A history of wear and wear prevention 1700-1940

Thesis

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A HISTORY OF WEAR AND WEAR PREVENTION 1700-1940

by

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PREFACE

Some of the more recently published books on tribology have included aspects of the history of friction or lubrication, but, at the time when I began this research (1977), no publication gave a complete account of the history of tribology. My original intention was to write such an account, and the material which is presented in Chapters 1 and 2 was collected during 1977 and 1978 and submitted to the Open University as research credits. The research on the work of Hirn was carried out during 1979.

In 1979 Professor Dowson published his "History of Tribology", the result of more than a decade of patient and painstaking research. This book covers very many aspects of the history of the subject, and is broad in time and scope. However, only a few examples of studies of wear prior to 1940 are given, and their is little information on the metallurgy of bearing alloys prior to this date. This resulted in a change of course in my research towards an historical account of scientific studies of wear in the period leading up to the Second World War, and the various method that were used to mitigate the effects of wear.

The material contained in this thesis is the product of the author's own research, and has not previously been published, or submitted for any other degree or qualification.

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ABSTRACT

Much of the present knowledge of the processes involved in the wear of materials has been derived since the end of the Second World War. This thesis shows, however, that many of the basic concepts of wear were understood, at least empirically, prior to 1940. Factors which influenced the rate of wear of components in machines began to be investigated during the second half of the last century, and particular combinations of sliding

materials were chosen to give an adequate wear life for their applications.

As background, the first two chapters describe the work on sliding and rolling friction during the eighteenth and nineteenth centuries. The third chapter present evidence which shows how the empirical understanding of wear developed up to 1940. This covers wear in both sliding and rolling contact, the relationship between wear and hardness as well as wear under abrasive conditions. The next chapter shows how the concept of the real area of contact, as opposed to the apparent area, emerged from studies of the electrical resistance between two metals in contact. With this technique, measurements of the real area of contact between surfaces under various loads were made in the late nineteen thirties. The chapter also traces the development of instruments for assessing the roughness of surfaces during the same decade.

Chapters 5,6 and 7 deal with wear prevention. Chapter 5 shows how developments in plain bearings kept pace with the duties imposed on them and describes some special forms, such as the "anti-friction" pivot and the marine thrust bearing. Data is also provided on the way in which the loads and speeds of bearings increased from 1700 to 1900. Chapter 6 deals with fluid lubrication and with the pioneering work of G.A.Hirn. Hirn's experiments were the first to demonstrate convincingly the complete separation of surfaces by a film of fluid. In chapter 7 the advances in metallurgy which enabled improved bearing metals to be made are outlined. In particular, the origins of the production of high-lead bronzes is described. These alloys proved to be highly wear resistant. Some aspects of white metals (both lead and tin based) are also described.

The emphasis in the thesis is on the practical steps which were taken to mitigate the detrimental aspects of wear and to develop wear resistant materials, particularly for sliding bearings. The evidence presented shows that whilst separation of surfaces by a fluid film is the ideal means of preventing wear, in many instances lubrication conditions were far from ideal.

CHAPTER 1

THE FRICTION OF SOLID BODIES: EXPERIMENT AND THEORY IN THE EIGTHEENTH CENTURY

1.1 Introduction.

Tribology as a subject is nearly twenty years old. It is a name which was coined in 1966 [HMSO 1966] for the "science and technology of interacting surfaces in relative motion and of practices relating thereto" and is derived from the Greek "tribos" meaning "to rub". It thus encompasses friction lubrication and wear and their effects on all bodies in relative motion. However, whilst the modern theories of friction emerged between 1938-40 [Bowden 1950,Ernst 1940] and the theory of fluid lubrication in the last quarter of the nineteenth century [Cameron 1966], these subjects have been written about since the Renaissance. Indeed techniques for mitigating the resistance to movement were practised by the early civilisations [Davison 1957].

A number of recently published books on tribology [Halling 1973,1974] begin with an outline of the history of the subject. Others have chapters giving an historical survey of earlier theoretical and experimental work on sliding and rolling friction [Bowden 1964] or on journal bearing history. There have also been papers presented to engineering institutions giving an historical outline of tribology history [Dowson 1974].

Friction is the resistance to relative motion between two surfaces that are in direct contact [Bronowski 1963] and lubrication concerns the reduction of friction and wear by interposing a layer, either liquid or solid, between the relatively moving surfaces. Wear has been defined [Inst.Mech.Engrs.1967] as "progressive loss of substance from the surface of a body brought about by mechanical action". These are essentially modern definitions, although the distinction between, for example friction and wear, has not been made so clearly by early writers. Terms such as attrition and abrasion have been used in describing the effects of both friction and wear.

It is clear that the Egyptians used techniques for reducing friction. Bow drills were used by them [Davison 1957] and these incorporated hand-supported stone or wooden bearings. Exploration of the tomb of Yucca and Thuiu revealed that one of the chariots still had some of the original lubricant on the axle [Bowden 1964] and it has been suggested that it might have been mutton or beef tallow [Davison 1957]. A mural painting in a grotto at El Bersheh, dated about 1880 BC has been the cause of some speculation. The mural depicts a stone colossus being pulled along on a sledge moving on a path of trimmed tree branches. Teams of slaves are shown pulling on ropes whilst a man on the sledge pours lubricant from a jar onto the ground immediately in front of the sledge. Making assumptions of the weight of the colossus and the average pull of the team, Dowson [Dowson 1974] and others [Halling 1973,1974] have shown that the coefficient of friction (the ratio of pull to load) is roughly what would be expected for wet wood sliding on wet wood. The original suggestion [Layard 1853] that wooden rollers were used in the transportation of these large stone blocks has been questioned by Davison [Davison 1957] who argued that the rollers are depicted parallel to to the direction of movement and that they are neither round nor straight. He suggested that they were used as a pathway on which the load moved.

An archaeological discovery of the 1920's when two sunken Roman ships were exposed in Lake Nimi, Italy, revealed a number of trunnion mounted bronze balls and wooden taper rollers dated at around AD 50. these are believed to have come from thrust bearings of a revolving wooden platform, and, as Dowson [Dowson 1974] comments "we thus find the sudden appearance of rolling element bearings which form the basis of modern arrangements".

Much study of the sketches of Leonardo da Vinci (1452-1519) in the last seventy years [MacCurdy 1938] has revealed the scope of his interest in mechanics both in the theory and classification of mechanical elements and his practical approach [Reti 1974]. The discovery of the Madrid Codex in 1967 [Reti 1974], which deals almost exclusively with theoretical and applied mechanics, has led to speculation that Leonardo intended to write a book on this subject. It became evident in the 1920's that Leonardo had investigated the phenomena of friction [Benton 1926]. MacCurdy's translations [MacCurdy 1938] of Leonardo's writing contain two important statements on friction. The first is that "friction produces double the amount of effort if the weight be doubled", and also, "the friction made by the same weight will be of equal resistance at the beginning of its movement although the contact may be of different breadths or lengths". These are statements of the two accepted laws of friction; that it is proportional to the applied load and independent of the area of the bodies in contact. Thus the formulation of the same laws by Amontons in 1699 was predated by almost 200 years [Bowden 1964].

Both Reti in a recent article [Reti 1974], and Kraghelsky and Shchedrov in their monograph on the history of friction [Kraghelsky 1956] have reproduced the sketches of

Leonardo depicting experimental methods for measuring the friction between both plane surfaces and the cylindrical surfaces of bearings. According to Reti [Reti 1974] "he introduced the concept of the coefficient of friction and estimated that for "polished and smooth" surfaces the ratio of F/P was 0.25, or one fourth of the weight". He also recognised that friction could be reduced by interposing rolling elements or lubricating fluids between the surfaces in contact.

The Madrid Codices provide new evidence that Leonardo analysed the effects of friction in machines and sketched methods of turning it to advantage, for example in belt drives. He was also concerned with the shape taken up by axles as they wear in bearings, and with methods of preventing wear. He sketched a design for a bearing with split bushes which could be adjusted to take up wear. The cheeks of the block, in which the axle rotated, would be made of smooth "mirror metal" consisting of "three parts copper and seven of tin melted together". Again this anticipated the designs of bearings of similar principle by Plumier [Plumier 1701] in his book "L'art de tourner en perfection". Also Leonardo sketched different forms of true rolling bearings which used either straight or tapered rollers as well as balls.

Thus in many respects Leonardo anticipated the developments of later centuries in his study of friction and in his practical designs for bearings. However, since his manuscripts and notes were dispersed after his death, and some only published in 1890-1905, his influence was lost to those who followed. Nor is there any evidence that his designs were ever turned into real components.

1.2 The Eighteenth Century.

1.2.1 The French school and the "inclined plane" theory of friction.

Traditionally, those writing on the history of friction and the development of ideas concerning it, have, after describing the work of Leonardo, turned to the French scholars of the late seventeenth and early eighteenth centuries as a staring point for the chronological development of theories of friction. Kraghelsky and Shchedrov adopted a strictly chronological approach with Leonardo as the starting point. They dealt in this way with both experimental and theoretical developments and with the people connected with them. Bowden and Tabor traced the development along similar lines but chose to deal mainly with the theories put forward to explain friction and divided the subject into the French and English schools.

However, the subject of the history of friction can be discussed and classified according to the school of thought, the theory and the important question which concerned the writers of the time. This method is not strictly chronological, but it does contrast the opinions held at a particular time. The train of argument and discussion can be traced, and also the way in which opinions were fostered by the results of a variety of experiments. The history of the development of ideas on friction is essentially one of laws and principles formulated from experimental evidence. As is the case today, in the eighteenth century there were as many different types of friction-measuring apparatus as people involved in the subject.

The science of classical mechanics had its origin in the seventeenth century. Galileo rejected the Aristotelian philosophy [Crombie 1959] in favour of analysis and abstraction of physical phenomena by experiment. Part of his book "Two New Sciences", published in 1638 towards the end of his life, was concerned with the motion of bodies. According to one biographer of Galileo [Gillespie 1970] this work "underlies modern physics not only because it contains the elements of the mathematical treatment of motion but also because most of the problem came rather quickly to be seen as problems amenable to physical experiment".

Thus the systematic study of the friction of solids, essentially and experimental study, was made possible by the work of Galileo, and later Newton. There was also the dawn of the awareness of motive power with the developments of Papin and Savery on heat engines [Kolin 1972]. In 1699, Amontons, in a Memoir to the French Royal Academy of Sciences [Academie Royale 1702] described his "Moulin a Feu", and engine which used the expansion of heated air to do work.

The History of the Royal Academy of Sciences, Paris for 1699, written by the secretary Fontenelle, contains the following passage:

> "In the discourse of M. Amontons on his heat engine he advanced, only i passing, that it was a commonly made error of belief that the friction of two bodies which move in being applied one against the other would be greater the greater the rubbing surfaces. He said that he had found by experiment that the friction increased accordingly as the bodies are pressed against each other and covered with a greater weight".

