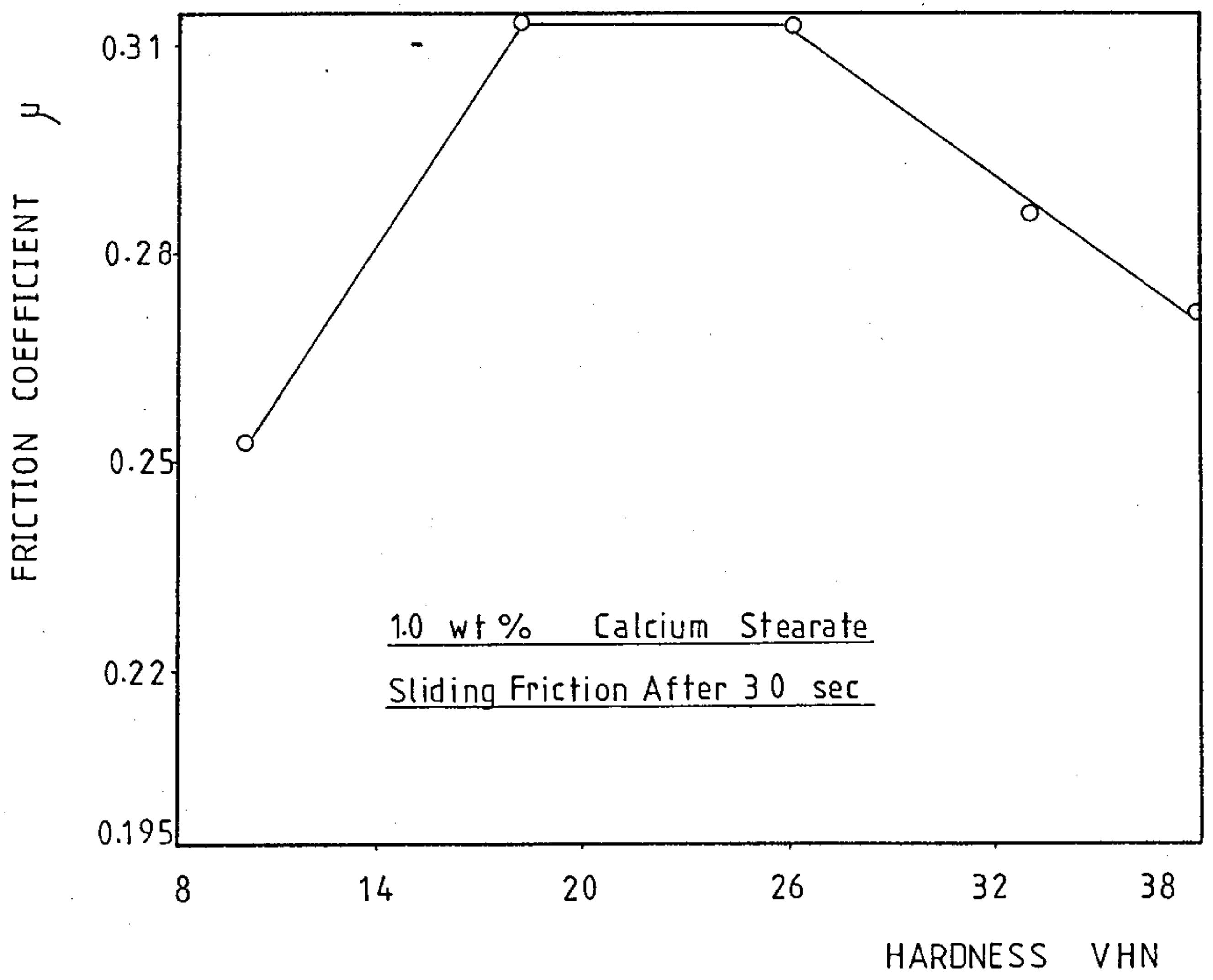

0.31
0.28
0.25
0.22
0.195
FRICTION COEFFICIENT μ
1.0 wt % Calcium Stearate
Sliding Friction After 30 sec
8
14
20
26
32
38
HARDNESS VHN

Fig. 146

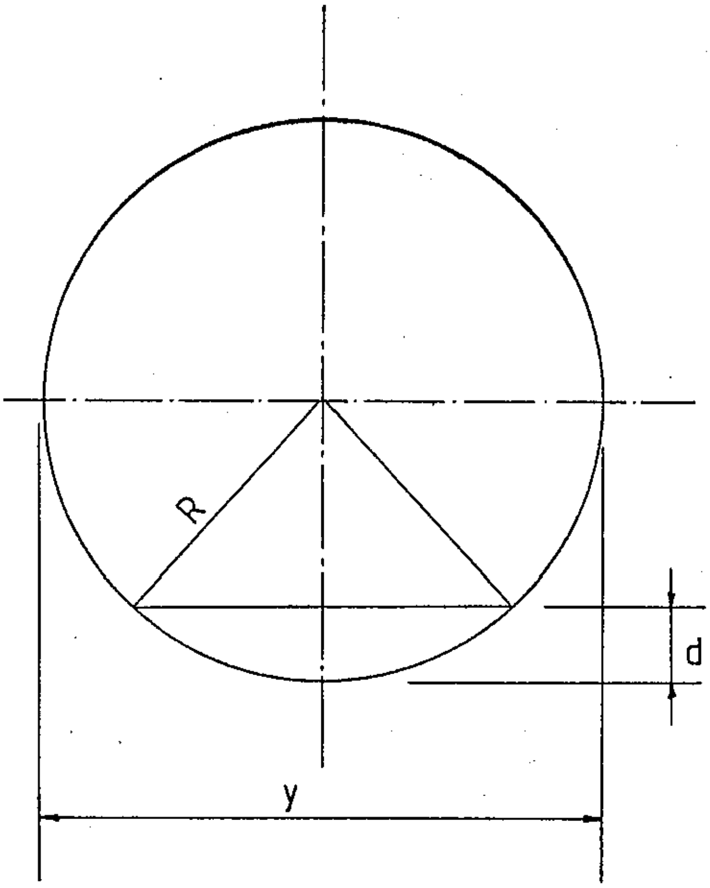


Fig.147

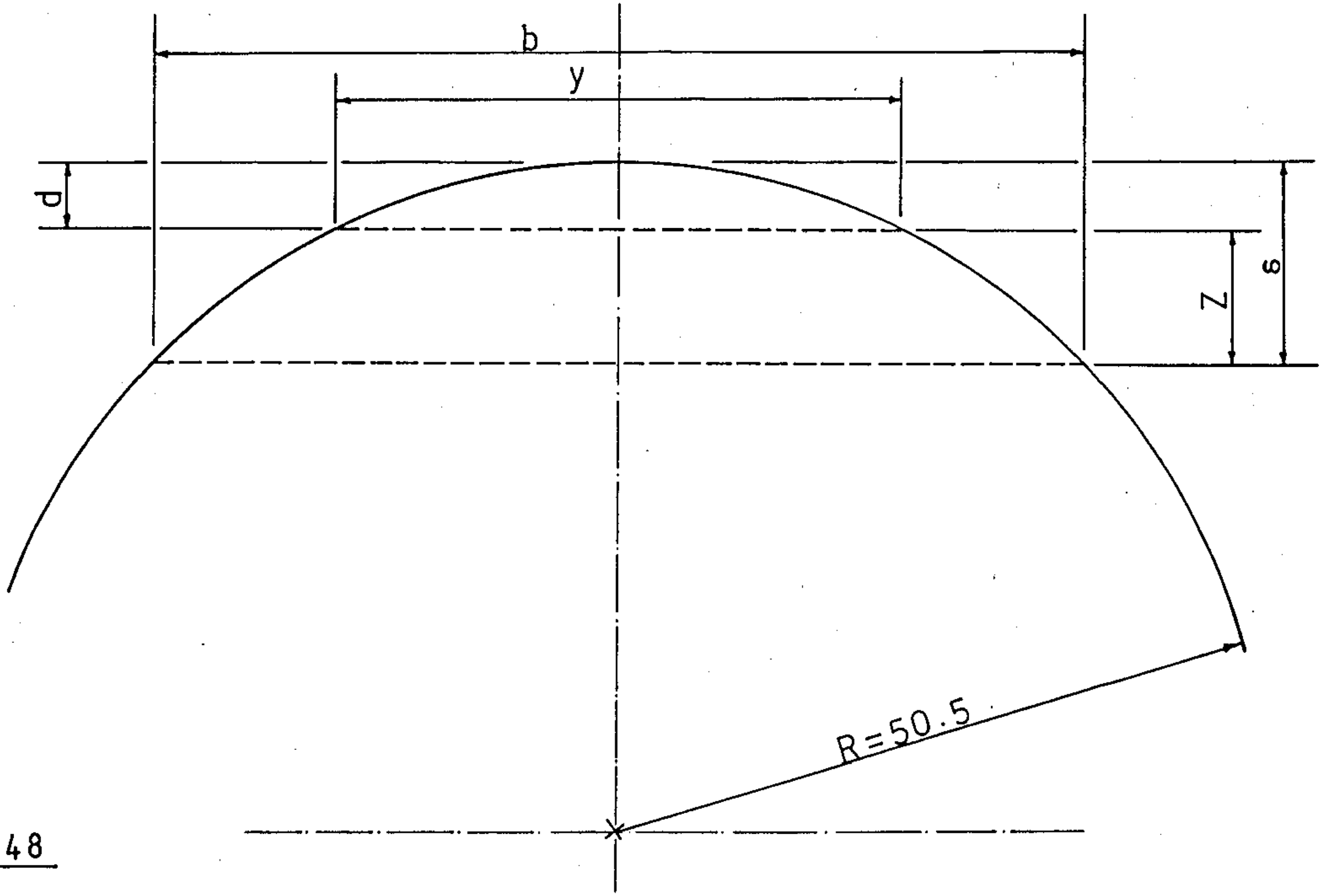


FIG.148

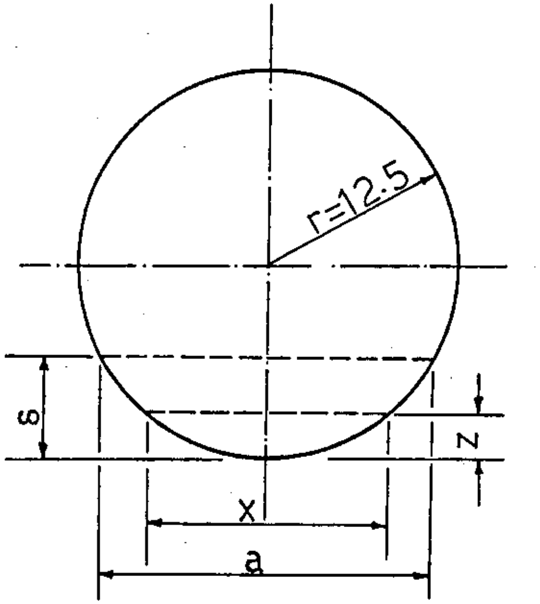


FIG. 149

| TYPES OF LUBRICANT | ZINC STEARATE | | | SODIUM STEARATE | | | MAGNESIUM STEARATE | | | ALUMINIUM STEARATE | | | CALCIUM STEARATE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DENSITY g/cm$^3$ | 6.3 | 6.5 | 6.8 | 6.3 | 6.5 | 6.8 | 6.3 | 6.5 | 6.8 | 6.3 | 6.5 | 6.8 | 5.5 | 5.9 | 6.3 | 6.5 | 6.8 |
| LUBRICANT RATIO wt % | 0.5 | 0.5 | 0.5 | 1.0 | | | 1.0 | | | 1.0 | | | 1.0 | | | | |
| | 1.0 | 1.0 | 1.0 | | | | | | | | | | | | | | |
| | 1.5 | 1.5 | 1.5 | | | | | | | | | | | | | | |

Table 1 . The densities of the compact s which have been used in this research and the types of the lubricants and the ratios of these lubricants which have been used in the wear and friction experiments .

Table 2

COMPARISON BETWEEN THE HOGANAS ASC 100.29 IRON POWDER WHICH USED IN THIS WORK AND SIMILAR IRON POWDERS .

| TYPE OF IRON POWDER | METHOD OF MANUFACTURING | APPARENT DENSITY g / $cm^3$ | TAPPED DENSITY g / cm3 | FLOW RATE sec /50 g | SURFACE AREA $cm^2/g$ |
|---|---|---|---|---|---|
| HOGANAS ASC 100.29 | ATOMISED | 3.035 | 4.06 | 34.8 | 212 |
| HOGANAS SC 100.29 | SPONGE | 2.636 | 3.72 | 40.4 | 207 |
| MANNSMANN WPL 200 | ATOMISED | 2.508 | 3.40 | 45.6 | 207 |
| MAKINS 100 PI | REDUCED | 2.413 | 3.28 | 46.0 | 332 |

PROPERTIES OF SOME IRON POWDERS

Table 3 PROPERTIES OF STEARATE LUBRICANTS

| LUBRICANT TYPE | LUBRICANT RATIO wt % | | | MOISTURE | FINES % | BULK VOLUME cc / gm | FREE FATTY ACID % | ASH % | WATER SOLUBLE MATTER |
|---|---|---|---|---|---|---|---|---|---|
| ZINC STEARATE PRECIPITATED | 1.5 | 1.0 | 0.5 | 0.7 | $\frac{99.5}{300}$ | 5.5 | 0.8 | 14.5 | 0.4 |
| CALCIUM STEARATE PRECIPITATED | 1.0 | | | 2.3 | $\frac{99.8}{300}$ | 5.5 | 0.3 | 9.6 | 0.9 |
| Mg STEARATE PRECIPITATED | 1.0 | | | 3.5 | $\frac{99.8}{300}$ | 5.0 | 0.7 | 8.4 | 0.7 |
| Al STEARATE 22 | 1.0 | | | 1.2 | $\frac{98}{200}$ | 4.0 | 3.8 | 10.7 | 1.0 |
| SODIUM STEARATE FUSED | 1.0 | | | 3.0 | $\frac{94}{100}$ | 2.5 | 0.5 | 10.0 | --- |

Table 4

| Axial Readings | Lubricant Type :Zinc Stearate ,Lub.Ratio:0.5 wt%, Density: 6.3 g/cm$^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance ( mm.) | 1.0 | 1.75 | 2.5 | 3.25 | 4.0 | 4.75 | 5.5 | 6.25 | 7.0 | 7.750 |
| Hardness ( VHN ) | 25.27 | 27.22 | 28.83 | 27.8 | 26.27 | 26.38 | 27.27 | 26.4 | 25.38 | 23.78 |

Table 5

| Axial Readings | Lubricant Type: Zinc Stearate ,Lub.Ratio:0.5 wt%, Density: 6.5 g/cm$^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance ( mm.) | 1.0 | 1.75 | 2.5 | 3.25 | 4.0 | 4.75 | 5.5 | 6.25 | 7.0 | 7.75 |
| Hardness ( VHN ) | 32.45 | 35.32 | 36.82 | 33.88 | 31.52 | 33.2 | 34.67 | 35.43 | 35.12 | 32.95 |