Also in the History for 1699, from the English translation by Chambers and Martyn (1742) [Martyn 1742], is a description of an experiment with which Amontons was connected on the polishing of glass. Here the polishing discs were forced against the glass by flexed springs called arrows. From the five experiments quoted the following observation is drawn:

> "From these experiments we may observe, by the by, that it is an error to think that the friction in machines increases or diminishes in proportion as the parts which rub are more or less extended; and that wheels, for example, of a mill turn so much the more easily as the gudgeons are shorter".

Late in 1699, Amontons presented a Memoir to the Academy entitled "De la resistance causee dans les machines tout par les frottements des parties qui les composent, que par la roideur des cordes qu'on y employe, et la maniere de calculer l'un l'autre". The Memoir [Amontons 1699] bears the date of 19th December, 1699 and in it Amontons presented a discussion on the friction in machines with the conclusions from his experiments on the stiffness of ropes. Amontons described his experimental work on friction as follows;

> "We put on some planes of copper, iron, lead and wood anointed with old lard, other planes of like materials and different bignesses; they were pressed one upon the other differently by springs ..... of which the quantity of pressure was known. these planes were changed all possible ways .... and at each time we observed with a spring balance the quantities of force necessary to make them move".

A table of results is not given but the conclusions are set out clearly:

> "First, that the resistance caused by the friction increases and diminishes only in proportion to the greater of less pressures, according as the parts which rub have more or less extent".
>
> "Second, that the resistance caused by the friction is nearly the same in the iron, the copper, the lead and the wood, let them be varied how you will, when these substances are anointed with old lard".
>
> "Third, that this resistance is nearly equal to a third of the pressure".

there then follows a discourse on the effect of leverage on the resistance of friction; the example chosen is that of a disc turning on a flat plane. the resistance to turning will decrease as the turning force moves further away from the centre. Amontons extended this reasoning to the axle of a waggon. He argued, rightly, that the greater the ratio of the wheel diameter to that of the axle, the less will be the resistance. After this discourse he then went on to say:

> "But though all the experiments above related seem to prove sufficiently, that the resistance caused by the friction of the surfaces which rub increase or diminishes according to the greater or less pressures and not according to the greater or less extent of these surfaces; as this does not always suffice to convince a reasonable mind, it is good, however, to establish this truth by demonstrating".

Amontons' view of the cause of friction was that it arose because of the roughnesses on the surfaces of bodies interlock and act like small inclined planes. These roughnesses must then be raised over each other when the surfaces slide. His argument that the friction does not depend on the extent of the surfaces was as follows. For surfaces of different extents (surface areas) loaded with the same weight, the surface of greater area will be subjected to a lower pressure assuming the load to be uniformly distributed over the area. Also (assuming the surfaces to be equally rough, i.e. to have the same height of roughness), the product of the pressure and the area, and the height to which it must be raised, will be a constant.

Thus:

> ".. it follows also that the resistance caused by the friction of the surfaces of different extents is always the same when they are loaded with equal weights".

Amontons also reasoned that the same holds true whether the surface inequalities are rigid or elastic since the force needed to bend the elastic irregularity would be the same as to raise the load to the same height.

Further demonstrations that the resistance of friction is independent of area of contact are then put forward before Amontons moves on to the stiffness of ropes.

This "inclined plane" theory of friction as proposed by Amontons is based on the reasoning that, for a given load between two surfaces, the number of roughnesses in contact is proportional to the area of the surfaces. the more points in contact, given that the load is equally distributed, the lower the fraction of load will each bear; yet the resistance of friction is the product of the number of points in contact, the load each bears and the heights to which they must be raised over the opposing roughnesses. Thus the frictional resistance is proportional to load and not to surface area.

It is clear that the Academy was sceptical about this hypothesis. Referring again to the history for 1699 :-

> "This novelty (that friction is independent of the area of he surfaces) caused some astonishment at the Academy. M. de la Hire at once consulted experiment. He placed on an unpolished wooden table several pieces of wood whose sizes were unequal. He saw that to start them sliding on the table, by means of a weight attached to them and which passed over a small pulley, the same weight was required in spite of the inequality of the rubbing surfaces. the experiment had the same success with pieces of unpolished marble which slid on a marble table whose surface was similar".

Phillipe de la Hire was a senior member of the Academy, a painter and architect. His theory of the nature of friction, as reported in the History, was as follows. The resistance of friction, he reasoned, comes from the roughnesses of the surfaces. If the roughnesses are flexible they will bend over when the surfaces slide; if they are hard they will be disengaged. In the first case since the flexible, spring-like, roughnesses each bear apart of the load, they will bend according to the load they carry. Thus a large surface, with more roughnesses in contact, each less deflected, will have the same friction as a small surface where each roughness is more deflected. Where the roughnesses are hard and inflexible, De la

Hire argued, they are broken off "then their number makes the difficulty and then friction will follow the proportion of the surfaces".

Since Amontons' memoir was presented late in 1699 it is possible that De la Hire's experiments were carried out, and Amontons hypothesis on the effect of surface area checked, before Amontons read his memoir to the Academy. It is clear that Amontons anticipated difficulty in convincing his fellow Academicians of the truth of his statements. That scepticism still remained after his 1699 memoir was presented is evident from the History for succeeding years [Academie Royale 1704]. the History of the Academy for 1703 contains a section "on frictions" written by the Secretary, Fontenelle. It begins:

> "the new discovery of M.Amontons that frictions are always proportioned to the pressure and to the velocity, and never to the surfaces, was important enough not to be received without strict examination".

Several cases are cited in which, apparently, friction increases with surface area and Amontons explanations of these case are published. The writer continues:

> "Notwithstanding all these proofs and observations of M.Amontons who had set his system in a pretty good light, we are here obliged to acknowledge to the public that the Academy was not fully persuaded of it. They allowed that the pressure was to be considered, and often to be solely considered, but they could not, with M. Amontons, absolutely exclude consideration of the surface".

However, in 1704 a mathematical analysis of friction using model surface roughnesses was published in the History of the Academy for that year, and to some extent supported Amontons' experimental conclusions. This was the work of Antoine Parent, a member of the Academy and a mathematician [Parent 1704]. Parent used hemispheres as a model surface asperities. With two such surfaces in contact he calculated, for a given load, the force required to lift the roughnesses on one surface over those on the other. His analysis gave the ration of this force to the load as nearly one third; the same ratio put forward by Amontons.

Thus the experimental work of Amontons and the analysis of Parent began an era of experiment and speculation on the nature of friction. To quote Bowden and Tabor [Bowden 1964];

> "Although De la Hire's picture of the frictional process clearly involves surface deformation and shearing, the concept of rigid asperities continued to fascinate the French scientists of the day".

The inclined plane theory of friction was analysed by Leonard Euler in 1748. Euler presented two memoirs to the Royal Academy of Sciences in Berlin that year [Euler 1748]. The two memoirs appear consecutively in the History and Memoirs of the Academy for the year and are entitled respectively "On the friction of solid bodies", and "On the diminution of the resistance of friction".

Euler considered, like Amontons, that friction was due to the roughness of the surfaces and that materials such as wood and metal, of which machines were made, could not in practice be polished to a degree which would decrease their friction. Friction, wrote Euler, could be regarded as a force in the opposite sense to the direction of motion. He analysed the case of a body on an inclined plane; it just moves when $F\cos(a) = P\sin(a)$ where F is the friction force, P is the weight of the body, a the angle of the plane thus:

$$F/P = \tan(a) \quad \text{and } F/P = \mu$$

the same applies if the body is composed of several inclined planes. Indeed, the planes do not all need to have the same angle since the smaller angle do not facilitate movement and, Euler argued, the number of prominences does not affect the friction.

If the surface of a body is composed of a series of inclined planes, which rest on a similar surface, then in the course of movement the body ascends and descends alternately:

> "since the descents are made between themselves when the bodies move, the difficulty of friction is only felt at intervals, that is to say at the moments when the body is obliged to ascend. From which it appears ......that when the body is actually in motion the effect of friction will be half of that to set the body in motion".

Euler then described an experiment with a body on an inclined plane which is tilted until the ratio of the friction to the pressure is as the tangent of the angle. He calculated the accelerating force when the plane was inclined slightly above the equilibrium position and produced a mathematical expression for calculating the coefficient of kinetic friction. Euler noted that when the plane was raised above equilibrium angle the motion of the body down the plane does not occur slowly but takes place suddenly and in a short time.

Apart from his remarks on the "inclined plane" theory of friction, Euler's memoir is essentially an essay on the mechanics of a body descending down an inclined plane. However, the memoir is notable for the fact that an explanation is offered for the kinetic friction between two bodies and also that, despite his well-known work on the elasticity of solids, surface roughnesses are treated as rigid.

None of the writings on friction in the eighteenth century seems to contain a record or description of an actual examination of solid surfaces or of the kind or size of roughnesses on them. Only in Chambers Cyclopaedia of 1779 is there a reference to microscopic examination of surfaces:

> "witness those numerous ridges discovered by the microscope on the smoothest surfaces".

1.2.2 The English School: the Cohesion theory of Friction

An alternative explanation of the resistance of friction developed in England at much the same time that the "inclined plane" theory was being put forward in France. In 1734 Jean Theophile Desaguliers published "A Course of Experimental Philosophy" [Desaguliers 1763]. Desaguliers was the son of a French Protestant who left France and settled in England. In this book one lecture (Lecture V) is entitled "Concerning the Friction in Mechanical Engines". One of his first observations in this lecture is a practical one, which holds true even today. He wrote:

> "Tho' there are so many circumstances in the Friction of Bodies that the same Experiment does not always succeed with the same Bodies, so that a Mathematical

> theory cannot be easily settled; yet we may deduce a theory sufficient to direct us in our Practise from a great number of experiments, always taking a Medium between Extremes."

Desaguliers knew of Amontons' work on friction and he quotes the main results from Amontons' 1699 Memoir. However in 1725 Desaguliers had presented to the Royal Society [Desaguliers 1725] the results of some experiments on the cohesion of lead. He found that if two balls of lead of 1 to 2 pounds in weight, each having a small segment cut off them, were pressed together, considerable force was required to separate them. The force required to separate them varied between experiments, but in one case was as high as 45 pounds. This cohesion was not due to air pressure on the surfaces since Desaguliers observed that marble plates would cohere when suspended in the receiver of an air pump. In his lecture on friction he introduced this "Attraction of Cohesion" in connection with the friction of smooth surfaces:

> "For tho' one may at first imagine that metals must needs slip over one another more easily, because they may be made smoother and will take a better polish; yet it is found by experience, that the flat surfaces of metals or other bodies may be so far polished as to increase friction; and this is a mechanical paradox; but the reason will appear when we consider that the attraction of cohesion becomes sensible as we bring the surfaces of bodies nearer and nearer to contact".

Desaguliers included an English translation of Camus' "Traite des Forces Mouvantes" [Camus 1724] whose experiments on friction he said he had repeated with similar results. In discussing Camus' experiments, Desaguliers wrote:

> "Since the attraction of cohesion is proportionable to the surface or the number of the touching parts, and the friction proportionable to the weight, the hinderance or loss of force on account of the said attraction will always be less in proportion to the whole friction, as the weight increases."

Clearly Desaguliers considered that for a fixed surface area an increase in normal load would increase the roughness component of friction but not the adhesion.

In 1785 the Rev. Samuel Vince presented a paper to the Royal Society "On the motion of bodies affected by friction" [Vince 1785]. This paper presented the results of his experiments on friction. Previous writers has expressed differing opinions on the moving (kinetic) friction of bodies; some believing that friction increased with speed and others that it remained constant. Vince set out to repeat some of their experiments and to answer four questions:

1. Whether friction is a uniformly retarding force.
2. The quantity of friction.
3. Whether friction varies in proportion to the pressure or weight.
4. Whether friction is the same on whichever of its surfaces a body moves.

Vince's apparatus consisted of a horizontal plane with the body under test being pulled by a string passing over a pulley at one end with a weight attached. He chose to study the kinetic friction of bodies, and measured the distance moved by them in a given time. He found that "hard bodies" were uniformly accelerated and, from the second law of motion, deduced that "the retarding force of all hard bodies arising from friction is uniform, the quantity of friction considered as an equivalent to a weight without inertia drawing the body on the horizontal plane backwards".

He found that the friction was not strictly proportional to load, increasing more slowly than the load. Also, he found that the force required to set a body in motion was greater than that required to keep it in motion. He explained this by saying that to start a body moving required a force to overcome both the friction and cohesion. Once moving, the only resistance is the friction. His objection to the results of previous writers was that they had measured the force needed to set a body in motion but that this was not the true friction.

Vince's conclusions were based on carefully conducted experiments and included the concept of cohesion to explain why the static friction was higher than kinetic friction. Yet this work was not continued. One reason may be that in the same year, 1785, Coulomb's memoir "Theorie des Machines Simples" [Coulomb 1785] was published by the French Academy of Sciences. This memoir, an extensive experimental study of friction, became, to quote one biography [Gillespie 1970], "the standard of theory and experiment for a century and a half until the advent of molecular theories of friction in the twentieth century".

1.2.3 Composite theory of friction: the work of Coulomb

Nearly eighty years after Amontons' memoir and the debate in the French Academy of Sciences which followed its publication, the Academy again turned to the question of the friction of solids. In 1779 a prize was offered by the Academy [Academie Royale 1780] which was subsequently doubled in 1781. What the Academy required was essentially a practical method of measuring friction in machines. A requirement was "that the laws of friction and the examination of the effects resulting from the stiffness of ropes be determined after new large scale experiments". The Academy required also that the experiments be applicable to devices used in the Navy, such as the pulley, the capstan and the inclined plane. It is evident that the academy had not been convinced by Amontons memoir, since the argument about the laws of friction particularly that friction is independent of surface area, had continued in the intervening years. The Academy evidently felt that a large scale investigation would settle the issue.

Charles Augustin Coulomb (1736-1805) was trained as an engineer in the Corps du Genie in France where he graduated with the rank of first lieutenant [Gillespie 1970]. Following a posting to Martinique in the West Indies, where he supervised the construction of fortifications, he was posted to Rochefort in 1779. During this period he engaged in a series of experiments on friction in the shipyards there. This work won Coulomb the prize for 1781 and was published in 1785 under the title "Sur le theorie des machines simples", and it also gained Coulomb election as a member of the Academy. Coulomb settled in Paris and pursued research in magnetism and electricity which was published in a series of memoirs to the Academy for which he is best known. After the Revolution of 1789 he resigned from the Corps du Genie but continued to participate in the activities of the Academy. His last public service was as Inspector General of

Public Instruction, a post he held until his death.

The first and major part of "Theorie des Machine simples" is a systematic investigation of sliding friction. Coulomb recorded his observations and findings methodically and in detail. Whilst the work may be "systematic and very well done but rather dull" [Bowden 1964] it was the first investigation of its kind ever done and was of value. The preface to the memoir makes this clear:

> "M. Coulomb has equally satisfied the plan of the Academy as proposed and for practical utility and for the progress of physics".

Having first constructed a substantial piece of apparatus for his work, Coulomb reported the results of more than thirty experiments on the static friction of wood on wood (chiefly oak and pine), wood on metal and metal on metal (iron copper and brass). For wood on wood he found that the friction increased with the length on time under load and that the inclusion of tallow between the surfaces increase the time to reach maximum friction. He worked out a mathematical expression relating friction to time under load. For all combinations of material used, Coulomb found that friction was proportional to the pressure between the surfaces. This held true, with only small errors, for a range of loads up to several thousand pounds. In investigating the effect of area of contact on friction, he compared the friction of surfaces of widely different contact areas under the same load. For example, runners of oak sliding on oak, with a contact area of 28 square inches gave the same friction as for runners "rounded to a small angle" under the same load. Also he compared the friction of iron runners with that of the heads of four nails, again carrying the same load, and obtained similar results. Although there were small variations, and the experiments were repeated several times, Coulomb showed that, for all practical purposes, the resistance of friction depended upon the load and was independent of the area of contact. This was full confirmation of the two laws originally proposed by Amontons.

Like Vince, Coulomb also measured the acceleration of the sliding body from rest under different traction forces and compared the force required to set the body moving with that needed to keep it in motion. He found, again like Vince, that the former was always greater than the latter for wood on wood but not for metal on metal. His results from the experiments on kinetic friction led him to the general conclusion that friction is independent of sliding velocity. In some cases this is quoted as a "third law" of friction.

Chapter 3 of Coulombs' memoir contains a short essay on the nature of friction. His view was that the interlocking of asperities was the principle cause, but that cohesion has a small part to play, principally in static friction. He was doubtful about the role of cohesion because this would imply that friction should increase with area of contact, whereas his experiments showed that it did not. In some cases the friction was best expressed as the sum of an "asperity" term and another term which Coulomb attributed either to cohesion or, more probably to the effect of a surface film. In the friction of wood he explained the action of the fibres of the wood in terms of the bristles of a brush. The bristles on the two surfaces interlock and the effect becomes more marked the longer they are in contact. On the other hand with metals, where the roughnesses are rigid, the static friction is almost identical to the kinetic. Coulomb, a skilled experimenter, ends this chapter on a cautious note:

> "I will not enlarge on this theory any further; it seems to explain easily all the phenomena of friction; but the Academy only expects, nowadays, experiments which can be useful; and it might be dangerous to rely too much on a system which might influence the way of reporting experiments which still have to be done".

Subsequently, the essence of Coulomb's work was included in an edition of Ferguson's Tracts [Ferguson 1791] in the form of a list of his findings. Also, the entry under "Friction" in Rees' Cyclopaedia of 1819 [Rees 1819] contains a long reference to Coulomb's work including some of his results. The original Memoir, published by the Academy in 1785, was included in its entirety, in a collection of Coulomb's memoirs on mechanics which was published in 1821 [Coulomb 1821].

1.3 The laws of friction and its magnitude

It has already been noted that the two laws of friction were originally stated by Leonardo and rediscovered by Amontons in 1699 and that the evidence that friction is independent of the area of contact between surfaces was disputed. However, most of those who wrote on the subject, or carried out experiments, subsequently confirmed both laws or at least referred to them. De la Hire confirmed them experimentally in the same year, as did Camus in 1724. Helsham [Helsham 1743] described experiments which demonstrated that the two laws hold good for a block of wood sliding on a table.

There were, however, contrary opinions on the second law. De la Hire reasoned that the friction would depend on the area where surface asperities were broken or worn away. Such was the debate that the entry in Chambers Cyclopaedia (1779) under friction contains the following:

> "There is scarce any subject of experiment, with regard to which different persons have formed such various conclusions, so that the nature and laws of friction are not yet sufficiently clear and decisive. It is granted that the pression has a great effect, and, in many cases is the only thing to be considered in frictions: but it will be hard to persuade us absolutely to exclude consideration of the surface".

A different approach to friction testing was adopted by Pieter van Musschenbroek [Musschenbroek 1769] who was Professor of Physics at Utrecht and Leiden. He used a steel axle resting in half bearings of the material under test. The axle was loaded with weights and a turning moment exerted by a small basin loaded with weights attached to a cord wrapped around the axle. This apparatus is an early form of journal bearing tester and was given the name "tribometre" by van Musschenbroek. He carried out a series of experiments with the steel axle resting on bearings of steel, lignum vitae, brass, tin and lead; these were tested both dry and lubricated with olive oil. The lowest friction was obtained with steel on brass, but friction coefficients tended to vary with load, albeit that the maximum load was low (3lb). Musschenbroek ascribed the cause of friction to the interlocking of asperities and its magnitude depends upon the degree of polish given to the surfaces. He summed up his experimental results thus:

> "These experiments show clearly that the general rules of friction cannot be established and that all that can be given on this matter are singular and can only be deduced from experiments on different bodies".

The coefficients of friction in these experiments were all lower than Amontons' value of one third. Musschenbroek criticised Amontons' experiments by saying that they were done with "bad instruments .... since the friction is not so considerable as this celebrated Academician pretends".

Ten years earlier, in 1752, a translation from the French of Nollet's "Lectures in Experimental Philosophy" [Nollet 1752] was published. In this book, Nollet was critical of those who considered friction to be independent of area of contact. He went on:

> "Repeated trials have almost always proved to me ... that the surfaces must be reckoned as something though much less than the pressures".

An unusual and rather ornate piece of apparatus is described by Nollet. It comprised a shaft with a central flywheel resting on rollers at each end. The shaft was wound up against a spiral spring and when released it oscillated until the motion died away due to friction. The friction was provided by a pivoted lever resting on the shaft. The lever had a forked end and either one or both forks rested against the shaft. Nollet described an experiment in which he counted the number of oscillations (for a given wind up) with first one fork in contact and then both. In the first case the shaft did 40 oscillations before coming to rest, and in the second case 29. This is the only supporting experimental evidence presented, and with hindsight several objections could be raised to this experiment although none apparently were.

This dispute on the second law of friction persisted up to the work of Coulomb and it is evident that his careful work settled the matter. for all practical purposes friction is independent of the area of contact. Those who followed Coulomb do not raise the question again. For the line of enquiry took a different course; the idea that all rubbing combinations had the same coefficient of friction had been abandoned. Camus had shown this as early as 1724. The coefficient of friction was distinctly different for wood on iron from iron on iron. Although Amontons' laws are now thought of as applying to dry friction, Amontons in fact used the same lubricant (pork fat or lard) in all his experiments. It is perhaps not surprising that he obtained the same friction coefficient in each test. Camus' results are probably the first recorded friction coefficients for combinations of materials in dry sliding.

1.4.Limitations of the theories of friction.

The predominant concept of the nature of friction during the eighteenth century was undoubtedly that it arises because of the interlocking of surface roughnesses. Solid bodies were treated generally as rigid and inelastic. During sliding the moving body ascends a perpetual series of inclined planes and no matter how smooth the surfaces were, it was agreed, they could never be entirely removed. The concept of cohesion of smooth surfaces as an element of friction was introduced by Desaguliers but his ideas were not fully developed. Coulomb considered a composite theory of friction with interlocking being the dominant term.