Table 6

| Axial Readings | Lubricant Type: Zinc Stearate ,Lub.Ratio:0.5 wt%, Density: 6.8 g/cm$^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance ( mm.) | 1.0 | 1.75 | 2.5 | 3.25 | 4.0 | 4.75 | 5.5 | 6.25 | 7.0 | 7.75 |
| Hardness ( VHN ) | 45.57 | 46.95 | 44.23 | 42.03 | 38.4 | 41.42 | 43.53 | 47.10 | 48.62 | 43.57 |

Table 7

| Axial Readings | Lubricant Type: Zinc Stearate ,Lub.Ratio:1.0 wt %,Density: 6.3 g/cm$^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance ( mm.) | 1.0 | 1.75 | 2.5 | 3.25 | 4.0 | 4.75 | 5.5 | 6.25 | 7.0 | 7.75 |
| Hardness ( VHN ) | 23.88 | 26.37 | 28.72 | 27.78 | 26.12 | 24.88 | 26.88 | 26.13 | 25.23 | 22.92 |

Table 8

| Axial Readings | Lubricant Type: Zinc Stearate , Lub.Ratio: 1.0 wt% ,Dens.:6.5 g/cm$^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance ( mm.) | 1.0 | 1.75 | 2.50 | 3.25 | 4.0 | 4.75 | 5.50 | 6.25 | 7.0 | 7.75 |
| Hardness ( VHN ) | 30.27 | 33.52 | 34.62 | 34.98 | 31.93 | 33.22 | 34.9 | 35.65 | 34.8 | 29.83 |

Table 9

| Axial Readings | Lubricant Type:Zinc Stearate ,Lub.Ratio: 1.0 wt% ,Density: 6.8 g/cm$^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance ( mm.) | 1.0 | 1.75 | 2.5 | 3.25 | 4.0 | 4.75 | 5.5 | 6.25 | 7.0 | 7.75 |
| Hardness ( VHN ) | 35.13 | 39.77 | 40.2 | 40.23 | 35.03 | 37.83 | 40.82 | 40.85 | 38.43 | 34.23 |

Table 10

| Axial Readings | Lubricant Type:Zinc Stearate, Lub.Ratio:1.5 wt % , Density:6.3 g/cm$^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance ( mm.) | 1.0 | 1.75 | 2.5 | 3.25 | 4.0 | 4.75 | 5.5 | 6.25 | 7.0 | 7.75 |
| Hardness ( VHN ) | 20.63 | 22.68 | 23.68 | 23.52 | 22.93 | 24.63 | 25.02 | 24.58 | 23.75 | 20.63 |

Table 11

| Axial Readings | Lubricant Type:Zinc Stearate,Lub.Ratio: 1.5 wt % , Density:6.5 g/cm$^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance (mm.) | 1.0 | 1.75 | 2.5 | 3.25 | 4.0 | 4.75 | 5.5 | 6.25 | 7.0 | 7.75 |
| Hardness ( VHN ) | 25.80 | 30.92 | 32.62 | 32.55 | 30.6 | 29.83 | 31.08 | 31.8 | 30.03 | 26.32 |

Table 12

| Axial Readings | Lubricant Type:Zinc Stearate,Lub.Ratio: 1.5 wt % ,Density:6.8 $g/cm^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance ( mm.) | 1.0 | 1.75 | 2.5 | 3.25 | 4.0 | 4.75 | 5.5 | 6.25 | 7.0 | 7.75 |
| Hardness ( VHN ) | 32.96 | 35.17 | 33.27 | 31.68 | 30.97 | 35.72 | 35.57 | 35.98 | 34.57 | 32.77 |

Table 13

| Diametrical Readings | Lubricant Type : Zinc Stearate , Lubricant Ratio : 0.5 wt % , Density : 6.3 g / cm$^3$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reads.Number | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 30.0 |
| Reading Distance mm. | 1.83 | 2.95 | 4.68 | 5.2 | 6.33 | 7.45 | 8.78 | 9.7 | 10.82 | 11.95 | 13.08 | 14.20 | 15.33 | 16.45 | 17.58 | 18.70 | 19.83 | 20.95 | 20.08 | 23.2 | | | | | | | | | | |
| Hardness (VHN) | 30.10 | 31.92 | 32.27 | 32.27 | 32.63 | 33.280 | 33.13 | 32.03 | 32.98 | 32.53 | 32.3 | 32.93 | 33.1 | 34.12 | 34.07 | 33.77 | 33.43 | 33.23 | 31.67 | 30.58 | | | | | | | | | | |

Table 14

| Diametrical Readings | Lubricant Type : Zinc Stearate , Lubricant Ratio : 0.50 wt % , Density : 6.5 g /cm$^3$ | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Read.Number | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 |
| Reading Distance( mm) | 1.25 | 2.0 | 2.750 | 3.5 | 4.250 | 5.0 | 5.75 | 6.5 | 7.250 | 8.0 | 8.75 | 9.5 | 10.25 | 11.0 |
| Hardness (VHN) | 41.617 | 43.550 | 42.83 | 43.62 | 43.10 | 43.07 | 42.14 | 42.25 | 41.87 | 42.53 | 43.33 | 42.72 | 43.67 | 43.45 |

| Read.Number | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 30.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance( mm) | 11.75 | 12.50 | 13.25 | 14.00 | 14.75 | 15.5 | 16.25 | 17.0 | 17.75 | 18.5 | 19.25 | 20.0 | 20.75 | 21.50 | 22.25 | 23.0 |
| Hardness (VHN) | 43.45 | 44.02 | 44.43 | 43.43 | 44.7 | 44.6 | 44.32 | 43.43 | 43.30 | 43.12 | 43.4 | 42.10 | 42.12 | 42.98 | 44.10 | 41.7 |

Table 15

| Diametrical Readings | Lubricant Type : Zinc Stearate , Lubricant Ratio : 0.5 wt % , Density : 6.8 g / cm$^3$ | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reads.Number | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 |
| Reading Distance mm. | 1.25 | 2.0 | 2.75 | 3.5 | 4.25 | 5.0 | 5.75 | 6.5 | 7.25 | 8.0 | 8.75 | 9.5 | 10.25 | 11.0 |
| Hardness (VHN) | 52.820 | 53.930 | 53.867 | 53.650 | 52.9 | 51.63 | 52.60 | 52.35 | 52.53 | 53.23 | 53.68 | 53.2 | 50.8 | 52.43 |

| Reads.Number | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 30.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance mm. | 11.75 | 12.50 | 13.25 | 14.0 | 14.75 | 15.5 | 16.25 | 17.0 | 17.75 | 18.50 | 19.25 | 20.0 | 20.75 | 21.50 | 22.25 | 23.0 |
| Hardness (VHN) | 51.12 | 51.82 | 51.22 | 51.63 | 51.08 | 51.33 | 49.97 | 49.97 | 50.95 | 50.7 | 50.85 | 52.30 | 52.1 | 51.37 | 50.78 | 50.23 |

Table 16

| Diametrical Readings | Lubricant Type : Zinc Stearate , Lubricant Ratio : 1.0 wt % , Density : 6.3 g/ cm$^3$ | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reads.Number | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 |
| Reading Distance mm. | 1.824 | 2.95 | 4.075 | 5.20 | 6.33 | 7.45 | 8.58 | 9.70 | 10.83 | 11.95 | 13.075 | 14.2 | 15.325 | 16.45 |
| Hardness (VHN) | 27.25 | 29.53 | 30.28 | 30.97 | 31.13 | 32.13 | 31.48 | 31.38 | 30.88 | 30.37 | 30.72 | 31.2 | 31.58 | 31.85 |

| Reads.Number | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 30.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance mm. | 17.58 | 18.70 | 19.83 | 20.95 | 22.08 | 23.20 | | | | | | | | | | |
| Hardness (VHN) | 32.30 | 32.08 | 31.68 | 31.35 | 30.63 | 28.93 | | | | | | | | | | |

Table 17

| Diametrical Readings | Lubricant Type : Zinc Stearate , Lubricant Ratio : 1.0 wt % , Density : 6.5 g / cm$^3$ | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reads.Number | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 |
| Reading Distance mm. | 1.25 | 2.0 | 2.75 | 3.5 | 4.25 | 5.00 | 5.75 | 6.5 | 7.250 | 8.00 | 8.75 | 9.5 | 10.25 | 11.0 |
| Hardness (VHN) | 23.68 | 37.58 | 39.43 | 41.75 | 42.15 | 42.22 | 42.87 | 42.9 | 41.8 | 41.02 | 40.37 | 39.88 | 39.23 | 38.67 |

| Reads.Number | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 30.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance mm. | 11.75 | 12.5 | 13.25 | 14.0 | 14.75 | 15.5 | 16.25 | 17.0 | 17.75 | 18.50 | 19.25 | 20.0 | 20.75 | 21.50 | 22.25 | 23.0 |
| Hardness (VHN) | 38.1 | 38.18 | 38.78 | 39.47 | 40.12 | 40.55 | 41.47 | 41.52 | 40.73 | 40.27 | 39.97 | 39.42 | 38.85 | 38.63 | 38.08 | 35.68 |

Table 18

| Diametrical Reading | Lubricant Type : Zinc Stearate , Lubricant Ratio : 1.0 wt % , Density : 6.8 g / cm$^3$ | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reads.Number | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 |
| Reading Distance mm. | 1.25 | 2.0 | 2.75 | 3.5 | 4.25 | 5.0 | 5.75 | 6.5 | 7.25 | 8.0 | 8.75 | 9.50 | 10.25 | 11.0 |
| Hardness (VHN.) | 44.72 | 46.98 | 47.77 | 48.83 | 49.48 | 49.2 | 50.82 | 51.17 | 51.0 | 49.67 | 48.82 | 47.23 | 46.95 | 46.28 |

| Reads.Number | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 30.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance mm. | 11.75 | 12.5 | 13.25 | 14.0 | 14.75 | 15.5 | 16.25 | 17.0 | 17.75 | 18.5 | 19.25 | 20.0 | 20.75 | 21.50 | 22.25 | 23.0 |
| Hardness (VHN.) | 45.33 | 46.62 | 47.78 | 48.78 | 48.35 | 48.47 | 48.37 | 48.02 | 48.55 | 47.9 | 46.47 | 46.32 | 46.15 | 45.23 | 44.42 | 42.83 |

Table 19

| Diametrical Reading | Lubricant Type : Zinc Stearate , Lubricant Ratio : 1.5 wt % , Density : 6.3 g / $cm^3$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reads.Number | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 30.0 |
| Reading Distance mm. | 1.25 | 2.0 | 2.75 | 3.5 | 4.25 | 5.0 | 5.75 | 6.5 | 7.25 | 8.0 | 8.75 | 9.5 | 10.25 | 11.0 | 11.75 | 12.5 | 13.25 | 14.0 | 14.75 | 15.5 | 16.25 | 17.0 | 17.75 | 18.5 | 19.25 | 20.0 | 20.75 | 21.5 | 22.25 | 23.0 |
| Hardness (VHN) | 30.25 | 30.88 | 31.3 | 32.0 | 32.7 | 33.12 | 33.05 | 32.7 | 32.15 | 31.28 | 30.95 | 30.55 | 30.18 | 29.83 | 29.12 | 29.73 | 30.35 | 30.43 | 30.93 | 31.4 | 30.22 | 32.17 | 32.42 | 31.8 | 31.10 | 31.07 | 30.73 | 30.33 | 29.75 | 28.67 |

Table 20

| Diametrical Reading | Lubricant Type : Zinc Stearate , Lubricant Ratio : 1.5 wt % , Density : 6.5 g / cm$^3$ | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reads.Number | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 |
| Reading Distance mm. | 1.25 | 2.0 | 2.75 | 3.5 | 4.25 | 5.0 | 5.75 | 6.5 | 7.25 | 8.0 | 8.75 | 9.5 | 10.25 | 11.0 |
| Hardness (VHN) | 36.92 | 38.35 | 38.93 | 39.13 | 39.23 | 40.23 | 39.02 | 38.98 | 38.7 | 38.35 | 37.67 | 36.93 | 36.35 | 35.93 |

| Reads.Number | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 30.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading Distance mm. | 11.75 | 12.5 | 13.25 | 14.0 | 14.75 | 15.50 | 16.25 | 17.0 | 17.75 | 18.50 | 19.25 | 20.0 | 20.75 | 21.50 | 22.25 | 23.0 |
| Hardness (VHN) | 36.37 | 37.17 | 37.68 | 38.3 | 40.25 | 38.67 | 39.12 | 38.5 | 39.25 | 39.08 | 38.08 | 37.88 | 36.58 | 38.08 | 36.78 | 35.28 |

Table 21

| Diametrical Reading | Lubricant Type : Zinc Stearate , Lubricant Ratio : 1.5 wt % , Density : 6.8 g / cm$^3$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reads. Number | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 30.0 |
| Reading Distance mm. | 1.25 | 2.0 | 2.75 | 3.5 | 4.25 | 5.0 | 5.75 | 6.5 | 7.25 | 8.0 | 8.75 | 9.50 | 10.25 | 11.0 | 11.75 | 12.5 | 13.25 | 14.0 | 14.75 | 15.5 | 16.25 | 17.0 | 17.75 | 18.50 | 19.25 | 20.0 | 20.75 | 21.50 | 22.25 | 23.0 |
| Hardness (VHN) | 39.55 | 38.7 | 40.8 | 42.4 | 42.6 | 43.45 | 43.5 | 41.95 | 41.35 | 40.95 | 41.8 | 42.3 | 40.3 | 40.85 | 43.00 | 39.45 | 43.20 | 46.95 | 42.65 | 43.6 | 44.0 | 45.65 | 46.05 | 46.7 | 45.8 | 44.95 | 45.35 | 46.5 | 42.25 | 39.25 |

Table 22 . The hardness values on the axial direction

| Lub.Ratio (wt %) | 0.50 | | | 1.00 | | | 1.50 | | |
|---|---|---|---|---|---|---|---|---|---|
| Hardness ( VHN ) | 26.49 | 34.136 | 44.14 | 26.0 | 33.0 | 38.0 | 23.204 | 30.069 | 33.870 |
| Density ( g/cm ) | 6.3 | 6.5 | 6.8 | 6.3 | 6.5 | 6.8 | 6.3 | 6.5 | 6.8 |

Table 23 .The hardness values on the diametrical direction

| Lub.Ratio (wt %) | 0.50 | | | 1.00 | | | 1.50 | | |
|---|---|---|---|---|---|---|---|---|---|
| Hardness ( VHN ) | 33.57 | 43.23 | 51.75 | 30.76 | 39.397 | 47.55 | 30.96 | 38.00 | 42.810 |
| Density ( g/cm ) | 6.3 | 6.5 | 6.8 | 6.3 | 6.5 | 6.8 | 6.3 | 6.5 | 6.8 |