The shortcomings of the inclined plane and cohesion theories of friction were discussed by John Leslie, Professor of Mathematics at Edinburgh. In 1804 he published "A Experimental Inquiry into the Nature and Propagation of Heat" [Leslie 1804]. Leslie realised that the lifting of surface roughnesses over each other could not account for the continuing resistance of friction during motion. With the inclined plane theory, the surfaces must alternately rise and fall:

> "Consequently if the actuating force might suffer a perpetual diminution in lifting up the weight it would the next moment receive an equal increase by letting it down again, and these opposite effects destroying each other could have no influence whatever on the general motion".

Leslie's hypothesis was that solid surfaces continually change during motion and:

> "The upper surface traverses over a perpetual system of inclined planes but that system is ever changing with alternate inversion. In this act the incumbent weight makes incessant yet unavailing efforts to ascend; for the moment it has gained the summits of the superficial prominences, these sink down beneath it and the adjoining cavities start up into elevations presenting a new series of obstacles".

Implicit in Leslie's criticism of the inclined plane theory is that it does not account for the work expended in overcoming friction during motion and his hypothesis is an attempt to take account of this. To quote Bowden and Tabor [Bowden 1964]:

> "If adhesion is trivial and friction arises from interactions with the asperities how can energy be lost?"

Most experimental work on friction in the eighteenth century, with the exception of Coulomb's work was done on a small scale, chiefly on static friction so that the work required to overcome it was extremely small. The experimental work on sliding friction, as Kraghelsky and Shchedrov noted, was carried out at low sliding speed and under relatively light loads so that again the energy expended was low. It has also been said [Naylor 1966] that in the eighteenth century, the working conditions imposed upon bearings were not particularly severe so that there was no particular incentive to improve them or reduce their friction by other than crude lubrication. Not until the latter part of the Industrial Revolution when the demands on bearings on bearings became more severe did the need to improve them and reduce their friction become more urgent.

In the eighteenth century it can be said that sliding friction was a study mainly of academic interest. Those who wrote on the topic were mainly scholars and academics, often lacking the practical approach. There were, of course, notable exceptions such as Coulomb. His was the most thorough study of friction, undertaken with the requirements of a learned society in mind, which also included a practical purpose for the work.

CHAPTER 2

ROLLING FRICTION : EXPERIMENT AND THEORY 1700 – 1900

2.1 Introduction.

It is self evident that the resistance to motion of a body which rolls on a surface is much lower than for sliding motion. This Chapter deals with the historical development of theories put forward to explain rolling friction and the experiments to discover the laws that govern it. Even with the most perfect rollers and the smoothest surface there is a small, but finite resistance. Special reference is made to the experiments of Dupuit, whose ideas, though discounted at the time, foreshadowed the modern theory of rolling friction. In particular, the debate between between Morin and Dupuit (from 1839-1842) is recounted, following the work of Coulomb.

The distinction must be drawn between the unimpeded rolling of a body, for example the rolling of a sphere down an inclined plane, and the 'harnessing' of rolling, for example in wheeled vehicles. Practical application of the beneficial effects of rolling contact almost invariably contain an element of other resistance to motion, for example the axle friction in wheeled vehicles. This work deals with 'applied' rolling contact, and in particular with the resistance of vehicles which was discussed during the eighteenth and nineteenth centuries and with the later analysis of rolling contact.

2.2 The Traction of wheeled vehicles.

One of the concerns during the eighteenth century in relation to vehicles was the most suitable diameter and width of wheels. Writers and experimenters were concerned not only with the resistance to rolling over smooth level surfaces, but also with the force required to draw vehicles over obstacles. Such obstacles were the potholes and ruts in unmetalled roads. The governments of both England and France became concerned with the upkeep of roads which prompted research, particularly in France, on the destruction of roads by traffic.

Towards the end of the seventeenth century two English writers dealt with the subject of the resistance of wheels. In 1685 a paper entitled "Advantages of High Wheels Experimented" was presented to the Royal Society [Royal Society 1685] by a member of the Society. This paper described some experiments on a one-fifth scale model carriage to which wheels of different diameters could be fitted. The model was loaded with lead weights and the force to draw the carriage along a level table was applied by weights on a string which passed over a pulley. Two diameters of wheel were used (5.66 inches and 4.33 inches). For each size of wheel the force required to pull the model over square and round half inch rods was measured. The results of a dozen such experiments were described and the conclusion was that the use of larger wheels reduced the force required to pull the coach over obstacles and "rough ways". It was also noted that "high wheels would not cut so deeply into soft ground".

In 1684 Robert Hooke published an essay on carriages [Hooke 1685]. In discussing the resistance of wheels, Hooke described two principal causes, firstly the yielding of the ground and secondly sticking of the ground to the wheels. Hooke reasoned that if the ground were perfectly hard but uneven there should be little resistance, likewise if the surface on which the wheel rolled were elastic, provided that the surface recovered fully behind the arc of contact. One advantage of large diameter wheels could be the increase leverage on the wheel bearing, reducing the effect of its friction.

The force to draw wheels over obstacles was analysed by Richard Helsham, Professor of Physics at the University of Dublin, in his "Course of Lectures in Natural Philosophy" [Helsham 1743] the second edition of which was published in 1743. Lecture 9 of this book deals with friction and with carriages. In his analysis of the forces acting on wheels, Helsham related the height of a step-shaped obstacle to the wheel radius. For two wheels of radius R and r, he concluded that the forces required to surmount an obstacle of height x would be in the ratio

$$\frac{\sqrt{2R - x}}{R} \quad \text{to} \quad \frac{\sqrt{2r - x}}{r}$$

By reducing the height of the obstacle until it vanished i.e. until the wheels rolled on a smooth plane, the resistances to movement would be respectively proportional to:

$$\frac{1}{\sqrt{R}} \quad \text{and} \quad \frac{1}{\sqrt{r}}$$

or inversely as the square root of the wheel radii.

Helsham described an experiment which demonstrated the inverse square root law. Using a model carriage with wheels of 0.75 inches diameter, with a fixed load, he measured the force required to pull it along a horizontal plane. The experiment was repeated with 1.5 inch wheels and the conclusion was that:

> "the force requisite to move the two carriages along the same plane are inversely as the square roots of the heights of the wheels".

Helsham's arguments in favour of large wheels for carriages are similar to those of Hooke - a reduced depth of impression and a greater lever arm with respect to the axle bearing.

In 1755 a short monograph by Moses Wickham entitled "The Utility of Broad, High Wheel Carriages" was published [Wickham 1755]. This work was concerned with the upkeep of roads and in particular with the damage to them caused by road traffic. Wickham argued that the larger the carriage wheels, the less the force to keep them in motion. Although he offered no experimental evidence, Wickham wrote:

> "... and the difference (in traction force), if I conceive right is in arithmetical proportion to the wheels diameter".

For example, a wheel of 60 inches diameter would need half the force of one 30 inches diameter for a given load and making allowance for any angle of impression (sinking in). In discussing the rolling of wheels Wickham described the wheel and road as being like cogs with teeth that engage as the wheel rolls forward.

An essay on the construction of roads and carriages was presented to the Academy of Sciences in Dublin in 1797 by Richard Lovell Edgeworth [Edgeworth 1817]. This work was subsequently re-published as a momgraph in 1817. Edgeworth, in experiments with models like those of Helsham, confirmed the latter's conclusion that the traction force to surmount an obstacle of given height varied with the inverse square root of the wheel diameter. He also investigated wheels having rims with a small conical taper on angle axle trees. This was used to improve steering but he found that slipping of the wheel due to the differential velocity on each side of the wheel increased the traction force and also tended to accelerate wear and tear on roads.

The influence of rim width on the draught of suspended carriages was investigated by Benjamin Thompson (Count Rumford) in 1811 [Thompson 1811]. He used full size carriages and fitted wheels with rim width ranging from 1.9 to 4 inches and found that the traction force on pave roads decreased as the rim width increased.

Engineers of bridges and roads in France were particularly interested in the traction of vehicles and the effects of traffic on the state of roads. A system of maximum vehicle loading was introduced in 1806 [Morin 1842]. For each type of vehicle, maximum loads increased in proportion to the width of the wheel rim. As a result of further investigations, ammendments to this system were proposed by Navier in a report in 1835 [Morin 1842].

As a result of the requirement to regulate vehicle loads and thus to know the traction forces, independent investigations by two French engineers were carried out almost concurrently. The reporting of their results, and the difference in findings led to a debate in the French Academy of Sciences.

2.3 Morin and Dupuit.

One of the participants in the debate was Arthur Jules Morin (1795-1880). Morin graduated from the Ecole Polytechnique in Paris in 1817 and became a military engineer, stationed at Metz. He rose to the rank of lieutenant-colonel and was appointed Professor of Industrial Mechanics at the Conservatoire National des Arts et Metiers in Paris in 1839. He became its director in 1851 and a Commander of the Legion d'Honneur in 1854 [Nouvelle Biographie 1861].

Morin was an experimenter who produced copious data but was not much given to detailed theoretical analysis. In 1831 he carried out a series of experiments on sliding friction at Metz [Morin 1831] and investigated the friction of axle bearings in

1834 [Morin 1834]. These works became the main reference source for the friction of material for much of the nineteenth century. In 1837 a French government Commission on road and traffic had been set up and Morin was invited to carry out a series of experiments to measure the traction forces of wheeled vehicles with various loads and wheel diameters. This work was carried out in 1837 and a memoir on it was presented to the Academy of Sciences in 1838 [Morin 1838]. This memoir, with a report on additional work of 1838, was published as a book in 1839 [Morin 1839].

Morin set out to determine the influence of load, wheel diameter and rim width on the traction force. Over 200 experimental results were reported in the memoir for both two and four wheeled vehicles on gravel, pave and metalled roads. He developed a dynamometer for the work which was fitted between the traces of the vehicle (Fig. 2.1). The traction force was recorded by a stylus on a rotating drum, and a continuous trace of the force was obtained. Later a British Association committee, set up to study the problem of measuring the power output of railway locomotives, recommended a design based on Morin's dynamometer.

Allowances were made for the friction of the axles and the results were that, in all cases, the traction force was proportional to the load on the wheels and was inversely proportional to the radius of the wheel. Morin also found that, in general, the traction force decreased slowly as the width of the wheel increased. A traction coefficient, A, was calculated from:

$$A = \frac{Rr}{P}$$

where P is the load per wheel, r is the radius and R the traction force. The coefficients were nearly constant for a given road surface and rim width. These conclusions were taken by Morin to be a vindication of the conclusions of Coulomb from his rolling friction experiments of 1779 [Coulomb 1785].

The other, independent investigation on the subject was by Dupuit who also published his results in 1837 [Dupuit 1837]. Arsene Jules Etienne Juvenal dupuit (1804-66) graduated from the Ecole Polytechnique in 1824 and became an engineer of bridges and roads. Later, in 1840, he was appointed Chief Engineer of the Department of the Marne. In 1850 he became Director of Municipal Services in Paris and later Inspector General of bridges and roads [Dictionaire de l'economie politique 1852]. His "Essai sur le tirage des voitures" in 1837 was divided into tow parts. The first presented the results of his experiments on the traction of wheeled vehicles; the second part was devoted to a theoretical analysis of rolling friction.

Like Morin, Dupuit measured the traction force using his own design of spring dynamometer. However, Dupuit's experiments were less numerous and the results were presented in less detail. His conclusions, however, were clearly set out. He found that the traction force was directly proportional to load and inversely proportional to the square root of the wheel diameter. He also concluded that rolling resistance was independent of the width of the wheel rim. Another observation was that a flat iron rim wore rapidly at its edges on a metalled road.

In November 1839 Dupuit presented a memoir to the Academy of Sciences [Comptes Rendues 1839] which was based on the results published in 1837. In a continuation of some experiments reported then, he measured the distance rolled by wheels along horizontal ground when started from an inclined plane. By using this method, all other frictional resistances were eliminated. The results from these and other experiments with wheeled vehicles using a Morin dynamometer confirmed his previous conclusion that rolling friction was inversely proportional to the square root of the rolling diameter.

Morin presented a second memoir on the subject in January 1840 [Comptes Rendues 1840]. In a resume he compared Rr/P and R r/P. The first expression was more nearly constant; the second diverged in a regular manner. Morin re-emphasised his belief that rolling resistance was proportional to load and inversely as the radius. He also refuted the objections to his previous work that had been raised by Dupuit, namely that the different locations of his experiments had influenced the results. On sand or soft earth, new experiments had at equal loading had shown that the rim width did the traction force. Far from being exceptional terrain, wrote Morin, soft ground was frequently encountered by military and agricultural vehicles.

The following month (February 1840) Dupuit added a supplement to his memoir [Comptes Rendues 1840] which included the results of further experiments with wheels rolled from an inclined plane. In 1837 he had analysed the "work lost" in some rolling cylinder experiments and showed how this related to the distance run by the cylinder, and its diameter (see Table 2.1). These latter results confirmed that rolling resistance was proportional to the inverse square root of wheel diameter. These experiments, said Dupuit, did not give rise to slipping or shocks as Morin had alleged. Had this been so the results would have been irregular, whereas they were not.

During 1841 the debate concerned the publication by Morin of his repetition and extension of Coulomb's experiments with wooden rollers [Comptes Rendues 1841]. Objections to this technique and the results obtained were raised by Dupuit [Comptes Rendues 1841] (see Section 2.4). In 1842 both Morin and Dupuit summed up their respective findings. Dupuit set out his arguments in an article published in the Annales des Ponts et Chausees [Dupuit 1842]. Here he reiterated his criticism of Morin's results, his use of roads with different surface conditions and his proneness to arithmetical mistakes. In answer to Morin's earlier criticism of his spring dynamometer, Dupuit quoted a crucial hypothetical experiment. A waggon with wheels of 2 metres diameter requires a traction force of 100 kg. If the wheels are reduced to a diameter of 0.5 metres the traction force according to Morin, is 400 kg, according to Dupuit 200 kg. What sort of sensitivity, he demanded, is necessary to distinguish between these two? All his experiments on carriages and free rolling wheels supported the conclusion that the traction force was proportional to load and the inverse square root of wheel diameter. In the introduction to this 1842 paper, it is clear that Dupuit had been cautious in publishing results which contradicted those of Coulomb. He wrote:

> "believing myself to have been mistaken, I repeated the experiment and varied the circumstances as much as possible and sided only on the evidence of the facts".

Also in 1842 Morin published a lengthy resume [Morin

1842] of all his experimental results, discussion and conclusions. This also included the report of the Academy's Commission on his work in 1838. This Commission comprised Arago, Poncelet and Coriolis and they received Morin's work favourably. Their report commented that:

> "A young French engineer, M. Dupuit published in 1837 a work on the same question. The law he gave ... does not seem to us to be preferable to the results of M.Morin".

The Academy thus adopted Morin's conclusions. However both Morin and Dupuit were awarded gold medals by the Government Commissions for their work.

The point at issue was the influence of wheel or cylinder diameter on rolling resistance. Each, however, employed a different technique for measuring the rolling resistance. Morin was content to measure the traction force of a vehicle moving at constant speed or the force required just to set a loaded cylinder rolling, making due allowance for other losses. Dupuit was concerned with the "lost work" during rolling and produced a detailed analysis of the mechanics of rolling. Both Morin's and Dupuit's results are summarised in Fig. 2.4, (see the appendix at the end of this chapter).

On the specific point of the influence of radius on rolling friction, Morin used wheels from 1.1 to 2.05 metres diameter and also used wheels of different diameters at the front and rear of the same vehicle. This led to some experimental scatter in his results. On the other hand, Dupuit employed a greater range of wheels from 6 to 62cm and by rolling the wheels from an inclined plane, was able to eliminate other sources of friction, which Morin had to allow for.

2.4 Experiments on Rolling Friction

In 1785 at the end of the Theorie des Machines Simples [Coulomb 1785] which was mainly about sliding friction, Coulomb described some experiments to measure the friction of wooden cylinders rolling on a horizontal plane. The apparatus he used is shown in Fig. 2.2. A light cord was wrapped around the rollers to which weights were attached. A small additional weight was added to one side, sufficient to initiate rolling. From the results of about a dozen experiments with lignum vitae and elm rollers on oak runners, Coulomb concluded that rolling friction was proportional to the load and inversely proportional to roller diameter. This was later referred to as Coulomb's "law".

Using a similar type of apparatus, Morin repeated and extended Coulomb's work. He undertook two series of experiments, the first at Vincennes in 1839 [Morin 1839] and the second at the Conservatoire des Arts et Metiers, Paris in 1841 [Morin 1842]. With wooden rollers on iron and wooden rails, Morin confirmed Coulomb's conclusions and added that the rolling friction was inversely proportional to the length of the cylinder.

After publication of the 1839 experiments Dupuit [Comptes Rendues 1839] objected to this experimental method because:

> "it is impossible to know if the movement of the cylinder is uniform or accelerated in a distance of only 80 centimetres"

In presenting the results of his experiments in 1841 Morin was careful to determine any acceleration of the rollers and he repeated each experiment with slightly different traction forces and made due allowance for acceleration. Later in 1841

Dupuit replied to this memoir and recalled his previous criticism of the method. He went on to say that the deformation of the cord and roller contact gave rise to additional resistance. Also:

> "the work lost during rolling is the resistance to determine in these experiments".

Dupuit also pointed out that a decrease in rolling friction with cylinder length was incompatible with its linear dependence on load. For if the cylinder was cut into four equal slices each carrying one quarter of the load, the total friction of the four parts would be twice as great as that of the original cylinder. According to Dupuit the friction did not depend on the width so not contradictions of this kind were introduced.

Dupuit first related his method of rolling wheels from an inclined plane onto the horizontal in his book of 1837. He used a similar technique to determine the rolling friction of wooden cylinders. This was also described in the same book. The apparatus consisted of a smooth horizontal wooden board with inclined planes at each end joined by appropriate curves (Fig. 2.3). A cylinder released on one inclined plane would roll back and forth until it came to rest. The vertical face of the apparatus had divisions staring from the middle and going to each extremity. Dupuit recorded at each half of the track the division which the cylinder just attained and added together all the lengths to give the total distance travelled. He verified that the resistance was independent of speed by releasing the same cylinder from different heights on the inclined plane and he found that the distances travelled were proportional to these heights.

From analysis he calculated that the rolling resistance should be proportional to

$$\frac{h\sqrt{D}}{s}$$

where h is the height of release, s the distance travelled and D the cylinder diameter.Dupuit confirmed that this quantity was nearly constant for wooden and iron cylinder from 6 to 60 millimetres diameter, rolling on wood.

2.5 Theories of Rolling Friction

Dupuit first set out his theory of rolling friction in 1837 and extended it in 1842. He observed that a wheel or cylinder will sink slightly into a flat plane. Because of "imperfect elasticity", the rear portion does not provide its full share of normal reaction. So the centre of reaction is shifted slightly ahead of the centre of the wheel or cylinder. If it is shifted by a distance d there is a retarding couple Wd which must be overcome by the traction force F. If R is the radius and W is the load then

$$FR = Wd \text{ in equilibrium rolling}$$

and

$$F = \frac{Wd}{R}$$

In fact Dupuit arrived at this expression by considering the lengths of the arcs of contact ahead of and behind the centre of contact and the relative compression of the plane. He considered how d depends upon R and derived the expression

$$F = \frac{\rho W}{\sqrt{2R}}$$

where ρ is a constant which depended, according to Dupuit, only upon the nature of the surfaces in contact. This is the main defect in his analysis; the assumption that the depth sunk by the rolling body was a function only of the materials and not of the load. However Dupuit seems to have been attempting to describe what is now termed hysteresis loss in rolling resistance.

In November 1841, Morin prepared a note on the elastic behaviour of rolling bodies [Morin 1841]. He had done some experiments on the depth of impression of rollers in blocks of rubber to determine how the speed of recovery of the material might affect the rolling friction. Morin wrote:

> "I next show with what slowness the elastic reaction effects of rubber are produced and show that it dependes on that which I call the "speed of return" of the body to its original shape. From which I conclude that on metalled roads, on ordinary pave and on railways, the effects of this reaction must have little influence on the running of vehicles".

Morin argued that in general the rolling resistance due to "imperfect elasticity" would be only slight.

Osborne Reynolds presented a paper to the Royal society in 1876 on the subject of rolling friction. Reynolds, who was Professor of Engineering at the University of Manchester, was apparently only aware of Morin's work. He analysed the rolling of a cylinder on a flat plane. When a cast iron cylinder rolls on flat rubber, in one revolution it traces out a distance on the rubber rather less than its circumference. This is due to the extension of the rubber in the region of contact. The deformation of the softer plane surface would be similar to that obtained during compression between parallel plated where friction at the surface prevented uniform expansion of the material. The cycle of deformation during rolling contact would give rise to relative slip and hence friction between the surfaces. However, in his experiments with cast iron and brass rollers on rubber and cast iron planes, Reynolds found that lubricating oil or graphite made little difference to the coefficient of rolling friction.

He had, however, indicated a source of rolling resistance which later came to be recognised as a phenomenon in ball and roller bearings. He did refer, in passing to the hysteresis loss in the extension and contraction of rubber and noted that the rubber would offer less resistance to the rollers when the motion was slow than when it was rapid. At the conclusion of his paper, Reynolds could "see no reason to doubt the two laws propounded by Coulomb".

In 1886 C.L.Crandall of Cornell University reported experiments to determine the rolling friction of cast iron and steel rollers of different diameters rolling between cast iron nd steel plates [Crandall 1886]. Reference was made to the experiments of both Morin and Dupuit and in particular to their different findings on the effect of rolling radius. The results of Crandall's experiments clearly follow the inverse square root law, in keeping with Dupuit's results. In the second part of the paper, the stress pattern in a cylindrical glass roller was demonstrated by the use of polarised light. This showed the pattern of stress predicted fron the Hertzian theory, the foundation of which was laid by Heinrich Hertz in his famous paper of 1881 [Hertz 1881].

It seems that Dupuit's results were not accepted at the time. His papers appear, apart from the refernece by Crandall, to have been unknown to later workers. Yet from recent research on rolling friction, it is clear that, whilst slip at the contact zone may play an important part, in many cases the main source of rolling friction arises from the causes described by Dupuit 150 years ago.