Table 24 . The hardness values on the axial direction

| Density ( g/cm ) | 6.30 | | | 6.50 | | | 6.80 | | |
|---|---|---|---|---|---|---|---|---|---|
| Hardness (VHN) | 26.490 | 26.0 | 23.204 | 34.136 | 33.0 | 30.069 | 44 .14 | 38.0 | 33.870 |
| Lub.Ratio (wt %) | 0.5 | 1.0 | 1.5 | 0.5 | 1.0 | 1.5 | 0.5 | 1.0 | 1.5 |

Table 25 . The hardness values on the diametrical direction

| Density ( g/cm ) | 6.30 | | | 6.50 | | | 6.80 | | |
|---|---|---|---|---|---|---|---|---|---|
| Hardness ( VHN ) | 33.570 | 30.765 | 30.960 | 43.236 | 39.397 | 38.0 | 51.750 | 47.55 | 42.81 |
| Lub.Ratio (wt %) | 0.5 | 1.0 | 1.5 | 0.5 | 1.0 | 1.5 | 0.5 | 1.0 | 1.5 |

Table 26

| EFFECT OF LOAD | Density g/cm$^3$ | Lub. Type : Zinc Stearate , Distance : 3.0144 x $10^4$ cm<br>Lub.Ratio : 0.5 wt % , Speed : 6.0287 x $10^3$ cm/minute | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 1.34 | 1,45 | 2.145 | 2.18 | 2.38 | 2.415 | 2.52 | 2.88 | |
| | 6.5 | 1.220 | 1.48 | 1.955 | 2.075 | 2.145 | 2.285 | 2.45 | 2.475 | 2.680 |
| | 6.8 | 2.28 | 2.52 | 2.78 | 3.04 | 3.24 | 3.37 | 3.925 | 4.05 | |
| Volume of Wear ( mm$^3$) | 6.3 | 0.0255 | 0.0349 | 0.167 | 0.178 | 0.253 | 0.2685 | 0.3183 | 0.543 | |
| | 6.5 | 0.0175 | 0.0379 | 0.1153 | 0.1463 | 0.167 | 0.2152 | 0.2844 | 0.2962 | 0.4072 |
| | 6.8 | 0.2133 | 0.3183 | 0.4714 | 0.6741 | 0.8698 | 1.0181 | 1.873 | 2.124 | |
| Applied Load g | | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 | 2400.0 | 2700.0 |

Table 27

| EFFECT OF LOAD | Density $g/cm^3$ | Lub. Type : Zinc Stearate , Distance : $3.0144 \times 10^4$ cm<br>Lub.Ratio : 1.0 wt % , Speed : $6.0287 \times 10^3$ cm/minute | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 1.775 | 2.165 | 2.185 | 2.29 | 2,5 | 2.835 | 3.07 | 3.275 | |
| | 6.5 | 1.7050 | 2.135 | 2.2750 | 2.65 | 2.405 | 2.560 | 2.990 | 3.735 | 3.990 |
| | 6.8 | 1.655 | 1.95 | 2.255 | 2.295 | 3.18 | 3.575 | 3.685 | 3.815 | |
| Volume of Wear ( $mm^3$ ) | 6.3 | 0.0784 | 0.1734 | 0.1799 | 0.2171 | 0.3083 | 0.5099 | 0.7011 | 0.908 | |
| | 6.5 | 0.0667 | 0.164 | 0.2114 | 0.3893 | 0.2641 | 0.3497 | 0.6309 | 1.5361 | 2.0005 |
| | 6.8 | 0.0592 | 0.1141 | 0.2041 | 0.219 | 0.8716 | 1.2893 | 1.4555 | 1.672 | |
| Applied Load g | | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 | 2400.0 | 2700.0 |

Table 28

| EFFECT OF LOAD | Density g/cm$^3$ | Lub. Type : Zinc Stearate , Distance : $3.0144 \times 10^4$ cm<br>Lub. Ratio: 1.5 wt % , Speed : $6.0287 \times 10^3$ cm/mint | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 1.71 | 2.15 | 2.13 | 2.235 | 2.375 | 2.98 | 3.45 | 3.73 | 3.850 |
| | 6.5 | 1.73 | 1.885 | 2.035 | 2.23 | 2.26 | 2.325 | 2.845 | 3.73 | 3.790 |
| | 6.8 | 1.695 | 1.83 | 2.62 | 2.19 | 2.915 | 3.12 | 3.475 | 3.3 | 3.810 |
| Volume of Wear ( mm$^3$ ) | 6.3 | 0.0675 | 0.1687 | 0.1625 | 0.197 | 0.2511 | 0.623 | 1.1182 | 1.5279 | 1.7342 |
| | 6.5 | 0.0707 | 0.0997 | 0.1354 | 0.1952 | 0.2059 | 0.2306 | 0.5171 | 1.5279 | 1.6286 |
| | 6.8 | 0.0652 | 0.0885 | 0.3719 | 0.1816 | 0.5699 | 0.7479 | 1.151 | 0.936 | 1.663 |
| Applied Load g | | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 | 2400. | 2700. |

Table 29

| EFFECT OF LOAD | Density $g/cm^3$ | Lub . Type : Calcium Stearate<br>Lub . Ratio : 1.0 wt %<br>Distance : $3.0144 \times 10^4$ cm<br>Speed : $6.0287 \times 10^3$ cm/minute | | | | | |
|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 5.53 | 1.64 | 2.14 | 2.38 | 2.64 | | |
| | 5.93 | 1.62 | 1.975 | 2.195 | 2.415 | 2.465 | 2.515 |
| Volume of Wear ( $mm^3$ ) | 5.53 | 0.0571 | 0.1655 | 0.2533 | 0.3834 | | |
| | 5.93 | 0.0544 | 0.1201 | 0.1832 | 0.2685 | 0.2914 | 0.3158 |
| Applied Load g | | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 |

Table 30

| EFFECT OF LOAD | Density g/cm$^3$ | Lub. Type : Calcium Stearate<br>Lub.Ratio : 1.0 wt %<br>Speed : : 6.0287 x10$^3$ cm/minute<br>Distance : 3.0287 x10$^4$ cm | | | | |
|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 1.085 | 1.625 | 1.975 | 2.170 | 2.225 |
| | 6.5 | 0.96 | 1.525 | 1.885 | 3.105 | 2.91 |
| | 6.8 | 1.42 | 2.795 | 3.105 | 3.665 | 3.61 |
| Volume of Wear ( mm$^3$ ) | 6.3 | 0.0109 | 0.055 | 0.120 | 0.175 | 0.1935 |
| | 6.5 | 0.0067 | 0.0427 | 0.0997 | 0.7337 | 0.5660 |
| | 6.8 | 0.032 | 0.4817 | 0.7337 | 1.4241 | 1.3405 |
| Applied Load g | | 300.0 | 900.0 | 1500.0 | 2100.0 | 2700.0 |

Table 31

| EFFECT OF LOAD | Density g/cm$^3$ | Lub.Type :Aluminium Stearte<br>Lub.Ratio: 1.0 wt %<br>Distance : 3.0144 x10$^4$ cm<br>Speed: 6.0287 x 10$^3$cm/mint. | | | |
|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 1.72 | 2.10 | 2.4350 | 4.02 |
| | 6.5 | 1.9350 | 2.25 | 3.31 | 4.195 |
| | 6.8 | 1.980 | 2.99 | 3.58 | 4.095 |
| Volume of Wear ( mm$^3$ ) | 6.3 | 0.0691 | 0.1535 | 0.2775 | 2.0614 |
| | 6.5 | 0.1107 | 0.2023 | 0.9475 | 2.4444 |
| | 6.8 | 0.1213 | 0.631 | 1.2965 | 2.2196 |
| Applied Load g | | 600.0 | 1200.0 | 1800.0 | 2400.0 |

Table 32

| EFFECT OF LOAD | Density g/cm$^3$ | Lub.Type :Magnisium Steat.<br>Lub.Ratio: 1.0 wt %<br>Distance : 3.0144 x10$^4$ cm<br>Speed :6.0287 x10$^3$cm/mint. | | | |
|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 2.15 | 2.595 | 3.035 | 3.36 |
| | 6.5 | 2.075 | 3.055 | 3.985 | 4.26 |
| | 6.8 | 2.045 | 3.34 | 3.8 | 4.45 |
| Volume of Wear ( mm$^3$ ) | 6.3 | 0.1687 | 0.3579 | 0.6697 | 1.0060 |
| | 6.5 | 0.1463 | 0.6875 | 1.9905 | 2.599 |
| | 6.8 | 0.1381 | 0.982 | 1.646 | 3.095 |
| Applied Load g | | 600.0 | 1200. | 1800.0 | 2400.0 |

Table 33

| EFFECT OF LOAD | Density $g/cm^3$ | Lub.Type :Sodium Stearate<br>Lub.Ratio: 1.0 wt %<br>Distance : $3.0144 \times 10^4$ cm<br>Speed: $6.0287 \times 10^3$ cm/minute | | | |
|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 2.25 | 2.42 | 2.77 | 3.04 |
| | 6.5 | 2.085 | 2.520 | 3.085 | 3.840 |
| | 6.8 | 2.36 | 3.270 | 3.93 | 4.105 |
| Volume of Wear ( $mm^3$ ) | 6.3 | 0.2023 | 0.2707 | 0.4647 | 0.6741 |
| | 6.5 | 0.1492 | 0.3183 | 0.7159 | 1.7162 |
| | 6.8 | 0.24485 | 0.9025 | 1.8829 | 2.2413 |
| Applied Load g | | 600.0 | 1200.0 | 1800.0 | 2400.0 |

Table 34

| EFFECT OF SPEED | Density $g/cm^3$ | Lub.Type :Zinc Stearate , Running Time : 2 min<br>Lub.Ratio: 0.5 wt % , Load : 600.0 g | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 1.85 | 1.975 | 2.04 | 2.16 | 2.255 | 2.335 | 2.790 |
| | 6.5 | 1.73 | 1.8 | 2.06 | 2.19 | 2.110 | 2.235 | 2.71 |
| | 6.8 | 2.645 | 2.765 | 2.415 | 3.63 | 3.955 | 4.39 | 5.9450 |
| Volume Of wear ( $mm^3$ ) | 6.3 | 0.0925 | 0.120 | 0.1367 | 0.1718 | 0.204 | 0.2346 | 0.4783 |
| | 6.5 | 0.071 | 0.0827 | 0.1421 | 0.1816 | 0.1565 | 0.1970 | 0.426 |
| | 6.8 | 0.3863 | 0.4614 | 0.2685 | 1.3705 | 1.9312 | 2.9316 | 9.8596 |
| Speed $x10^3$ cm/ minute | | 6.0287 | 7.6152 | 10.154 | 15.230 | 18.277 | 22.846 | 30.461 |

Table 35

| EFFECT OF SPEED | Density $g/cm^3$ | Lub.Type :Zinc Stearate , Running Time : 2 min<br>Lub.Ratio: 1.0 wt % , Load : 600.0 g | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 1.770 | 1.97 | 2.07 | 2.29 | 2.3850 | 2.805 | 3.07 | 3.375 |
| | 6.5 | 1.80 | 1.81 | 1.955 | 2.06 | 2.22 | 2.59 | 3.4750 | 3.2 |
| | 6.8 | 3.29 | 2.665 | 3.090 | 4.44 | 4.490 | 5.6 | 6.875 | |
| Volume Of Wear ( $mm^3$ ) | 6.3 | 0.0775 | 0.119 | 0.1449 | 0.2170 | 0.2554 | 0.4886 | 0.7011 | 1.2260 |
| | 6.5 | 0.0829 | 0.847 | 0.1153 | 0.1421 | 0.1917 | 0.3552 | 1.1510 | 0.8277 |
| | 6.8 | 0.925 | 0.398 | 0.720 | 3.0675 | 3.208 | 7.7625 | 17.634 | |
| Speed x $10^3$ cm/minute | | 6.0287 | 7.6152 | 10.154 | 15.230 | 18.277 | 22.846 | 30.461 | 45.244 |

Table 36

| EFFECT OF SPEED | Density g/cm$^3$ | Lub.Type :Zinc Stearate , Running Time : 2 min<br>Lub.Ratio: 1.5 wt % , Load : 600.0 g | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 1.705 | 1.960 | 2.120 | 2.175 | 2.32 | 2,685 | 3.05 | 4.445 |
| | 6.5 | 1.805 | 1.74 | 1.945 | 2.175 | 2.190 | 2.710 | 3.28 | 3.115 |
| | 6.8 | 2.28 | 1.935 | 2.015 | 3.010 | 4.02 | 4.625 | 5.47 | |
| Volume of Wear ( mm$^3$ ) | 6.3 | 0.0667 | 0.1165 | 0.1594 | 0.1766 | 0.2287 | 0.4102 | 0.683 | 3.0813 |
| | 6.5 | 0.0837 | 0.0724 | 0.1130 | 0.1766 | 0.1816 | 0.4257 | 0.9136 | 0.743 |
| | 6.8 | 0.213 | 0.111 | 0.13 | 0.648 | 2.0614 | 3.6116 | 7.0664 | |
| Speed x10$^3$ cm /minute | | 6.0287 | 7.6152 | 10.154 | 15.230 | 18.277 | 22.846 | 30.461 | 45.244 |

Table 37

| EFFECT OF SPEED | Density $g/cm^3$ | Lub.Type : Calciume Stearate<br>Lub.Ratio: 1.0 wt %<br>Running Time: 2.0 minutes<br>Load : 600.0 g | | | | |
|---|---|---|---|---|---|---|
| Worn Area's Small Diameter mm | 6.3 | 1.565 | 1.83 | 2.595 | 4.140 | - |
| | 6.5 | 1.435 | 2.320 | 3.365 | 4.335 | - |
| | 6.8 | 2.30 | 2.920 | 3.750 | 4.670 | - |
| Volume of Wear $mm^3$ | 6.3 | 0.0473 | 0.0885 | 0.358 | 2.3189 | |
| | 6.5 | 0.034 | 0.227 | 1.012 | 2.787 | |
| | 6.8 | 0.221 | 0.574 | 1.591 | 3.755 | |
| Speed x $10^3$ cm/minute | | 6.028 | 10.15 | 18.277 | 30.461 | |

Table 38

| EFFECT OF SPEED | Density $g/cm^3$ | Lub.Type : Sodium Stearate<br>Lub.Ratio: 1.0 wt %<br>Running Time : 2.0 minutes<br>Load : 600.0 g | | | | |
|---|---|---|---|---|---|---|
| Worn Area's Small Diameter mm | 6.3 | 1.44 | 1.725 | 2.052 | 3.775 | - |
| | 6.5 | 1.63 | 2.4 | 3.0 | 4.46 | - |
| | 6.8 | 1.735 | 2.87 | 3.435 | 4.415 | - |
| Volume of wear $mm^3$ | 6.3 | 0.034 | 0.0669 | 0.1394 | 1.603 | - |
| | 6.5 | 0.056 | 0.2619 | 0.639 | 3.1231 | - |
| | 6.8 | 0.072 | 0.536 | 1.099 | 2.999 | - |
| Speed x $10^3$ cm/minute | | 6.0287 | 10.154 | 18.277 | 30.461 | - |

Table 39

| EFFECT OF SPEED | Density $g/cm^3$ | Lub.Type :Magnesium Stearate<br>Lub.Ratio: 1.0 wt %<br>Running Time : 2.0 minutes<br>Load : 600.0 g | | | | |
|---|---|---|---|---|---|---|
| Worn Area's Small Diameter mm | 6.3 | 1.495 | 1.705 | 2.735 | 4.395 | - |
| | 6.5 | 1.77 | 2.420 | 3.060 | 4.550 | - |
| | 6.8 | 2.635 | 3.04 | 3.80 | 5.035 | - |
| Volume of Wear $mm^3$ | 6.3 | 0.0394 | 0.067 | 0.4417 | 2.945 | - |
| | 6.5 | 0.0775 | 0.271 | 0.692 | 3.383 | - |
| | 6.8 | 0.378 | 0.674 | 1.6458 | 5.0728 | - |
| Speed x $10^3$ cm/minute | | 6.0278 | 10.154 | 18.277 | 30.461 | - |

Table 40

| EFFECT OF SPEED | Density $g/cm^3$ | Lub.Type : Aluminium Stearate<br>Lub.Ratio: 1.0 wt %<br>Running Time : 2.0 minutes<br>Load :600.0 g | | | | |
|---|---|---|---|---|---|---|
| Worn Area's Small Diameter m m | 6.3 | 1.605 | 1.720 | 3.135 | 3.370 | - |
| | 6.5 | 1.48 | 1.660 | 1.925 | 4.50 | - |
| | 6.8 | 1.730 | 2.155 | 3.560 | 4.52 | - |
| Volume of Wear $mm^3$ | 6.3 | 0.0524 | 0.0691 | 0.7624 | 1.0181 | - |
| | 6.5 | 0.0379 | 0.0599 | 0.1084 | 3.2367 | - |
| | 6.8 | 0.0699 | 0.1702 | 1.2678 | 3.2946 | - |
| Speed x $10^3$ cm/minute | | 6.0278 | 10.154 | 18.277 | 30.461 | - |

Table 41

| EFFECT OF DISTANCE | Density $g/cm^3$ | Lub.Type :Zinc Stearate , Speed: 6.0287 $x10^3$ cm/minute<br>Lub.Ratio: 0.5 wt % , Load : 600.0 g | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 2.1 | 2.475 | 2.65 | 2.790 | 2.69 | 2.895 | 3.005 | 3.125 |
| | 6.5 | 1.985 | 2.39 | 2.545 | 2.676 | 2.755 | 2.815 | 2.825 | 2.925 |
| | 6.8 | 3.155 | 3.965 | 3.665 | 4.09 | 4.375 | 4.725 | | |
| Volume of Wear ( $mm^3$ ) | 6.3 | 0.1535 | 0.2962 | 0.3893 | 0.4783 | 0.4133 | 0.5544 | 0.6436 | 0.7528 |
| | 6.5 | 0.1225 | 0.2554 | 0.3311 | 0.4048 | 0.4547 | 0.4956 | 0.5027 | 0.5778 |
| | 6.8 | 0.7821 | 1.9508 | 1.4241 | 2.2087 | 2.905 | 3.9342 | | |
| Sliding Distance cm | | 30144. | 60287. | 90431. | 120574. | 150718. | 180861. | 211005. | 241149. |

Table 42

| EFFECT OF DISTANCE | Density $g/cm^3$ | Lub.Type :Zinc Stearate , Speed: 6.0287 x $10^3$ cm/min.<br>Lub.Ratio: 1.0 wt % , Load : 600.0 g | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 2.12 | 2.49 | 2.75 | 2.955 | 3.085 | 2.985 | 3.06 | 3.195 |
| | 6.5 | 1.665 | 2.25 | 2.560 | 2.745 | 2.80 | 2.825 | 2.96 | 3.255 |
| | 6.8 | 2.43 | 3.850 | 4.540 | 4.765 | 5.215 | 5.31 | | |
| Volume of Wear ( $mm^3$ ) | 6.3 | 0.1595 | 0.303 | 0.4514 | 0.6016 | 0.7149 | 0.6267 | 0.6921 | 0.8225 |
| | 6.5 | 0.061 | 0.2023 | 0.339 | 0.4482 | 0.4852 | 0.5027 | 0.6059 | 0.8861 |
| | 6,8 | 0.275 | 1.734 | 3.353 | 4.069 | 5.838 | 6.252 | | |
| Sliding Distance cm | | 30144. | 60287. | 90431. | 120574 | 150718. | 180861. | 211005. | 241149. |

Table 43

| EFFECT OF DISTANCE | Density $g/cm^3$ | Lub,Type :Zinc Stearate , Speed :$6.0287 \times 10^3$ cm/minute<br>Lub.Ratio: 1.5 wt % , Load : 600.0 g | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 2.04 | 2.47 | 2.68 | 2.81 | 3.035 | 3.155 | 3.275 | 3.325 |
| | 6.5 | 1.915 | 2.41 | 2.490 | 2.835 | 2.995 | 3.175 | 3.24 | 3.31 |
| | 6.8 | 1.975 | 2.285 | 3.54 | 3.88 | 4.775 | 4.795 | 5.13 | |
| Volume of Wear ( $mm^3$ ) | 6.3 | 0.1367 | 0.2938 | 0.4072 | 0.4921 | 0.6697 | 0.7821 | 0.908 | 0.9648 |
| | 6.5 | 0.1062 | 0.2663 | 0.3034 | 0.5099 | 0.6351 | 0.8021 | 0.8698 | 0.9475 |
| | 6.8 | 0.1201 | 0.2152 | 1.2396 | 1.7889 | 4.1034 | 4.1726 | 5.4667 | |
| Sliding Distance cm | | 30144. | 60287. | 90431. | 120574. | 150718. | 180861. | 211005. | 241149. |

Table 44

| EFFECT OF DISTANCE | Density g/cm$^3$ | Lub. Type : Calcium Stearate<br>Lub.Ratio : 1.0 wt %<br>Speed : 6.0287 x10$^3$cm/minute<br>Load : 600.0 g | | | | |
|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 5.93 | 2.340 | 2.990 | 3.49 | | |
| | 6.3 | 1.76 | 3.05 | 3.25 | 3.49 | 3.920 |
| | 6.5 | 1.565 | 2.62 | 3.165 | 3.39 | 3.720 |
| | 6.8 | 1.555 | 2.59 | 3.215 | 4.705 | 4.880 |
| Volume of Wear mm$^3$ x 10 | 5.93 | 0.0237 | 0.0631 | 0.1171 | | |
| | 6.3 | 0.0757 | 0.0683 | 0.0881 | 0.1171 | 0.1864 |
| | 6.5 | 0.0047 | 0.0372 | 0.0792 | 0.1042 | 0.1512 |
| | 6.8 | 0.0046 | 0.0358 | 0.0843 | 0.3868 | 0.4476 |
| Distance x 10$^3$ cm | | 30.144 | 90.431 | 150.72 | 211.01 | 271.29 |

Table 45

| EFFECT OF DISTANCE | Density $g/cm^3$ | Lub. Type : Aluminium Stearate<br>Lub.Ratio : 1.0 wt %<br>Speed : $6.0287 \times 10^3$ cm/min.<br>Load : 600.0 g | | | | |
|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 2.11 | 2.78 | 3.33 | 3.565 | 3.86 |
| | 6.5 | 2.12 | 2.69 | 3.225 | 3.545 | 3.65 |
| | 6.8 | 2.48 | 2.99 | 3.475 | 4.10 | 4.235 |
| Volume of Wear $mm^3 \times 10$ | 6.3 | 0.0157 | 0.0472 | 0.0971 | 0.1275 | 0.1752 |
| | 6.5 | 0.0159 | 0.0413 | 0.0886 | 0.1247 | 0.1401 |
| | 6.8 | 0.0299 | 0.0631 | 0.1151 | 0.2231 | 0.2539 |
| Distance $\times 10^3$ cm | | 30.144 | 90.431 | 150.72 | 211.01 | 271.292 |

Table 46

| EFFECT OF DISTANCE | Density $g/cm^3$ | Lub.Type : Magnisium Stearate<br>Lub.Ratio: 1.0 wt %<br>Speed : 6.0287 x $10^3$ cm/minute<br>Load : 600.0 g | | | | |
|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 2.065 | 2.82 | 3.195 | 3.555 | 3.85 |
| | 6.5 | 2.21 | 2.90 | 3.215 | 3.335 | 3.650 |
| | 6.8 | 3.14 | 4.18 | 4.43 | 4.65 | 4.970 |
| Volume of Wear $mm^3$ x 10 | 6.3 | 0.0144 | 0.0499 | 0.0823 | 0.1261 | 0.1734 |
| | 6.5 | 0.0187 | 0.0558 | 0.0843 | 0.0976 | 0.1401 |
| | 6.8 | 0.0767 | 0.241 | 0.304 | 0.369 | 0.4816 |
| Distance x $10^3$ cm | | 30.144 | 90.431 | 150.72 | 211.01 | 271.29 |

Table 47

| EFFECT OF DISTANCE | Density $g/cm^3$ | Lub. Type : Sodium Stearate<br>Lub.Ratio : 1.0 wt %<br>Speed : $6.0287 \times 10^3$ cm/min<br>Load : 600.0 g | | | | |
|---|---|---|---|---|---|---|
| Worn Area's Small Diameter ( mm ) | 6.3 | 2.085 | 2.825 | 3.225 | 3.55 | 3.68 |
| | 6.5 | 2.11 | 2.885 | 3.28 | 3.585 | 3.785 |
| | 6.8 | 2.930 | 4.285 | 4.855 | 5.16 | 2.935 |
| Volume of Wear $mm^3 \times 10$ | 6.3 | 0.01492 | 0.0503 | 0.0854 | 0.1254 | 0.1448 |
| | 6.5 | 0.0157 | 0.0547 | 0.0914 | 0.1304 | 0.1620 |
| | 6.8 | 0.058 | 0.266 | 0.439 | 0.5596 | |
| Distance $\times 10^3$ cm | | 30.144 | 90.431 | 150.72 | 211.01 | 271.29 |

Table 48

Load : 600.0 g , Speed : 6.0287 x$10^3$cm/min.

Distance : 3.0144 x$10^4$ cm , Lub.Ratio : 1.0 wt %

| EFFECT OF DENSITY & HARDNESS | Hardness VHN | Density g/$cm^3$ | Lubricant Stearate | | | | |
|---|---|---|---|---|---|---|---|
| | | | Ca | Zn | Mg | Al | So |
| VOLUME OF WEAR ( $mm^3$ ) x $10^{-1}$ | 10.0 | 5.54 | 1.655 | | | | |
| | 18.0 | 5.93 | 1.201 | | | | |
| | 26.0 | 6.3 | 0.4 | 1.7341 | 1.6866 | 0.6828 | 2.0229 |
| | 33.0 | 6.5 | 0.336 | 1.64 | 1.4633 | 1.107 | 1.4917 |
| | 38.0 | 6.8 | 3.0 | 1.1413 | 1.3805 | 1.213 | 2.4485 |

Table 49

Load : 1200.0 g , Speed : $6.0287 \times 10^3$ cm/min.

Distance : $3.0144 \times 10^4$ cm , Lub.Ratio: 1.0 wt %

| EFFECT OF DENSITY & HARDNESS | Hardness VHN | Density g/cm$^3$ | Lubricant Stearate | | | | |
|---|---|---|---|---|---|---|---|
| | | | Ca | Zn | Mg | Al | So |
| VOLUME OF WEAR ( mm$^3$ ) x $1\bar{0}^{1}$ | 10.0 | 5.54 | 3.834 | | | | |
| | 18.0 | 5.93 | 2.685 | | | | |
| | 26.0 | 6.3 | 0.880 | 2.171 | 3.579 | 1.535 | 2.707 |
| | 33.0 | 6.5 | 0.662 | 2.096 | 6.875 | 2.023 | 3.183 |
| | 38.0 | 6.8 | 6.0 | 2.1897 | 9.823 | 6.309 | 9.025 |

Table 50

Speed : $6.0287 \times 10^3$ cm/min . , Load : 600.0 g

Distance: $3.0144 \times 10^4$ cm , Lub.Ratio : 1.0 wt %

| EFFECT OF DENSITY & HARDNESS | Hardness VHN | Density $g/cm^3$ | Lubricant Stearate | | | | |
|---|---|---|---|---|---|---|---|
| | | | Ca | Zn | Mg | Al | So |
| VOLUME OF WEAR ( $mm^3$ ) | 10.0 | 5.54 | | | | | |
| | 18.0 | 5.93 | | | | | |
| | 26.0 | 6.30 | 0.043 | 0.0775 | 0.0394 | 0.0524 | 0.0339 |
| | 33.0 | 6.50 | 0.034 | 0.0829 | 0.0775 | 0.0379 | 0.0557 |
| | 38.0 | 6.80 | 0.221 | 0.9248 | 0.3805 | 0.0707 | 0.0715 |

Table 51

Speed : 18.2765 x $10^3$ cm/min , Load : 600.0 g

Distance : 3.0144 x $10^4$ cm , Lub.Ratio : 1.0 wt %

| EFFECT OF DENSITY & HARDNESS | Hardness VHN | Density g/$cm^3$ | Lubricant Stearate | | | | |
|---|---|---|---|---|---|---|---|
| | | | Ca | Zn | Mg | Al | So |
| VOLUME OF WEAR ( $mm^3$ ) | 10.0 | 5.54 | | | | | |
| | 18.0 | 5.93 | | | | | |
| | 26.0 | 6.3 | 0.3579 | 0.2554 | 0.4417 | 0.7624 | 0.1394 |
| | 33.0 | 6.5 | 1.012 | 0.1917 | 0.6920 | 0.1084 | 0.6393 |
| | 38.0 | 6.8 | 1.5609 | 3.2080 | 1.6458 | 1.2678 | 1.0989 |

Table 52

Distance : $3.0144 \times 10^4$ cm , Load : 600.0 g
Speed : $6.0287 \times 10^3$ cm/min , Lub.Ratio : 1.0 wt %

| EFFECT OF DENSITY & Hardness | Hardness VHN | Density g/cm$^3$ | Lubricant Stearate | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| VOLUME OF WEAR ( mm $^3$ ) | 10.0 | 5.53 | | | | | |
| | 18.0 | 5.93 | 0.2367 | | | | |
| | 26.0 | 6.3 | 0.0757 | 0.1594 | 0.1435 | 0.1565 | 0.1492 |
| | 33.0 | 6.5 | 0.0473 | 0.0599 | 0.1883 | 0.1594 | 0.1565 |
| | 38.0 | 6.8 | 0.0461 | 0.2729 | 0.7673 | 0.2986 | 0.5817 |

Table 53

Distance : 15.0718 x $10^4$ cm , Load : 600.0 g
Speed : 6.0287 x $10^3$ cm/min , Lub.Ratio : 1.0 wt %

| EFFECT OF DENSITY & HARDNESS | Hardness VHN | Density g/cm$^3$ | Lubricant Stearate | | | | |
|---|---|---|---|---|---|---|---|
| | | | Ca | Zn | Mg | Al | So |
| VOLUME OF WEAR ( mm$^3$ ) | 10.0 | 5.54 | | | | | |
| | 18.0 | 5.93 | 1.17 | | | | |
| | 26.0 | 6.3 | 0.8806 | 0.7149 | 0.823 | 0.971 | 0.854 |
| | 33.0 | 6.5 | 0.7920 | 0.485 | 0.843 | 0.886 | 0.854 |
| | 38.0 | 6.8 | 0.843 | 5.8381 | 3.0399 | 1.1510 | 4.3854 |