TABLE 2.1
Dupuit's Rolling Wheel Experiments

Wheels of various diameters released down an incline of height h, distance run, s.

Nature of Surfaces	Diameter (metres)	s metres	$\frac{h\sqrt{D}}{s}$	$\frac{h\ D}{s}$
Wooden cylinder on wooden plane	0.006	2.2	0.0173	0.0014
	0.0075	3.5	0.0172	0.0015
	0.0125	3.72	0.0152	0.0017
	0.0162	3.83	0.0166	0.0021
	0.0225	5.05	0.0148	0.0022
	0.0312	6.10	0.0143	0.0025
	0.0435	6.45	0.0163	0.0034
	0.0625	8.43	0.0148	0.0037
Iron cylinder on wood	0.0075	3.2	0.0137	0.0012
	0.0105	3.72	0.0127	0.0014
	0.0170	4.42	0.0147	0.0019
	0.0260	5.20	0.0152	0.0024
	0.034	6.37	0.0145	0.0027
	0.047	7.65	0.0140	0.0030
	0.060	8.36	0.0147	0.0036

APPENDIX

The results of both Morin's and Dupuit's experiments on rolling friction can be expressed in the form;

$$F/W = K(1/R)^n$$

where F/W is the ratio of traction force to load and R is the radius of the wheel (or cylinder). Their results are plotted logarithmically in Fig.2.4. By plotting the results in this way, the coefficients K and n can be determined. For Morin's results, n is consistently close to unity whilst K depends upon the type of surface with which the wheel or cylinder is in contact. K is relatively large for wheels on gravel roads and low for the rolling cylinder experiments.

Morin's results [Morin 1842]

Experiment Number	Wheels dia. (metres)	W kg	F kg	F/W	1/R
21	1.1	3865	320.9	0.083	1.82
22	"	"	323.9	0.084	"
23	"	"	289.6	0.075	"
24	"	"	324.3	0.084	"
			Average	0.081	

Experiment Number	Wheels dia. (metres)	W kg	F kg	F/W	1/R
25	1.564	3715	234.04	0.063	1.278
26	"	"	236.03	0.064	"
27	"	"	220.97	0.059	"

			Average	0.062	
28	2.03	3990	192.5	0.048	0.985
29	"	"	198.0	0.05	"
30	"	"	186.5	0.047	"
31	"	"	190.7	0.048	"

			Average	0.048	

A linear regression analysis can be performed on:

$$\log(F/W) = \log(K) + n\log(1/R)$$

this gives K=0.492 and n=0.855 with a correlation coefficient of 0.997.

Dupuit's Results [Dupuit 1837]

Wheel Dia.	F/W	1/R
0.76	0.039	2.63
0.91	0.0373	2.19
1.35	0.0293	1.48
1.82	0.0276	1.09
1.88	0.0256	1.06

With a similar analysis K=0.255 and n=0.45 with a correlation coefficient of 0.984.

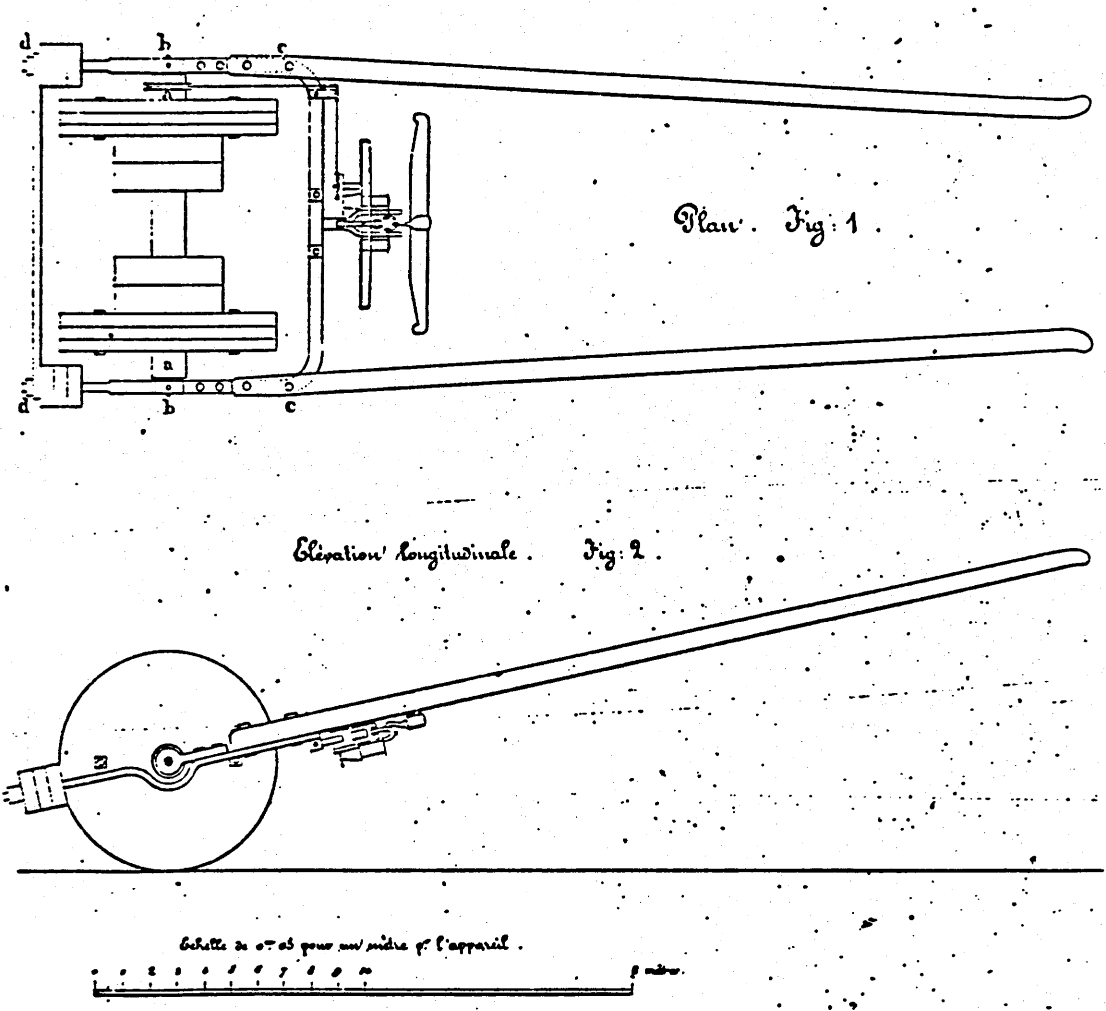


Fig. 2.1 Morin's apparatus for measuring traction forces.

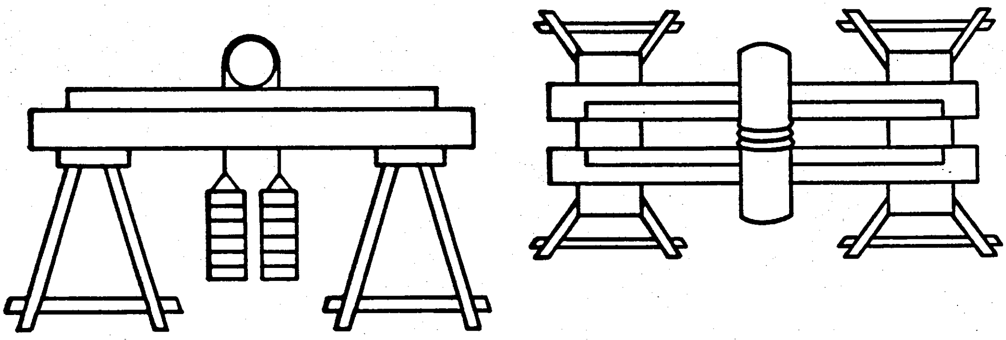


FIG.2-2 COULOMB'S APPARATUS FOR MEASURING ROLLING FRICTION

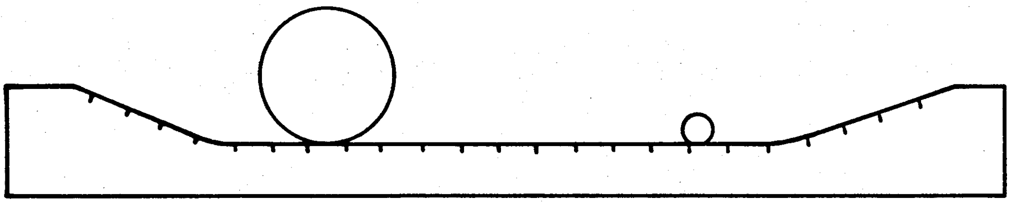


FIG.2-3 DUPUIT'S APPARATUS

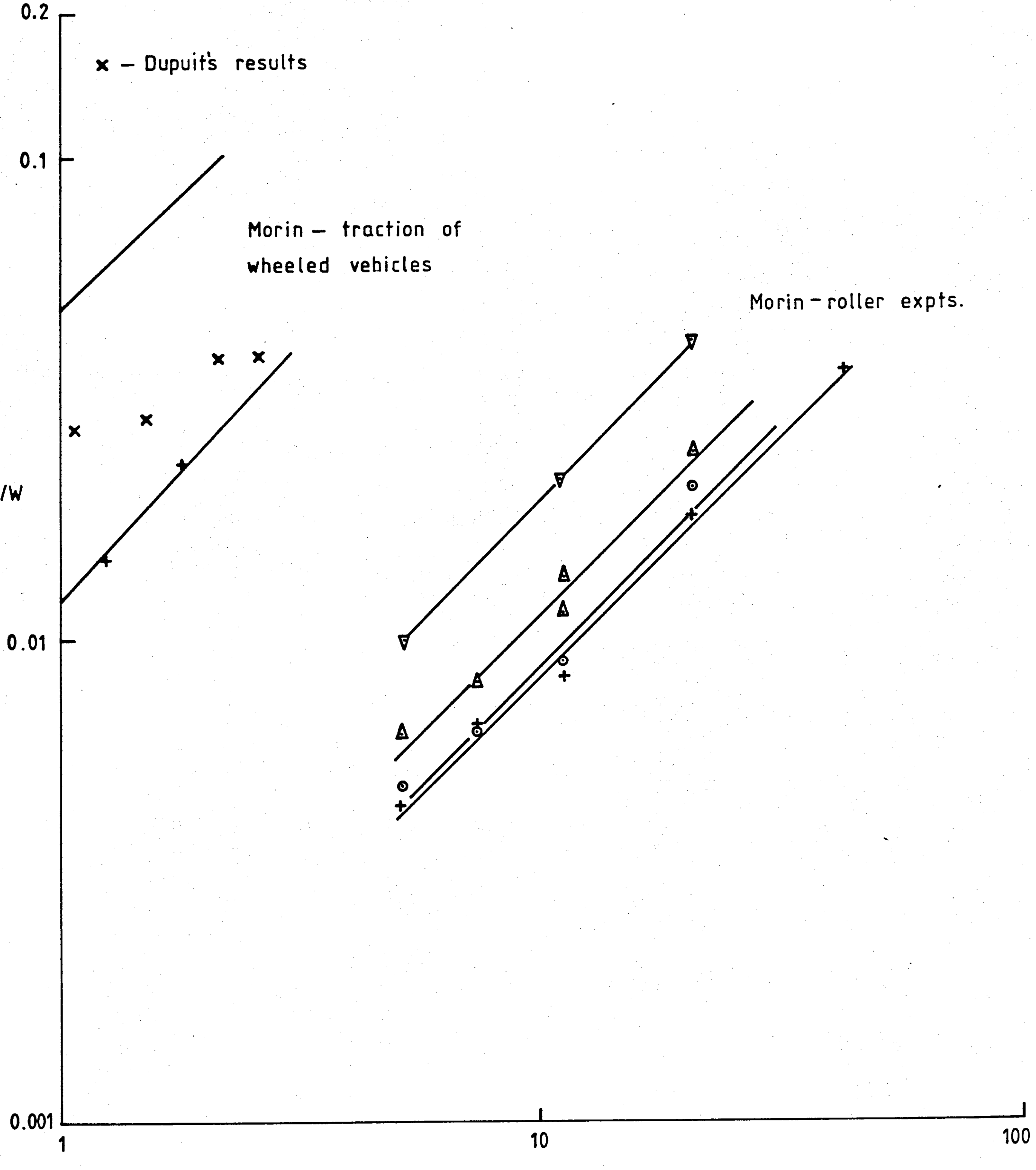

0.2
× – Dupuit's results
0.1
Morin – traction of wheeled vehicles
Morin – roller expts.
F/W
0.01
0.001
1
10
100
1/R m^{-1}

FIG. 2·4

CHAPTER 3

THE WEAR OF SOLIDS : EXPERIMENTS AND CONCEPTS

1850 - 1940

3.1 Wear in sliding contact

In general, the term "wear" is the name for the processes by which material is gradually lost from the surfaces of bodies. It is one of the ways in which mechanical components fail in service; the other include fracture and corrosion. In order to design machines which will work, a knowledge of the magnitude of friction between surfaces is necessary, since work is expended in overcoming it. But to build machines with a long life under arduous conditions needs some insight into the nature of wear and methods of mitigating it. Wear and friction are inter-related by both being a consequence of the relative motion of contacting bodies.

Dowson [Dowson 1979] has traced the history of wear studies from the Second World War but there are only a few references in his book to research on wear in the preceding decades. However the economic significance of wear was beginning to be recognised by the middle of the last century and many of the processes of wear, and the factors affecting it, were being investigated prior to 1940. Also, the foundations of present day experimental techniques had been laid, for example the necessity of simulating conditions of service in the laboratory wear test, and the use of accelerated tests and in-service trials. One example of an accelerated wear test was the work of Cavendish and Hatchett [Cavendish Hatchett 1803] on the wear of gold coins, reported to the Royal Society in 1803. A full account of this work has been given by Dowson. Cavendish and Hatchett accelerated the natural wear of coins to produce measurable results in a reasonable time.

Wear is a universal process which is easily recognised but difficult to define precisely. General definitions range from "impairment by use" to "injuring the appearance or efficiency by wearing or using". In 1931 Jordan [Jordan 1931] defined the wear of metals as "unintentional removal in service of the surface of a metal through the action of frictional forces". However Gillett [Gillet 1937] phrased it in a different way; "wear of a metal part is its undesired gradual change in dimensions in service under frictional pressure".

As an historical background, the development of theories of the friction of solids during the eighteenth century has already been described. The interlocking of rigid asperities was the dominant theory of friction during that period. If, as two surfaces slide, some of the asperities are broken off, then this would be the fundamental mechanism of wear. This was put forward by Phillipe de la Hire in 1699 in testing Amontons laws of friction. Oliver Goldsmith [Goldsmith 1776] in his "Survey of Experimental Philosophy" of 1776 wrote:

> "The little rising in one body stick themselves into the small cavities of the other in the same manner as the hairs of a brush run into the irregularities of the coat while it is brushing. If the bodies slide one over the other, the little risings of one body in some manner tear or are torn by the opposite depression".

A similar statement of the process of wear was given by William Emerson [Emerson 1793] in 1793 when he wrote:

> "For when one surface is dragged along another, some part of the resistance arises from some parts of the moving surface taking hold of parts of the other, and tearing them off; this is called wearing".

Wear became of practical concern during the nineteenth century as high speed machines were built, with greater loads on their component parts. Certainly, practical men like Robertson Buchanan were well aware of the effects of wear and that provision should be made for it. In 1808 [Robertson 1803] he wrote:

> "an allowance (on the diameter of a gudgeon) should be made for wear which will be nearly directly as the stress and inversely as the length of the gudgeon ... we may allow one fifth of the diameter as a provision against wear where no gritty substance is likely to affect it, and one third in all cases where the gudgeons are exposed to gritty matters".

By 1850 engineers were beginning to experience problems with railway axle boxes. From this time close attention was given to improving lubrication to prevent "hot boxes", and to improved bearing materials. Also, on ships there was a need for long life bearings, in particular stern tube bearings, to obviate the need for emergency repairs. This need was evidently the reason for John Penn's tests on materials for stern tube bearings (see chapter 5).

One of the primary figures concerned with the wear of materials on railways was the American Charles B. Dudley. He wrote three papers on the wear of steels and one on bearing metal alloys.

3.2 The wear of bearing metals

Dudley carried out one of the pioneering studies on the wear of bearing metals [Dudley 1892]. In the first part of this paper, Dudley reviewed the types of bearing alloys used and gave their composition (see chapter 7). Naturally, he was specifically concerned with alloys for railway axle boxes, and he wrote that one large corporation used between one and one and a quarter million pounds of bearing metal per year. Also:

> "It is a fairly good bearing metal that will not lose as much as a pound of its weight for every 25,000 miles it goes under a (railway) car".

Two major requirements of a bearing metal were that it must support the bearing pressure of typically 350-400 pounds per square inch. also it should not heat readily - the old alloy of 7 parts copper to one of tin resulted in a very large percentage of hot boxes, wrote Dudley. He also added that the harder the bearing metal the more readily would it heat.

In all Dudley listed 23 different bearing alloys which were selected from the many analyses made in the laboratory of the Pennsylvannia Railroad Company (of which he was Chief Chemist). The analyses had been made in the fifteen years up to 1891. Comparative wear rates were obtained by fitting bearings of the various alloys to the axles boxes of rolling stock in service. The weight losses were compared with a "standard" phosphor bronze bearing metal. For this material a large number of measurements had shown that it lost one pound in weight for every 18,00 - 25,000 miles of travel. The results of the trials were that plain tin bronze and arsenic bronze wore 48% and 42% faster than the standard. Bronzes containing 12.5% and 15% lead wore 8% and 13.5% respectively slower than phosphor bronze. Dudley's explanation for this was that the leaded bronzes possessed the required combination of high elongation to break and reasonable tensile strength together with a fine granular structure. In other words, the asperities would tend to bend rather than break under the action of frictional forces.

Further experimental confirmation of Dudley's findings on lead bronzes came from a series of laboratory tests reported by Clamer in 1903 [Clamer 1903]. In discussing the wear of bearing metals he wrote:

> "It is quite remarkable the relation which exists between composition and wear. This presents a wide field for research - a field almost unexplored".

He also quoted some statistics on the wear of railway axles themselves in terms of the average mileage run for half an inch of shaft wear. This ranged from 504,000 miles for passenger car axles to 490,000 miles on tenders and 274,000 on freight car axles.

During the years 1901 and 1902 Clamer carried out wear tests on a machine which had originally been designed by Professor Carpenter of Cornell University. In this machine half bearings 3 inches diameter and 3.5 inches long were loaded at 1,000 lbf/in^2. The steel shaft was rotated at 525 rev/min and the bearing wear determined by weight loss after 100,000 revolutions. In addition, the bearing friction and temperature rise were measured. The bearings were lubricated in "the manner commonly used on railroads" i.e. by means of a pad soaked in oil held on the under side of the journal. Clamer claimed that this machine overcame many of the defects of the Thurston machine. This presumably meant that Clamer's machine, with marginal lubrication was better suited for studying bearing wear rather than their friction and lubrication which was the pyrpose of the Thurston machine.

Clamer's table of wear results is reproduced in Table 3.1. The results show that the inclusion of lead in the alloy, whilst tending to increase friction slightly, reduced the rate of wear. However no data on the mechanical properties of the various alloys is given. The addition of zinc increased the wear rate and, according to Clamer, tended to segregate the lead.

The next major investigation of the wear properties of railway bearing materials was carried out at the National Bureau of Standards in Washington. Between 1925 and 1927 a lengthy study of the wear and mechanical properties was undertaken in their laboratory [French 1928]. The work was begun at the instigation of the Chicago Bearing Metal Company with a view to providing a sound basis for standardisation of bearing alloys. The wear tests, in both rolling and sliding conditions, were done on an Amsler machine, first introduced three years earlier. In addition, other mechanical tests on the materials were done including tensile tests, repeated impact (pounding) and resistance to abrasion by sandblasting.

Specimens of copper-tin bronzes with varying additions of lead were prepared both by sand casting and chill casting. For the sliding wear tests on the Amsler machine the upper (bronze) disc was locked in position. In the rolling tests the bronze disc was driven but there was relative slip between it and the lower steel disc.

After a lengthy series of experiments the following conclusions were drawn. For alloys with a constant ration of tin to copper, lead produced a general improvement in wearing properties. This effect was more marked with a lead content of between 0.25% and 12% than between 12% and 25%. however the resistance to pounding, notch toughness and tensile strength decreased with increasing lead content. With alloys having a constant ratio of copper to lead, a progressive increase in tin content from 0.7% to 5% produced a marked increase in wear resistance both in rolling and skiding wear. A further increase in tin from 5% to 10% did not materially modify wearing properties but improved the tensile strength and resistance to pounding.

Another conclusion was that sand cast bronzes, with a fairly coarse structure, in general wore fastewr than chill cast bronzes which had a finer grian size. In general then, this study confirmed the findings of Dudley and Clamer but it also demonstrated that reproducible wear test were possible in the laboratory and that the results obtained were consistent with experience in service.

3.3 Hardness measurement.

Hardness is a measure of the resistance to penetration of one body by another. It also has an intuitive association with resistance to wear and in some instances was synonymous with wear resistance. One of the earliest qualitative scales of hardness was given by F. Mohs [Mohs 1822] in 1822 in a book on mineralogy. The scale he proposed, which bears his name, has a scale from 1 to 10 for minerals ranging from talc (1) through gypsum, quartz and sapphire to diamond (10) (see Table 3.2). Later in the nineteenth century the need arose for a quantitative measure of hardness. One instrument designed to meet this need was the sclerometer or scratch test developed by Professor T.Turner of Birmingham [Turner 1886]. In this instrument a pointed pin of hard steel was loaded against the test specimen. The specimen was moved tangentially so that the pin produced a scratch in the specimen surface. The reciprocal of the width of the scratch, measured in fractions of an inch, was taken as a measure of the scratch hardness of the specimen.