Table 54

| WEAR RATE<br>******<br>EFFECT OF DENSITY & LUBRICANT RATIO | Zinc stearate Lubricant | | | |
|---|---|---|---|---|
| | Density g/cm$^3$ | Lubricant Ratio wt % | | |
| | | 0.5 | 1.0 | 1.5 |
| Wear Rate ( mm$^3$ / g) x $10^{-4}$ | 6.3 | 2.20 | 3.80 | 7.30 |
| | 6.5 | 1.50 | 7.0 | 6.30 |
| | 6.8 | 9.1 | 8.7 | 6.10 |

Table 55

| WEAR RATE<br>******<br>EFFECT OF<br>DENSITY<br>&<br>LUBRICANT<br>RATIO | Zinc Stearate Lubricant | | | |
|---|---|---|---|---|
| | Density g/cm$^3$ | Lubricant Ratio wt % | | |
| | | 0.5 | 1.0 | 1.5 |
| Wear Rate ( mm$^3$ / cm ) x $10^{-5}$ | 6.3 | 0.238 | 0.2971 | 0.4016 |
| | 6.5 | 0.0275 | 0.3287 | 0.4377 |
| | 6.8 | 1.8358 | 4.078 | 3.177 |

Table 56

| WEAR RATE<br>******<br>EFFECT OF DENSITY & LUBRICANT RATIO | Zinc Stearate Lubricant | | | |
|---|---|---|---|---|
| | Density g/cm$^3$ | Lubricant Ratio wt % | | |
| | | 0.5 | 1.0 | 1.5 |
| Wear Rate (mm$^3$/cm/minute) x $10^{-4}$ | 6.3 | 0.1378 | 2.510 | 0.2334 |
| | 6.5 | 0.1233 | 0.379 | 0.3517 |
| | 6.8 | 3.44 | 6.5110 | 2.79 |

Table 57

THE CALIBRATION VALUES OF THE PIN & DISC MACHINE USED IN FRICTION MEASURMENTS

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HORIZONTAL FORCE ( g ) | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 | 1300 | 1400 |
| RECORDED OUT PUT (mv) | 2.53 | 4.51 | 8.95 | 12.79 | 15.72 | 19.17 | 22.59 | 25.85 | 29.38 | 33.16 | 36.75 | 40.28 | 43.89 | 47.38 |

Table 58

| TIME<br>1.0<br>SECONDS | Lub.Type :Zinc Stearate ,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.167 | 5.967 | 4.967 | 6.233 | 5.733 | 6.033 | 5.933 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 139.43 | 195.79 | 193.71 | 221.84 | 210.73 | 217.40 | 215.18 |
| Friction Coefficient | 0.4648 | 0.3263 | 0.2152 | 0.1849 | 0.1405 | 0.1208 | 0.1025 |

Table 59

| TIME<br>5.0<br>SECONDS | Lub.Type : Zinc Stearate, Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.833 | 4.667 | 4.70 | 7.333 | 7.333 | 8.333 | 9.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 62.87 | 155.32 | 187.78 | 246.29 | 246.29 | 268.51 | 287.04 |
| Friction Coefficient | 0.2096 | 0.2589 | 0.2086 | 0.2052 | 0.1641 | 0.1492 | 0.1367 |

Table 60

| TIME<br>10.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.533 | 5.20 | 5.767 | 9.00 | 9.333 | 11.40 | 11.33 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 86.24 | 172.06 | 211.49 | 283.33 | 290.73 | 336.67 | 335.18 |
| Friction Coefficient | 0.2875 | 0.2868 | 0.235 | 0.2361 | 0.1938 | 0.187 | 0.1596 |

Table 61

| TIME<br>20.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.033 | 6.367 | 6.833 | 9.233 | 10.767 | 12.667 | 12.600 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 102.72 | 208.0 | 235.18 | 288.51 | 322.60 | 364.82 | 363.33 |
| Friction Coefficient | 0.3424 | 0.3467 | 0.2613 | 0.2404 | 0.2151 | 0.2027 | 0.173 |

Table 62

| TIME<br>40.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.3 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.2 | 6.9 | 9.067 | 11.1 | 11.333 | 16.50 | 14.333 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 108.19 | 224.09 | 284.82 | 329.99 | 335.18 | 449.99 | 401.84 |
| Friction Coefficient | 0.3606 | 0.3735 | 0.3165 | 0.275 | 0.2235 | 0.250 | 0.1914 |

Table 63

| TIME<br>50.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.3 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.233 | 7.167 | 10.0 | 11.50 | 13.0 | 18.0 | 15.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 109.26 | 232.07 | 305.55 | 338.89 | 372.22 | 483.33 | 435.18 |
| Friction Coefficient | 0.3642 | 0.3868 | 0.3395 | 0.2824 | 0.2482 | 0.2685 | 0.2072 |

Table 64

| TIME<br>60.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.333 | 7.067 | 10.60 | 11.667 | 13.667 | 19.667 | 16.267 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 112.52 | 229.08 | 318.89 | 342.60 | 387.04 | 520.37 | 444.82 |
| Friction Coefficient | 0.3751 | 0.3818 | 0.3543 | 0.2855 | 0.258 | 0.2891 | 0.2118 |

Table 65

| TIME<br>1.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.933 | 5.533 | 5.433 | 5.40 | 5.30 | 7.567 | 9.467 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 131.93 | 182.42 | 204.07 | 203.33 | 201.11 | 251.49 | 293.71 |
| Friction Coefficient | 0.4398 | 0.3040 | 0.2267 | 0.1694 | 0.1341 | 0.1397 | 0.1399 |

Table 66

| TIME<br>5.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.267 | 4.667 | 5.6 | 7.4 | 7.00 | 11.0 | 12.5 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 77.41 | 155.32 | 207.78 | 247.78 | 238.89 | 327.78 | 361.11 |
| Friction Coefficient | 0.258 | 0.2589 | 0.2309 | 0.2065 | 0.1593 | 0.1821 | 0.1710 |

Table 67

| TIME 10.0 SECONDS | Lub.Type : Zinc Stearate , Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.667 | 5.5 | 7.133 | 8.833 | 9.333 | 16.0 | 16.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 90.68 | 181.39 | 241.84 | 279.62 | 290.73 | 438.89 | 442.60 |
| Friction Coefficient | 0.3023 | 0.3023 | 0.2687 | 0.233 | 0.1938 | 0.2438 | 0.2108 |

Table 68

| TIME 20.0 SECONDS | Lub.Type : Zinc Stearate , Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.067 | 7.167 | 7.833 | 9.333 | 11.433 | 14.60 | 18.10 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 103.84 | 232.07 | 257.40 | 290.73 | 337.40 | 407.77 | 485.55 |
| Friction Coefficient | 0.3461 | 0.3868 | 0.286 | 0.2423 | 0.2249 | 0.2265 | 0.2312 |

Table 69

| TIME 40.0 SECONDS | Lub.Type : Zinc Stearate , Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : $6.0287 \times 10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.933 | 7.2 | 9.633 | 10.883 | 12.33 | 16.0 | 20.267 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 131.93 | 233.05 | 297.40 | 325.18 | 357.40 | 438.89 | 533.71 |
| Friction Coefficient | 0.4398 | 0.3884 | 0.3304 | 0.271 | 0.2383 | 0.2438 | 0.2542 |

Table 70

| TIME 50.0 SECONDS | Lub.Type : Zinc Stearate , Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.067 | 7.767 | 10.333 | 10.833 | 13.167 | 16.167 | 21.333 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 136.23 | 249.82 | 312.95 | 324.07 | 375.93 | 442.60 | 557.40 |
| Friction Coefficient | 0.4541 | 0.4164 | 0.3477 | 0.2701 | 0.2506 | 0.2459 | 0.2654 |

Table 71

| TIME 60.0 SECONDS | Lub.Type : Zinc Stearate , Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.167 | 8.167 | 10.4 | 11.5 | 12.73 | 16.5 | 21.87 |
| Friction Coefficient | 0.4648 | 0.4359 | 0.3494 | 0.2824 | 0.2442 | 0.250 | 0.2711 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 139.43 | 261.51 | 314.44 | 338.89 | 366.29 | 449.99 | 569.26 |

Table 72

| TIME<br>1.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.90 | 5.90 | 4.467 | 4.80 | 6.50 | 6.767 | 8.333 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 130.87 | 193.74 | 182.60 | 189.99 | 227.78 | 233.71 | 268.51 |
| Friction Coefficient | 0.4362 | 0.3229 | 0.2029 | 0.1583 | 0.1519 | 0.1298 | 0.1279 |

Table 73

| TIME<br>5.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.933 | 4.833 | 6.333 | 5.667 | 11.0 | 10.167 | 11.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 66.233 | 160.56 | 224.07 | 209.27 | 327.78 | 309.27 | 327.78 |
| Friction Coefficient | 0.2208 | 0.2676 | 0.249 | 0.1744 | 0.2185 | 0.1718 | 0.1561 |

Table 74

| TIME<br>10.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.233 | 6.433 | 7.233 | 7.50 | 12.33 | 13.50 | 12.5 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 76.271 | 210.00 | 244.07 | 249.99 | 357.38 | 383.33 | 361.11 |
| Friction Coefficient | 0.2542 | 0.350 | 0.2712 | 0.2083 | 0.2383 | 0.213 | 0.1720 |

Table 75

| TIME<br>20.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.467 | 6.5 | 7.267 | 9.333 | 12.0 | 11.667 | 12.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 116.88 | 212.03 | 244.82 | 290.73 | 349.99 | 342.60 | 353.71 |
| Friction Coefficient | 0.3896 | 0.3534 | 0.272 | 0.2423 | 0.2333 | 0.1902 | 0.1684 |

Table 76

| TIME<br>40.0<br>SECONDS | Lub.Type : Zinc Stearate , Density : 6.8 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.033 | 6.833 | 7.567 | 9.80 | 12.50 | 11.0 | 9.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 102.72 | 222.08 | 251.49 | 301.11 | 361.11 | 327.78 | 287.04 |
| Friction Coefficient | 0.3424 | 0.3701 | 0.2794 | 0.2509 | 0.2407 | 0.1821 | 0.1367 |

Table 77

| TIME<br>50.0<br>SECONDS | Lub.Type : Zinc Stearate., Density : 6.8 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.267 | 7.067 | 7.667 | 9.833 | 12.333 | 10.667 | 8.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 110.37 | 229.09 | 253.71 | 301.84 | 357.40 | 320.38 | 279.62 |
| Friction Coefficient | 0.3679 | 0.3818 | 0.2819 | 0.2515 | 0.2383 | 0.178 | 0.1332 |

Table 78

| TIME 60.0 SECONDS | Lub.Type : Zinc Stearate , Density : 6.8 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6,0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.467 | 7,033 | 7.833 | 10.067 | 11.833 | 11.50 | 8.067 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 116.88 | 228.07 | 257.40 | 307.04 | 346.29 | 338.89 | 262.60 |
| Friction Coefficient | 0.3896 | 0.3801 | 0.286 | 0.2559 | 0.2309 | 0.1883 | 0.1251 |

Table 79

| T I M E<br>1.0<br>S E C O N D S | Lub.Type : Aluminium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.00 | 4.70 | 4.733 | 5.267 | 5.933 | 7.30 | 6.90 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 130.87 | 156,36 | 188.51 | 200.38 | 215.18 | 245.56 | 236.67 |
| Friction Coefficient | 0.4362 | 0.2606 | 0.2095 | 0.167 | 0.1435 | 0.1364 | 0.1127 |

Table 80

| TIME<br>5.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.750 | 3.467 | 5.167 | 4.567 | 6.50 | 9.40 | 8.333 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 1.75 | 3.467 | 5.167 | 4.567 | 6.5 | 9.4 | 8.33 |
| Friction Coefficient | 0.2002 | 0.1948 | 0.2202 | 0.154 | 0.1519 | 0.1623 | 0.1279 |

Table 81

| TIME<br>10.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute. | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.2 | 4.333 | 6.0 | 6.333 | 9.667 | 12.50 | 11.33 |
| Friction Force ( g ) | 75.17 | 144.72 | 216.67 | 224.07 | 298.15 | 361.11 | 335.18 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Coefficient | 0.2506 | 0.2412 | 0.2407 | 0.1867 | 0.1988 | 0.2006 | 0.1596 |

Table 82

| TIME<br>20.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.867 | 4.433 | 6.90 | 8.433 | 10.833 | 14.767 | 14.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 97.272 | 147.91 | 236.67 | 270.73 | 324.07 | 411.49 | 412.95 |
| Friction Coefficient | 0.3242 | 0.2465 | 0.263 | 0.2256 | 0.216 | 0.2286 | 0.1966 |

Table 83

| TIME<br>40.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.80 | 7.067 | 10.0 | 10.667 | 14.833 | 19.0 | 19.333 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 127.65 | 229.09 | 305.55 | 320.38 | 412.95 | 505.55 | 512.95 |
| Friction Coefficient | 0.4255 | 0.3818 | 0.3395 | 0.267 | 0.2753 | 0.2809 | 0.2443 |

Table 84

| TIME<br>50.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.467 | 7.767 | 11.333 | 12.333 | 15.833 | 20.667 | 19.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 148.98 | 249.82 | 335.18 | 357.40 | 435.18 | 542.60 | 505.55 |
| Friction Coefficient | 0.4966 | 0.4164 | 0.3724 | 0.2978 | 0.2901 | 0.3014 | 0.2407 |

Table 85

| TIME 60.0 SECONDS | Lub.Type : Aluminium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.30 | 8.00 | 13.33 | 13.33 | 16.167 | 21.333 | 20.667 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 2100.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 143.67 | 256.65 | 379.62 | 379.62 | 442.60 | 557.40 | 542.60 |
| Friction Coefficient | 0.4789 | 0.4277 | 0.4218 | 0.3164 | 0.2951 | 0.3097 | 0.2584 |

Table 86

| TIME 1.0 SECONDS | Lub.Type : Aluminium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.933 | 4.367 | 4.633 | 4.867 | 6.333 | 6.433 | 6.933 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force( g ) | 131.93 | 145.81 | 186.29 | 191.49 | 224.07 | 226.29 | 237.40 |
| Friction Coefficient | 0.4398 | 0.243 | 0.207 | 0.1596 | 0.1494 | 0.1257 | 0.1131 |

Table 87

| TIME 5.0 SECONDS | Lub,Type : Aluminium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.833 | 4.033 | 3.667 | 4.833 | 7.0 | 9.0 | 7.333 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 62.87 | 135.14 | 164.82 | 190.73 | 238.89 | 283.33 | 246.29 |
| Friction Coefficient | 0.2096 | 0.2252 | 0.1831 | 0.1589 | 0.1593 | 0.1574 | 0.1173 |

Table 88

| TIME<br>10.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.267 | 5.033 | 4.367 | 6.50 | 7.833 | 11.70 | 9.333 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 77.41 | 166.84 | 180.38 | 227.78 | 257.40 | 343.33 | 290.73 |
| Friction Coefficient | 0.258 | 0.2781 | 0.2004 | 0.1898 | 0.1716 | 0.1907 | 0.1384 |

Table 89

| TIME<br>20.0<br>SECONDS | Lub.Type :Aluminium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.33 | 5.90 | 5.733 | 7.967 | 9.667 | 13.90 | 12.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 79.503 | 193.74 | 210.73 | 260.38 | 298.15 | 392.22 | 353.17 |
| Friction Coefficient | 0.265 | 0.3229 | 0.2342 | 0.217 | 0.1988 | 0.2179 | 0.1684 |

Table 90

| TIME<br>40.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.0 | 6.667 | 6.667 | 8.867 | 11.60 | 15.333 | 16.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 101.64 | 217.08 | 231.49 | 280.38 | 341.06 | 424.06 | 442.60 |
| Friction Coefficient | 0.3388 | 0.3618 | 0.2572 | 0.2337 | 0.2274 | 0.2356 | 0.2108 |

Table 91

| TIME<br>50.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.60 | 7.167 | 7.633 | 9.50 | 12.333 | 16.667 | 17.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 121.19 | 232.07 | 252.95 | 294.44 | 357.40 | 453.71 | 479.62 |
| Friction Coefficient | 0.404 | 0.3868 | 0.2811 | 0.2454 | 0.2383 | 0.2521 | 0.2284 |

Table 92

| TIME<br>60.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.867 | 7.60 | 7.867 | 10.40 | 13.33 | 16.833 | 17.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g) | 129.81 | 244.91 | 258.15 | 314.44 | 379.62 | 457.40 | 479.62 |
| Friction Coefficient | 0.4327 | 0.4082 | 0.2868 | 0.262 | 0.2531 | 0.2541 | 0.2284 |

Table 93

| TIME 1.0 SECONDS | Lub.Type : Aluminium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : $6.0287 \times 10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.233 | 4.967 | 5.367 | 5.033 | 5.80 | 5.733 | 5.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 141.54 | 164.77 | 202.60 | 195.18 | 212.22 | 210.73 | 198.16 |
| Friction Coefficient | 0.4718 | 0.2746 | 0.2251 | 0.1627 | 0.1415 | 0.1171 | 0.0944 |

Table 94

| TIME<br>5.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.90 | 3.567 | 4.333 | 4.667 | 5.333 | 5.833 | 5.50 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 65.125 | 120.12 | 179.62 | 187.04 | 201.84 | 212.96 | 205.55 |
| Friction Coefficient | 0.2171 | 0.2002 | 0.1996 | 0.1559 | 0.1346 | 0.1183 | 0.0979 |

Table 95

| TIME<br>10.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.833 | 4.10 | 5.333 | 6.00 | 5.73 | 6.50 | 7.00 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 62.872 | 137.29 | 201.84 | 216.67 | 210.73 | 227.78 | 238.89 |
| Friction Coefficient | 0.2096 | 0.2288 | 0.2243 | 0.1806 | 0.1405 | 0.1265 | 0.1138 |

Table 96

| TIME<br>20.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.233 | 5.533 | 6.7 | 8.5 | 7.233 | 9.167 | 9.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 76.27 | 182.42 | 232.22 | 272.22 | 244.07 | 287.04 | 301.84 |
| Friction Coefficient | 0.2542 | 0.3040 | 0.2580 | 0.2267 | 0.1627 | 0.1595 | 0.1437 |

Table 97

| TIME<br>40.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.50 | 5.50 | 8.0 | 8.533 | 9.433 | 10.833 | 13.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 85.15 | 181.39 | 261.11 | 272.95 | 292.95 | 324.07 | 372.22 |
| Friction Coefficient | 0.2838 | 0.3023 | 0.2901 | 0.2275 | 0.1953 | 0.1800 | 0.1773 |

Table 98

| TIME<br>50.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.367 | 5.533 | 7.233 | 8.333 | 9.867 | 10.833 | 13.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 80.73 | 182.42 | 244.07 | 268.51 | 302.60 | 324.07 | 372.22 |
| Friction Coefficient | 0.2691 | 0.3040 | 0.2712 | 0.2238 | 0.2017 | 0.1800 | 0.1773 |

Table 99

| TIME<br>60.0<br>SECONDS | Lub.Type : Aluminium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.833 | 5.50 | 7.833 | 8.533 | 9.667 | 11.00 | 12.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 96.15 | 181.39 | 257.40 | 272.95 | 298.15 | 327.78 | 368.51 |
| Friction Coefficient | 0.3205 | 0.3023 | 0.286 | 0.2275 | 0.1988 | 0.1821 | 0.1755 |

Table 100

| TIME<br>1.0<br>SECONDS | Lub.Type : Calcium Stat., Density :5.53 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.10 | 5.60 | 6.0 | | | | |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 137.29 | 184.49 | 216.67 | | | | |
| Friction Coefficient | 0.4576 | 0.3075 | 0.2407 | | | | |

Table 101

| TIME<br>5.0<br>SECONDS | Lub.Type : Calcium Stat., Density :5.53 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.25 | 4.0 | 5.0 | | | | |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | | | | |
| Friction Force ( g ) | 109.82 | 134.08 | 194.44 | | | | |
| Friction Coefficient | 0.3661 | 0.2235 | 0.2161 | | | | |

Table 102

| TIME<br>10.0<br>SECONDS | Lub.Type : Calcium Stat.,Density : 5.53 $g/ cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm/ minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put (mv ) | 3.45 | 4.6 | 6.5 | | | | |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | | | | |
| Friction Force ( g ) | 116.33 | 153.20 | 227.78 | | | | |
| Friction Coefficient | 0.3878 | 0.2553 | 0.2531 | | | | |

Table 103

| TIME<br>20.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 5.53 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 $x 10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.55 | 5.25 | 7.0 | | | | |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | | | | |
| Friction Force ( g ) | 119.57 | 173.62 | 238.89 | | | | |
| Friction Coefficient | 0.3986 | 0.2894 | 0.2654 | | | | |

Table 104

| TIME 40.0 SECONDS | Lub.Type : Calcium Stat., Density : 5.53 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put (mv) | 3.55 | 6.25 | 6.5 | | | | |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | | | | |
| Friction Force ( g ) | 119.57 | 204.44 | 227.78 | | | | |
| Friction Coefficient | 0.3986 | 0.3407 | 0.2531 | | | | |

Table 105

| TIME 50.0 SECONDS | Lub.Type :Calcium Stat., Density : 5.53 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.5 | 6.0 | 6.8 | | | | |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | | | | |
| Friction Force ( g ) | 117.95 | 196.8 | 234.44 | | | | |
| Friction Coefficient | 0.3932 | 0.328 | 0.2605 | | | | |

Table 106

| TIME<br>60.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 5.53 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.5 | 6.0 | 7.0 | | | | |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | | | | |
| Friction Coefficient | 0.393 | 0.328 | 0.265 | | | | |
| Friction Force ( g ) | 117.9 | 196.8 | 238.89 | | | | |

Table 107

| TIME<br>1.0<br>SECONDS | Lub.Type :Calcium Stat., Density : 5.93 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.533 | 5.933 | 4.233 | 4.8 | 5.733 | 6.5 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 119.02 | 194.75 | 177.40 | 189.99 | 210.73 | 227.78 | - |
| Friction Coefficient | 0.3967 | 0.3246 | 0.1971 | 0.1583 | 0.1405 | 0.1265 | - |

Table 108

| TIME<br>5.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 5.93 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.267 | 4.933 | 5.20 | 6.833 | 8.50 | 8.0 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 77.405 | 163.70 | 198.89 | 235.18 | 272.2 | 261.11 | - |
| Friction Coefficient | 0.258 | 0.273 | 0.221 | 0.196 | 0.182 | 0.145 | - |

Table 109

| TIME<br>10.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 5.93 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute. | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.467 | 6.033 | 6.267 | 8.5 | 10.10 | 10.25 | - |
| Friction Force ( g ) | 84.06 | 197.81 | 222.59 | 272.2 | 307.78 | 311.11 | - |
| Friction Coefficient | 0.280 | 0.330 | 0.247 | 0.227 | 0.205 | 0.173 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |

Table 110

| TIME<br>20.0<br>SECONDS | Lub.Type :Calcium Stat., Density : 5.93 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.167 | 6,867 | 6.533 | 9.60 | 11.167 | 13.5 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 107.11 | 223.1 | 228.51 | 296.67 | 331.49 | 383.33 | - |
| Friction Coefficient | 0.357 | 0.372 | 0.254 | 0.247 | 0.221 | 0.213 | - |

Table 111

| TIME<br>40.0<br>SECONDS | Lub.Type : Calcium Stat.,Density :5.93 $g/cm^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed :6.0287 x $10^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.933 | 7.433 | 11.10 | 11.467 | 15.567 | 18.25 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 131.93 | 239.97 | 329.99 | 338.15 | 429.26 | 488.88 | - |
| Friction Coefficient | 0.440 | 0.40 | 0.367 | 0.282 | 0.286 | 0.272 | - |

Table 112

| TIME<br>50.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 5.93 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : $6.0287 \times 10^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.067 | 8.033 | 11.5 | 13.333 | 15.667 | 18.75 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 136.23 | 257.61 | 338.89 | 379.62 | 431.49 | 499.99 | - |
| Friction COefficient | 0.454 | 0.4294 | 0.3765 | 0.3164 | 0.2877 | 0.2778 | - |

Table 113

| TIME<br>60.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 5.93 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : $6.0287 \times 10^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.333 | 8.367 | 11.267 | 14.167 | 16.333 | 16.50 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 144.72 | 267.31 | 333.71 | 398.15 | 446.29 | 449.99 | - |
| Friction Coefficient | 0.4824 | 0.4455 | 0.3708 | 0.3318 | 0.2975 | 0.25 | - |

Table 114

| TIME<br>1.0<br>SECOND | Lub.Type :Calcium Stat., Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed :6.0287 x10$^3$cm/minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.867 | 4.20 | 5.00 | 6.167 | 6.83 | 8.00 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 129.81 | 140.48 | 194.44 | 220.37 | 235.18 | 261.11 | - |
| Friction Coefficeint | 0.433 | 0.234 | 0.216 | 0.184 | 0.1568 | 0.1451 | - |

Table 115

| TIME<br>5.0<br>SECOND | Lub.Type :Calcium Stat., Density: 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.433 | 3.767 | 4.733 | 7.50 | 9.1670 | 11.0 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 82.927 | 126.59 | 188.51 | 249.99 | 287.04 | 327.78 | - |
| Friction Coefficient | 0.2764 | 0.211 | 0.2095 | 0.2083 | 0.1914 | 0.1821 | - |

Table 116

| TIME<br>10.0<br>SECONDS | Lub.Type :Calcium Stat. , Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.20 | 5.333 | 6.067 | 10.167 | 11.50 | 13.667 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 108.19 | 176.21 | 218.15 | 309.27 | 338.88 | 387.04 | - |
| Friction Coefficient | 0.3606 | 0.294 | 0.2424 | 0.2577 | 0.2259 | 0.2150 | - |

Table 117

| TIME<br>20.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm/ minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.833 | 6.233 | 6.9 | 10.833 | 13.167 | 14.667 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 128.71 | 203.92 | 236.67 | 342.07 | 375.93 | 409.26 | - |
| Friction Coefficient | 0.429 | 0.340 | 0.263 | 0.270 | 0.251 | 0.227 | |

Table 118

| TIME<br>40.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.3 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.733 | 7.167 | 10.233 | 14.933 | 18.667 | 20.767 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 157.40 | 232.07 | 310.73 | 415.18 | 498.2 | 544.82 | - |
| Friction Coefficient | 0.525 | 0.387 | 0.345 | 0.346 | 0.332 | 0.3027 | - |

Table 119

| TIME<br>50.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1cm<br>Speed : 6.0287 x $10^3$ cm/ minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 5.133 | 6.667 | 10.83 | 17.50 | 19.50 | 22.17 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 169.96 | 217.08 | 324.06 | 472.22 | 516.66 | 575.9 | - |
| Friction Coefficient | 0.566 | 0.362 | 0.360 | 0.394 | 0.344 | 0.320 | - |

Table 120

| TIME<br>60.0<br>SECONDS | Lub.Type : Calcium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 5.167 | 7.2 | 11.0 | 19.167 | 21.50 | 23.333 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 171.03 | 233.05 | 327.78 | 509.26 | 561.11 | 601.84 | - |
| Friction Coefficient | 0.57 | 0.388 | 0.364 | 0.424 | 0.374 | 0.3344 | - |

Table 121

| TIME<br>1.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute. | | | | | | |
|---|---|---|---|---|---|---|---|
| Out put ( mv ) | 3.33 | 5.233 | 5.333 | 4.4330 | 4.667 | 6.50 | 7.667 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 112.52 | 173.09 | 201.84 | 181.84 | 187.04 | 227.78 | 253.71 |
| Friction coefficient | 0.375 | 0.2885 | 0.2243 | 0.1515 | 0.1247 | 0.1265 | 0.1208 |

Table 122

| TIME<br>5.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.767 | 4.667 | 5.0 | 5.50 | 8.733 | 9.00 | 10.667 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 60.65 | 155.32 | 194.44 | 205.56 | 277.40 | 283.33 | 320.38 |
| Friction Coefficient | 0.202 | 0.259 | 0.2161 | 0.171 | 0.185 | 0.157 | 0.153 |

Table 123

| TIME<br>10.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6,5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.133 | 6.333 | 6.50 | 7.33 | 9.6670 | 10.667 | 16.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 72.93 | 206.97 | 227.77 | 246.29 | 298.15 | 320.37 | 457.40 |
| Friction Coefficient | 0.243 | 0.345 | 0.253 | 0.205 | 0.199 | 0.178 | 0.2178 |

Table 124

| TIME<br>20.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.033 | 6.167 | 7.50 | 7.833 | 10.07 | 12.50 | 13.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 102.72 | 201.91 | 249.99 | 257.40 | 307.04 | 361.11 | 390.73 |
| Friction Coefficient | 0.342 | 0.337 | 0.278 | 0.215 | 0.205 | 0.201 | 0.1861 |

Table 125

| TIME<br>40.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.433 | 7.933 | 8.533 | 8.50 | 10.433 | 12.50 | 14.67 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 115.78 | 254.69 | 272.95 | 272.22 | 315.18 | 361.11 | 409.26 |
| Friction Coefficient | 0.386 | 0.4245 | 0.303 | 0.2268 | 0.2101 | 0.2006 | 0.1949 |

Table 126

| TIME<br>50.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.967 | 6.767 | 9.0 | 10.233 | 10.667 | 12.50 | 14.67 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 133.0 | 220.09 | 283.33 | 310.73 | 320.38 | 361.11 | 409.26 |
| Friction Coefficient | 0.443 | 0.367 | 0.315 | 0.259 | 0.214 | 0.201 | 0.1949 |

Table 127

| TIME<br>60.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / mivute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.833 | 6.767 | 9.0 | 9.833 | 12.067 | 13.50 | 17.000 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 128.71 | 220.09 | 283.33 | 301.84 | 351.49 | 383.33 | 461.108 |
| Friction Coefficient | 0.4291 | 0.3668 | 0.3148 | 0.2515 | 0.2343 | 0.2129 | 0.2196 |

Table 128

| TIME<br>5 .0<br>SECONDS | Lub.Type :Calcium Stat., Density :6.8 g/cm$^3$<br>Lub.Ratio:1.0 wt% , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.167 | 4.667 | 6.0 | 7.50 | 9.333 | 11.33 | 8.667 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 74.07 | 155.32 | 216.67 | 249.99 | 290.73 | 335.18 | 275.93 |
| Friction Coefficient | 0.2469 | 0.2589 | 0.2407 | 0.2083 | 0.1938 | 0.1862 | 0.1314 |

Table 129

| TIME<br>1.0<br>SECONDS | Lub.Type :Calcium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.067 | 5.50 | 5.30 | 5.167 | 6.167 | 7.667 | 7.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 103.84 | 181.39 | 201.11 | 198.16 | 220.38 | 253.71 | 242.60 |
| Friction Coefficient | 0.346 | 0.3023 | 0.2235 | 0.165 | 0.147 | 0.141 | 0.1155 |

Table 130

| TIME<br>10.0<br>SECONDS | Lub.Type :Calcium Stat., Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.8 | 5.833 | 8.1 | 9.5 | 13.0 | 13.833 | 12.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 95.066 | 191.68 | 263.33 | 294.44 | 372.22 | 390.73 | 368.51 |
| Friction Coefficient | 0.3169 | 0.3195 | 0.2926 | 0.2454 | 0.2482 | 0.2171 | 0.175 |

Table 131

| TIME<br>20.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.50 | 7.367 | 8.1 | 10.167 | 10.00 | 11.667 | 15.00 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 117.95 | 238.02 | 263.33 | 309.27 | 305.55 | 342.60 | 416.66 |
| Friction Coefficient | 0.393 | 0.397 | 0.293 | 0.258 | 0.204 | 0.1903 | 0.1984 |

Table 132

| TIME 40.0 SECONDS | Lub.Type : Calcium Stat., Density : 6.8 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : $6.0287 \times 10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.933 | 6.0 | 7.167 | 9.333 | 7.667 | 11.167 | 13.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 131.93 | 196.80 | 242.60 | 290.73 | 253.71 | 331.49 | 357.93 |
| Friction Coefficient | 0.4398 | 0.328 | 0.2696 | 0.2423 | 0.169 | 0.1842 | 0.1790 |

Table 133

| TIME<br>60.0<br>SECONDS | Lub.Type : Calcium Stat. ,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put (mv ) | 3.667 | 6.1 | 7.333 | 9.167 | 6.667 | 11.667 | 13.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 123.36 | 199.86 | 246.29 | 287.04 | 231.49 | 342.60 | 372.22 |
| Friction Coefficient | 0.4112 | 0.333 | 0.273 | 0.2392 | 0.154 | 0.1903 | 0.1773 |

Table 134

| TIME<br>50.0<br>SECONDS | Lub.Type : Calcium Stat., Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.567 | 6.067 | 7.667 | 8.667 | 6.667 | 11.333 | 12.667 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 120.12 | 198.85 | 253.71 | 275.93 | 231.49 | 335.18 | 364.82 |
| Friction Coefficient | 0.401 | 0.331 | 0.282 | 0.2299 | 0.1543 | 0.1862 | 0.1737 |

Table 135

| TIME<br>1.0<br>SECONDS | Lub.Type : Magnesium Stat., Density : 6.3 g/$cm^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.2 | 5.767 | 5.3 | 4.233 | 6.2 | 7.75 | 9.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 108.19 | 189.64 | 201.11 | 177.40 | 221.11 | 255.56 | 283.33 |
| Friction Coefficient | 0.3606 | 0.3161 | 0.2235 | 0.1478 | 0.1474 | 0.142 | 0.1349 |

Table 136

| TIME<br>5.0<br>SECONDS | Lub.Type : Magnesium Stat.,Density :6.3 g/$cm^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.0 | 4.067 | 5.667 | 6.0 | 8.5 | 9.5 | 9.5 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 68.48 | 136.23 | 209.27 | 216.67 | 272.22 | 294.44 | 294.44 |
| Friction Ceefficient | 0.2283 | 0.227 | 0.2325 | 0.1806 | 0.1815 | 0.1636 | 0.1402 |

Table 137

<table>
<tr><td>TIME<br>10.0<br>SECONDS</td><td colspan="7">Lub.Type : Magnesium Stat., Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute .</td></tr>
<tr><td>Out Put ( mv )</td><td>2.467</td><td>5.167</td><td>7.833</td><td>8.0</td><td>10.5</td><td>12.5</td><td>11.0</td></tr>
<tr><td>Applied Load ( g )</td><td>300.0</td><td>600.0</td><td>900.0</td><td>1200.0</td><td>1500.0</td><td>1800.0</td><td>2100.0</td></tr>
<tr><td>Friction Force ( g )</td><td>84.06</td><td>171.03</td><td>257.40</td><td>261.11</td><td>316.66</td><td>361.11</td><td>327.78</td></tr>
<tr><td>Friction Coefficient</td><td>0.2802</td><td>0.2851</td><td>0.286</td><td>0.2176</td><td>0.2111</td><td>0.2006</td><td>0.1561</td></tr>
</table>

Table 138

<table>
<tr><td>TIME<br>20.0<br>SECONDS</td><td colspan="7">Lub.Type :Magnesium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute .</td></tr>
<tr><td>Out Put ( mv )</td><td>2.833</td><td>5.833</td><td>8.767</td><td>9.667</td><td>11.333</td><td>14.55</td><td>16.5</td></tr>
<tr><td>Applied Load ( g )</td><td>300.0</td><td>600.0</td><td>900.0</td><td>1200.0</td><td>1500.0</td><td>1800.0</td><td>2100.0</td></tr>
<tr><td>Friction Force ( g )</td><td>96.153</td><td>191.68</td><td>278.15</td><td>298.15</td><td>335.18</td><td>406.66</td><td>449.99</td></tr>
<tr><td>Friction Coefficient</td><td>0.3205</td><td>0.3195</td><td>0.3091</td><td>0.2485</td><td>0.2235</td><td>0.2259</td><td>0.2143</td></tr>
</table>

Table 139

| TIME<br>40.0<br>SECONDS | Lub.Type :Magnesium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.567 | 6.867 | 12.5 | 11.933 | 16.16 | 17.0 | 17.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 120.12 | 223.1 | 361.11 | 348.51 | 442.60 | 461.11 | 461.11 |
| Friction Coefficient | 0.4004 | 0.3718 | 0.4012 | 0.2904 | 0.2951 | 0.2562 | 0.2196 |

Table 140

| TIME<br>50.0<br>SECONDS | Lub.Type :Magnesium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.833 | 7.167 | 12.50 | 13.00 | 17.167 | 18.4 | 18.5 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 128.71 | 232.07 | 361.11 | 372.22 | 464.82 | 492.22 | 494.44 |
| Friction Coefficient | 0.4291 | 0.3868 | 0.4012 | 0.3102 | 0.3099 | 0.2735 | 0.2355 |

Table 141

| TIME<br>60.0<br>SECONDS | Lub.Type :Magnesium Stat.,Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.867 | 7.0 | 12.833 | 14.167 | 17.20 | 17.65 | 19.5 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 129.81 | 227.08 | 368.51 | 398.15 | 465.55 | 475.55 | 516.66 |
| Friction Coefficient | 0.4323 | 0.3785 | 0.4095 | 0.3318 | 0.3104 | 0.2642 | 0.2460 |

Table 142

| TIME 1.0 SECONDS | Lub.Type :Magnesium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.433 | 5.0 | 4.033 | 5.767 | 5.667 | 9.333 | 9.333 |
| Applied Load ( G ) | 300.0 | 600.0 | 900.0. | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 115.78 | 165.8 | 172.96 | 211.49 | 209.27 | 290.73 | 290.73 |
| Friction Coefficient | 0.3859 | 0.2763 | 0.1922 | 0.1762 | 0.1395 | 0.1615 | 0.1384 |

Table 143

| TIME<br>5.0<br>SECONDS | Lub.Type :Magnesium Stat.,Density :6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.933 | 3.233 | 4.667 | 7.333 | 6.167 | 12.667 | 12.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 66.233 | 109.26 | 187.04 | 246.29 | 220.38 | 364.82 | 353.71 |
| Friction Coefficient | 0.2208 | 0.1821 | 0.2078 | 0.2052 | 0.1469 | 0.2027 | 0.1684 |

Table 144

| TIME<br>10.0<br>SECONDS | Lub.Type :Magnesium Stat.,Density : 6.5 g /cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.333 | 4.10 | 6.167 | 10.167 | 7.667 | 18.667 | 16.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 79.603 | 137.29 | 220.38 | 309.27 | 253.71 | 498.15 | 438.89 |
| Friction Coefficient | 0.2653 | 0.2288 | 0.2449 | 0.2577 | 0.1691 | 0.2768 | 0.209 |

Table 145

| TIME<br>20.0<br>SECONDS | Lub.Type :Magnesium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.5 | 5.833 | 7.1 | 11.667 | 20.833 | 20.833 | 20.333 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 85.151 | 191.68 | 241.11 | 342.60 | 546.29 | 546.29 | 535,17 |
| Friction Coefficient | 0.2838 | 0.3195 | 0.2679 | 0.2855 | 0.3642 | 0.3035 | 0.2548 |

Table 146

| TIME 40.0 SECONDS | Lub.Type :Magnesium Stat.,Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.10 | 6.0 | 8.267 | 11.533 | 13.067 | 26.00 | 25.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 104.92 | 196.8 | 267.04 | 339.62 | 373.62 | 661.11 | 657.4 |
| Friction Coefficient | 0.3497 | 0.328 | 0.2967 | 0.283 | 0.2491 | 0.3673 | 0.3131 |

Table 147

| TIME 50.0 SECONDS | Lub.Type :Magnesium Stat.,Density : 6.5 g/ cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.17 | 6.0 | 8.333 | 12.10 | 13.80 | 23.50 | 25.867 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 107.11 | 196.8 | 268.51 | 352.22 | 389.99 | 605.55 | 658.15 |
| Friction Coefficient | 0.357 | 0.328 | 0.2983 | 0.2935 | 0.260 | 0.3364 | 0.3134 |

Table 148

| TIME<br>60.0<br>SECONDS | Lub.Type :Magnesium Stat.,Density : 6.5 $g/cm^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.233 | 6.10 | 8.667 | 12.233 | 14.33 | 23.667 | 26.667 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 109.26 | 199.86 | 275.93 | 355.18 | 401.84 | 609.26 | 675.93 |
| Friction Coefficient | 0.3642 | 0.3331 | 0.3066 | 0.296 | 0.2679 | 0.3385 | 0.3219 |

Table 149

| TIME<br>1.0<br>SECONDS | Lub.Type : Magnesium Stat.,Density :6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.267 | 5.3 | 4.967 | 5.333 | 6.933 | 7.767 | 7,5 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 110.37 | 175.18 | 193.71 | 201.84 | 237.40 | 255.93 | 249.99 |
| Friction Coefficient | 0.3679 | 0.292 | 0.2152 | 0.1682 | 0.1583 | 0.1422 | 0.1191 |

Table 150

| TIME<br>5.0<br>SECONDS | Lub.Type :Magnesium Stat.,Density :6.8 g /cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.567 | 4.50 | 4.2 | 5.7 | 8.267 | 9.900 | 10.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Coefficient | 0.1797 | 0.2501 | 0.1963 | 0.175 | 0.178 | 0.1685 | 0.1543 |
| Friction Force ( g ) | 53.899 | 150.03 | 176.67 | 209.99 | 267.04 | 303.33 | 324.07 |

Table 151

| TIME<br>10.0<br>SECONDS | Lub.Type :Magnesium Stat.,Density : 6.8 g/$cm^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.9 | 5.5 | 5.6 | 8.167 | 10.833 | 12.00 | 13.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1900.0 | 2100.0 |
| Friction Force ( g ) | 65.125 | 181.39 | 207.78 | 264.82 | 324.82 | 349.99 | 375.93 |
| Friction Coefficient | 0.2171 | 0.3023 | 0.2309 | 0.2207 | 0.216 | 0.1944 | 0.179 |

Table 152

| TIME<br>20.0<br>SECONDS | Lub.Type : Magnesium Stat.,Density : 6.8 g/$cm^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.3 | 6.333 | 7.0 | 10.80 | 13.167 | 15.667 | 17.5 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 111.45 | 206.97 | 238.89 | 323.33 | 375.93 | 431.49 | 472.22 |
| Friction Coefficient | 0.3715 | 0.3449 | 0.2654 | 0.2694 | 0.2506 | 0.2397 | 0.2249 |

Table 153

| TIME<br>40.0<br>SECONDS | Lub.Type : Magnesium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.367 | 6.667 | 6.733 | 9.333 | 12.20 | 16.567 | 19.033 |
| Applied Load ( g ) | 300.0 | 600.0 | 9000.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Coefficient | 0.2691 | 0.2318 | 0.2588 | 0.2423 | 0.2363 | 0.2508 | 0.2411 |
| Friction Force ( g ) | 80.73 | 217.08 | 232.96 | 290.73 | 354.44 | 451.49 | 506.29 |

Table 154

| TIME<br>50.0<br>SECONDS | Lub.Type : Magnesium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.733 | 6.233 | 6.133 | 11.167 | 12.367 | 18.333 | 19.50 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 92.857 | 203.92 | 219.62 | 331.49 | 358.15 | 290.73 | 416.66 |
| Friction Coefficient | 0.3095 | 0.3399 | 0.2440 | 0.2762 | 0.2388 | 0.2726 | 0.2460 |

Table 155

| TIME<br>60.0<br>SECONDS | Lub.Type : Magnesium Stat.,Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % ,Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.333 | 6.033 | 6.467 | 11.33 | 13.167 | 18.833 | 16.50 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 79.603 | 197.81 | 227.04 | 335.18 | 375.93 | 501.84 | 449.99 |
| Friction Ceefficient | 0.2653 | 0.3297 | 0.2523 | 0.2793 | 0.2506 | 0.2788 | 0.2143 |

Table 156

| TIME<br>1.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.3 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.0 | 4.667 | 4.133 | 4.0 | 5.75 | 8.0 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 134.08 | 155.32 | 175.18 | 172.22 | 211.11 | 261.11 | - |
| Friction Coefficient | 0.4469 | 0.2589 | 0.1946 | 0.1435 | 0.1407 | 0.1451 | - |

Table 157

| TIME<br>5.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.3 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 1.667 | 4.5 | 4.5 | 4.25 | 6.75 | 10.50 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 57.28 | 150.03 | 183.33 | 177.78 | 233.33 | 316.66 | - |
| Friction Coefficient | 0.1909 | 0.2501 | 0.2037 | 0.1482 | 0.1556 | 0.1759 | - |

Table 158

<table>
<tr><td>TIME<br>10.0<br>SECONDS</td><td colspan="7">Lub.Type : Sodium Stat., Density :6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute .</td></tr>
<tr><td>Out Put ( mv )</td><td>2.08</td><td>5.167</td><td>6.10</td><td>6.90</td><td>8.75</td><td>14.25</td><td>-</td></tr>
<tr><td>Applied Load ( g )</td><td>300.0</td><td>600.0</td><td>900.0</td><td>1200.0</td><td>1500.0</td><td>1800.0</td><td>2100.0</td></tr>
<tr><td>Friction Force ( g )</td><td>71.26</td><td>171.03</td><td>218.89</td><td>236.67</td><td>277.78</td><td>399.99</td><td>-</td></tr>
<tr><td>Friction Coefficient</td><td>0.2375</td><td>0.2851</td><td>0.2432</td><td>0.1972</td><td>0.1952</td><td>0.2222</td><td>-</td></tr>
</table>

Table 159

<table>
<tr><td>TIME<br>20.0<br>SECONDS</td><td colspan="7">Lub.Type :Sodium Stat., Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute .</td></tr>
<tr><td>Out Put ( mv )</td><td>3.0</td><td>6.33</td><td>6.867</td><td>8.25</td><td>11.75</td><td>15.25</td><td>-</td></tr>
<tr><td>Applied Load ( g )</td><td>300.0</td><td>600.0</td><td>900.0</td><td>1200.0</td><td>1500.0</td><td>1800.0</td><td>2100.0</td></tr>
<tr><td>Friction Force ( g )</td><td>101.64</td><td>206.97</td><td>235.93</td><td>266.67</td><td>344.44</td><td>422.22</td><td>-</td></tr>
<tr><td>Friction Coefficient</td><td>0.3388</td><td>0.3449</td><td>0.2622</td><td>0.2222</td><td>0.2296</td><td>0.2346</td><td>-</td></tr>
</table>

Table 160

| TIME<br>40.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.3 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.867 | 7.833 | 11.167 | 12.250 | 16.750 | 20.250 | - |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 129.81 | 251.76 | 331.49 | 355.55 | 455.55 | 533.33 | - |
| Friction Coefficient | 0.4327 | 0.4196 | 0.3683 | 0.2963 | 0.3037 | 0.2963 | - |

Table 161

<table>
<tr><td>TIME<br>50.0<br>SECONDS</td><td colspan="7">Lub.Type : Sodium Stat., Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute .</td></tr>
<tr><td>Out Put ( mv )</td><td>4.333</td><td>8.433</td><td>11.50</td><td>14.50</td><td>19.0</td><td>20.50</td><td>-</td></tr>
<tr><td>Applied Load ( g )</td><td>300.0</td><td>600.0</td><td>900.0</td><td>1200.0</td><td>1500.0</td><td>1800.0</td><td>2100.0</td></tr>
<tr><td>Friction Force ( g )</td><td>144.72</td><td>269.22</td><td>338.89</td><td>405.55</td><td>505.55</td><td>538.89</td><td>-</td></tr>
<tr><td>Friction Coefficient</td><td>0.4824</td><td>0.4487</td><td>0.3765</td><td>0.3380</td><td>0.3370</td><td>0.2994</td><td>-</td></tr>
</table>

Table 162

<table>
<tr><td>TIME<br>60.0<br>SECONDS</td><td colspan="7">Lub.Type : Sodium Stat., Density : 6.3 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute .</td></tr>
<tr><td>Out Put ( mv )</td><td>4.5</td><td>8.7</td><td>12.5</td><td>17.25</td><td>21.0</td><td>20.75</td><td>-</td></tr>
<tr><td>Applied Load ( g )</td><td>300.0</td><td>600.0</td><td>900.0</td><td>1200.0</td><td>1500.0</td><td>1800.0</td><td>2100.0</td></tr>
<tr><td>Friction Force ( g )</td><td>150.03</td><td>276.91</td><td>361.11</td><td>466.66</td><td>549.99</td><td>544.44</td><td>-</td></tr>
<tr><td>Friction Coefficient</td><td>0.50</td><td>0.4615</td><td>0.4012</td><td>0.3889</td><td>0.3667</td><td>0.3025</td><td>-</td></tr>
</table>

Table 163

| TIME<br>1.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.5 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.333 | 4.967 | 3.2 | 4.433 | 4.933 | 5.633 | 7.95 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 144.72 | 164.77 | 154.44 | 181.84 | 192.96 | 208.51 | 259.99 |
| Friction Coefficient | 0.4824 | 0.2746 | 0.1716 | 0.1515 | 0.1286 | 0.1158 | 0.1238 |

Table 164

| TIME<br>5.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.433 | 3.20 | 3.667 | 7.0 | 5.667 | 8.333 | 9.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 115.78 | 108.19 | 164.82 | 238.89 | 209.27 | 268.51 | 283.33 |
| Friction Coefficient | 0.3859 | 0.1803 | 0.1831 | 0.1991 | 0.1395 | 0.1492 | 0.1349 |

Table 165

| TIME<br>10.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.167 | 3.9 | 5.4 | 9.0 | 8.367 | 10.667 | 12.75 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 139.43 | 130.87 | 203.33 | 283.33 | 269.27 | 320.38 | 366.66 |
| Friction Coefficient | 0.4648 | 0.2181 | 0.2259 | 0.2361 | 0.1795 | 0.1780 | 0.1746 |

Table 166

| TIME<br>20.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 5.2 | 6.333 | 7.433 | 9.933 | 11.60 | 14.067 | 17.250 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 172.06 | 206.97 | 248.51 | 304.07 | 341.11 | 395.93 | 466.66 |
| Friction Coefficient | 0.5735 | 0.3449 | 0.2761 | 0.2534 | 0.2274 | 0.220 | 0.2222 |

Table 167

| TIME<br>40.0<br>SECONDS | Lub.Type : Sodium Stat., Density ;6.5 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 6.1 | 7.1 | 8.433 | 14.33 | 14.667 | 16.50 | 19.75 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 199.86 | 230.07 | 270.73 | 401.78 | 409.26 | 449.99 | 522.22 |
| Friction Coefficient | 0.6662 | 0.3835 | 0.3008 | 0.3348 | 0.2728 | 0.250 | 0.2487 |

Table 168

<table>
<tr><td>TIME<br>50.0<br>SECONDS</td><td colspan="7">Lub.Type : Sodium Stat., Density : 6.5 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : $6.0287 \times 10^3$ cm / minute .</td></tr>
<tr><td>Out Put ( mv )</td><td>5.9</td><td>7.333</td><td>8.833</td><td>12.93</td><td>15.0</td><td>18.5</td><td>20.00</td></tr>
<tr><td>Applied Load ( g )</td><td>300.0</td><td>600.0</td><td>900.0</td><td>1200.0</td><td>1500.0</td><td>1800.0</td><td>2100.0</td></tr>
<tr><td>Friction Force ( g )</td><td>193.74</td><td>237.01</td><td>279.62</td><td>370.73</td><td>416.66</td><td>494.44</td><td>527.77</td></tr>
<tr><td>Friction Coefficient</td><td>0.6457</td><td>0.395</td><td>0.3107</td><td>0.3098</td><td>0.2778</td><td>0.2747</td><td>0.2513</td></tr>
</table>

Table 169

<table>
<tr><td>TIME<br>60.0<br>SECONDS</td><td colspan="7">Lub.Type : Sodium Stat., Density : 6.5 $g/ cm^3$<br>Lub.Ratio: 1.0 wt % , Distance:18086.1 cm<br>Speed : $6.0287 \times 10^3$ cm / minute .</td></tr>
<tr><td>Out Put ( mv )</td><td>6.0</td><td>7.7</td><td>10.067</td><td>12.03</td><td>15.167</td><td>15.40</td><td>23.75</td></tr>
<tr><td>Applied Load ( G )</td><td>300.0</td><td>600.0</td><td>900.0</td><td>1200.0</td><td>1500.0</td><td>1800.0</td><td>2100.0</td></tr>
<tr><td>Friction Force ( g )</td><td>196.80</td><td>247.85</td><td>307.04</td><td>350.73</td><td>420.38</td><td>425.55</td><td>611.11</td></tr>
<tr><td>Friction Coefficient</td><td>0.656</td><td>0.4131</td><td>0.3412</td><td>0.2923</td><td>0.2803</td><td>0.2364</td><td>0.291</td></tr>
</table>

Table 170

| TIME<br>1.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 4.033 | 4.433 | 4.6 | 3.833 | 4.767 | 5.633 | 5.0 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 135.14 | 147.91 | 185.56 | 168.51 | 189.27 | 208.51 | 194.44 |
| Friction Coefficient | 0.4505 | 0.2465 | 0.2062 | 0.1404 | 0.1262 | 0.1158 | 0.0926 |

Table 171

| TIME<br>5.0<br>SECONDS | Lub.Type : Sodium Stat., Density :6.8 g/$cm^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.267 | 3.333 | 4.167 | 4.176 | 6.0 | 7.833 | 7.333 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 77.405 | 112.53 | 175.93 | 175.93 | 216.67 | 257.40 | 246.29 |
| Friction Coefficient | 0.2580 | 0.1875 | 0.1955 | 0.1466 | 0.1444 | 0.143 | 0.1173 |

Table 172

| TIME<br>10.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.8 g /$cm^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x $10^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 2.833 | 3.676 | 5.176 | 5.833 | 8.667 | 8.833 | 9.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 96.153 | 123.65 | 198.16 | 212.96 | 275.93 | 279.62 | 301.84 |
| Friction Coefficient | 0.3205 | 0.2061 | 0.2202 | 0.1775 | 0.1839 | 0.1553 | 0.1437 |

Table 173

| TIME<br>20.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.733 | 6.167 | 7.333 | 8.5 | 9.767 | 11.00 | 12.33 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 125.49 | 201.91 | 246.29 | 272.22 | 300.38 | 327.78 | 357.40 |
| Friction Coefficient | 0.4183 | 0.3365 | 0.2737 | 0.2269 | 0.2002 | 0.1821 | 0.1702 |

Table 174

| TIME<br>40.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.8 g /cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.667 | 6.0 | 7.0 | 7.5 | 8.333 | 8.767 | 7.667 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 123.36 | 196.8 | 238.89 | 249.99 | 268.51 | 278.15 | 253.71 |
| Friction Coefficient | 0.4112 | 0.328 | 0.2654 | 0.2083 | 0.179 | 0.1545 | 0.1208 |

Table 175

| TIME<br>50.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.8 g/cm$^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 x 10$^3$ cm / minute . | | | | | | |
|---|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.5 | 5.833 | 6.667 | 7.167 | 8.333 | 9.40 | 7.833 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 117.95 | 191.67 | 231.49 | 242.60 | 268.51 | 292.22 | 257.40 |
| Friction Coefficient | 0.393 | 0.3195 | 0.2572 | 0.2022 | 0.179 | 0.1623 | 0.1226 |

Table 176

| TIME<br>60.0<br>SECONDS | Lub.Type : Sodium Stat., Density : 6.8 $g/cm^3$<br>Lub.Ratio: 1.0 wt % , Distance: 18086.1 cm<br>Speed : 6.0287 cm / minute . | | | | | |
|---|---|---|---|---|---|---|
| Out Put ( mv ) | 3.9 | 5.667 | 6.667 | 7.333 | 8.067 | 10.10 | 7.167 |
| Applied Load ( g ) | 300.0 | 600.0 | 900.0 | 1200.0 | 1500.0 | 1800.0 | 2100.0 |
| Friction Force ( g ) | 130.87 | 186.56 | 231.49 | 246.29 | 262.60 | 307.78 | 242.60 |
| Friction Coefficient | 0.4362 | 0.3109 | 0.2572 | 0.2052 | 0.1751 | 0.171 | 0.1155 |

Table 177

Effect of Running Time on the Friction Coefficient

Load :600.0 g ,Distance:1.80861 x$10^4$ cm

Calcium St.Ratio: 1.0 wt% ,Speed :6.0287 x$10^3$ cm/min.

Friction Coefficient

| Density g/cm$^3$ / Time secs. | 5.5360 | 5.9320 | 6.30 | 6.50 | 6.80 |
|---|---|---|---|---|---|
| 1.00 | 0.2407 | 0.19711 | 0.2160 | 0.2243 | 0.22346 |
| 5.00 | 0.2160 | 0.2209 | 0.2095 | 0.21605 | 0.24074 |
| 10.00 | 0.2531 | 0.2473 | 0.2424 | 0.25309 | 0.29259 |
| 15.00 | 0.2654 | 0.24896 | 0.2572 | 0.2844 | 0.29834 |
| 20.00 | 0.2654 | 0.2539 | 0.26296 | 0.27778 | 0.29259 |
| 25.00 | 0.2654 | 0.26625 | 0.26955 | 0.29012 | 0.28684 |
| 30.00 | 0.2531 | 0.31481 | 0.3140 | 0.2860 | 0.2720 |
| 40.00 | 0.2531 | 0.36667 | 0.34526 | 0.30328 | 0.26955 |
| 50.00 | 0.26049 | 0.37654 | 0.39352 | 0.31481 | 0.2819 |
| 60.00 | 0.2654 | 0.37079 | 0.3642 | 0.31481 | 0.2737 |
| 120.00 | 0.3395 | 0.39711 | 0.3395 | 0.35185 | 0.24239 |

Table 178

Effect of Density and Hardness

Time : 1.0 sec.
Calcium Lub.Ratio: 1.0 wt %
Applied Load : 600.0 g

| Hardness (VHK) | Density ($g/cm^3$) | Friction Coefficient |
|---|---|---|
| 10.0 | 5.5360 | 0.240740 |
| 18.0 | 5.9300 | 0.19711 |
| 26.0 | 6.300 | 0.21605 |
| 33.0 | 6.500 | 0.22427 |
| 38.0 | 6.800 | 0.22346 |

Table 179

Effect of Density and Hardness

Time : 5.0 sec.
Calcium Lub.Ratio: 1.0 wt %
Applied Load : 600.0 g

| Hardness (VHK) | Density $(g/cm^3)$ | Friction coefficient |
|---|---|---|
| 10.0 | 5.536 | 0.21605 |
| 18.0 | 5.932 | 0.22099 |
| 26.0 | 6.30 | 0.20946 |
| 33.0 | 6.50 | 0.21605 |
| 38.0 | 6.80 | 0.24074 |

Table 180

Effect of Density and Hardness

Time : 30.0 sec.
Calcium Lub.Ratio: 1.0 wt %
Applied Load : 600.0 g

| Hardness (VHK) | Density $(g/cm^3)$ | Friction Coefficient |
|---|---|---|
| 10.0 | 5.536 | 0.253090 |
| 18.0 | 5.932 | 0.314810 |
| 26.0 | 6.30 | 0.31400 |
| 33.0 | 6.50 | 0.28600 |
| 38.0 | 6.80 | 0.27202 |