At the turn of the century J.A.Brinell, Technical Manager of the Fagersta Iron and Steel works in Sweden, was concerned at the lack of an easy and trustworthy means of determining hardness [Wahlberg 1901]. Brinell outlined the requirements of a hardness test. It must give repeatable results and must be easily learned and applied; the specimen should not need elaborate pre-treatment and finally the indentor should be cheap, easy to obtain and of sufficient hardness. He hit on the idea of using balls from ball bearings as indentors. He obtained a supply of balls from the Deutsche Gusstahlkugelfabrik at Schweinfurt in Germany. After some experiments, Brinell found that the ration of indentation load to the square of the diameter of the impression was reasonably constant for a range of loads and ball diameters for a given sample of steel. s ohe took this ratio as the hardness number expressed in kilograms per square millimetre. The Brinell hardness test was widely adopted in he succeeding years and became established as a standard.

Other forms of hradness test continued to be developed. A variant of the Brinell method was that developed by Rockwell [Rockwell 1922] in which the depth of impression of a conical indentor into the specimen under a fixed load was measured. The dial gauge measuring the penetration was calibrated directly in Rockwell Hardness Number and this removed the need for a separate measurement of indentation diameter. A.F.Shore invented the scleroscope in 1907 [Shore 1907]. In this instrument the height of rebound of a sharp indentor, dropped from a fixed height, was measured. In a similar manner to the Rockwell instrument, a direct reading of hardness was obtained.

3.4 Wear and hardness

Some of the tests devised to measure the hardness of materials would now be thought of as wear tests because relative motion of two surfaces under load was involved, whereas those discussed above are static tests. An example is the test described by Bottone in 1873 [Bottone 1873]. He arranged that the edge of an iron disc, rotating at constant speed, was loaded against the material to be tested (see Fig. 3.1). With the load constant, the experiment was run for a specific time and the length of the cut in the specimen was measured. The table of results obtained with this test is shown in Table 3.3. He held that the hardness of any metallic element had "for its natural measure the ratio of the specific gravity divided by the atomic weight". The experimental arrangement was latter used by an number of researchers [Spindel 1922, Brownsdon 1936].

3.5 Wear by abrasives

One of the earliest, and most comprehensive studies of the wear of steels by abrasives, was by Felix Robin in Paris durinf the period between 1908 and 1910. He published a short paper on his results in conjunction with Pierre Brueil, who was Chief of Metals Testing at the Conservatoire National des Arts et Metiers in Paris [Robin 1909]. The final report of the work was published by the Iron and Steel Institute as a Carnegie Scholarship Memoir in 1910 [Robin 1910].

The reason for undertaking the work was to assess wear as a function of the minerlogical hardness of the constituents of steels. His method of measuring the wear of steels rubbing against abrasives was intended to fill a gap in hardness testing methods and also to have practical applicability. The apparatus used consisted of a rotating steel disc to which was fixed a disc of abrasive paper. The steel specimen was in the form of a pin clamped in a pivoted load arm. Weights were applied to the arm to load the pin against the abrasive paper. A spring balance restrained the lateral movement of the load arm and this gave a measure of friction (see Fig. 3.2). This is of interset since it is probably the first recorded use of what is now called a pin on disc machine - one of the most widely used wear testing methods used today.

Robin obtained specimens of over 20 different type of carbon steel and cast iron in various states of treatment, i.e. annealed, quenched, tempered. He ran the specimens against commercially available abrasive papers and measured specimen wear by weight loss. Repeated experiments showed that a reasonably reproducible weight loss was obtained after 3 minutes running against the disc rotating at 150 rev/minute, and with a load of 1kg. Prolonged rubbing against the abrasive paper resulted in a reducing wear rate due to the paper becoming clogged with wear debris. The rate of wear increased either in a linear or a parabolic manner with applied pressure (Fig. 3.3 & 3.4). Also, carbon steels did not wear in inverse proportion to their percentage carbon content. They showed a maximum wear resistance at about 0.4% carbon. Pure and fine grained metals offered the best wear resistance and phosphorus greatly increased resistance to wear. However, Robin was unable to find a general correlation between wear resistance and hardness.

Whilst Robin was concerned with the wear resistance of industrial metals like cast iron and steel, a series of similar experiments were conducted by Honda and Yamada in 1925 [Honda 1925], also using a pin on disc machine. They tested pins of soft metals such as lead, tin, zinc and copper against a cast iron disc which had been roughened with emery sand. In addition to measuring wear by weight loss, the friction coefficient was also measured. Their conclusion was that the ammount of wear in a given time was proportional to the friction horse power, provided that the friction coefficient remained constant. The implication of this conclusion was that the volume of material worn away (V) was equal to a constant times the product of the load (W) and sliding distance (L). Thus:

$$V = k\ W\ L$$

This is today a widely accepted "law" of wear. The constant of proportionality, k, is now called the specific wear rate or wear factor.

A rather different approach to testing for abrasive wear resistance was taken by Brinell. Brinell's original paper was published in Swedish, but was translated by Holz [Holz 1924]. Brinell's apparatus was like that of Bottone, with the edge of a rotating disc was loaded against a flat specimen. Pure, dry quartz sand was fed continuously between the disc and the specimen so that they did not come into actual contact during the tests. The abrasion produced a groove segment in the specimen and the resistance to wear was expressed in the form:

$$\text{Resistance to wear (Nm)} = \frac{1{,}000}{A}$$

where A was the volume of the wear segment per millimetre of disc thickness (the disc was 4mm thick). For tests on ferrous metals, Brinell used a constant load of 10kg and each test ran for a period of 10 minutes with the disc rotating at 20 rev/min. Holz's included a large number of test results in his review and these were later summarised by Hankins [Hankins 1929]. The graph of resistance to wear plotted against indentation hardness is reproduced in Fig. 3.5. Whilst the results exhibited a good deal of scatter, a mean line indicated a marked increase to direct abrasion as the hardness increased from 100 to 200 (Brinell Hardness Number). Manganese steels proved to be superior to carbon steels. Although the tensile strengths and ductilities of many of the materials were given, it was not possible to say whether high ductility or toughness was important in this form of test.

3.6 Wear in rolling contact

The resistance to wear of steels in rolling contact was important in connection with the wear of rails and of the tyres of locomotives. In 1855 Daniel Kinnear Clark [Clark 1855] described in some detail the type of wear observed. Tyres had a conical profile for self-centering on the track and the material used was cast iron. There was a tendency for axles to "hunt" from side to side causing wear of the rims and also of the flanges. Fig. 3.6 shows the profiles of some of the tyres examined, with the dotted lines showing the original profile. In addition to lateral motion, imbalance of the crank shafts also caused uneven wear around the rims. Whilst clark described the wear of locomotive tyres, Dudley produce an extensive survey of the wear of rails.

Dudley entitled his first short paper on wear (1879) "Does the wearing power of steel rails increase with the hardness of the steel?" [Dudley 1879]. His observation from rails examined was that the wear resistance increased with the toughness of the steel rather than its hardness. The following year [Dudley 1880] he published a lengthier survey of the wear of rails. Sections of rail from many different tracks were taken and their change of profile was measured (see Fig. 3.7). Mechanical properties of the steel were then tabulated against wear. The overall conclusion was that "the wearing power of steel in rails not only does not increase as the hardness increases, but on the contrary decreases".

Secondly, Dudley found that mild steel gave less loss of metal in service than hard steel. He also considered the mechanism of wear involved in a wheel rolling on a rail. He recognised that neither the surface of the rail nor that of the wheel were perfectly smooth and he envisaged, as others had, that the surface roughnesses would more or less mesh together as a small scale rack and pinion but without the regularity. As the wheel rolled over the rail there would be both the normal force at the contact and a tangential traction force. The resultant of these two forces would apply bending stresses to the surface roughnesses. Dudley reasoned that if the surfaces were hard and brittle the asperities would be broken off by the strain imposed. With softer, more ductile steels, the asperities would tend to bend and flatten without breaking off. Yet the steel could not be so soft that they would squeeze out under the applied loads or bend between the ties.

A series of tests aimed at ascertaining the relative wearing properties of rail steel was carried out by E.H.Saniter of Rotherham [Saniter 1908]. In these tests a 1 inch Hoffman bearing was loaded against a half-inch diameter shaft of the material under test. The shaft rotated a 4000 rev/min. (see Fig 3.8). The applied load was 205 pounds and each test was run for 50 minutes. Wear was determined by measuring the diameter of the shaft with a micrometer before and after the test. A wear number was assigned to each test which was the reduction in diameter of the shaft in ten-thousandths of an inch during the test.

With carbon steels subjected to different heat treatments, Saniter found that the wear number decreased in a linear fashion as the ball indentation hardness increased. In other words there was a direct relationship between wear resistance and hardness. A similar result was obtained by T.E.Stanton and R.G.Batson at the National Physical Laboratory [Stanton 1916] when they repeated Saniter's experiments. Stanton and Batson carried out tests on abrasion in rolling contact on two types of test machine. This work was commissioned by the Committee on Hardness Test Research of the Institution of Mechanical Engineers, and it is interesting to note that it was completed on a budget of £200. Half this sum was supplied by the Institution and half was a grant from the Research Council of the Board of Education.

In addition to repeating Saniter's experiments, Stanton and Batson also built a rolling wear test machine in which a hardened steel ring rolled over a test piece. The ring was driven by an Oldham coupling so that the degree of slip between the ring and the test piece could be varied by altering their relative diameters. In fact, initial trials showed that a relative slip of 0.25 inch per revolution was possible with a load of 40lb. A total of 36 tests were made with a variety of low, medium and high carbon steels, which had been subjected to various heat treatments. In each test the specimen hardness was measured before and after the test and the reduction in diameter in thousandths of an inch per 1000 feet of slip was also measured. The resistance to abrasion was taken as the reciprocal of this number.

In these tests the hardness of manganese steel remained virtually unaltered with wear whereas a significant increase in hardness with wear was apparent when it was tested on the Saniter machine. The explanation offered was that work hardening of the deformed layer of this steel occurred at the higher pressure present in the Saniter test compared with the sliding abrasion test. The graph of resistance to sliding abrasion plotted against Brinell hardness number for these tests is reproduced in Fig. 3.9. There is a large amount of scatter in the results and thus the conclusion was that there was no general correlation between wear resistance and indentation hardness.

In 1922 the Swiss firm of Amsler introduced a new type of wear test machine (see Fig 3.10). Two discs were loaded together and each was driven. By using various diameters of discs, conditions could be varied from pure rolling to rolling with relative slip. The drive train from the electric motor incorporated a pendulum dynamometer which gave a direct reading of friction torque. Also, the machine had a mechanical integrator from which the work expended in overcoming friction could be determined. The Amsler machine was the first commercial wear test machine and it was at once adopted by researchers. It has been made by Amsler ever since 1922 and it is commonly used even today since it is a rugged and fairly versatile machine. A chronology of wear testing is given in Fig. 3.11.

3.7 The effect of the atmosphere on wear.

3.7.1 Wear oxidation.

In 1930 Max Fink reported the results of some experiments on the wear of tyre steel on an Amsler machine [Fink 1930]. These results were taken from his doctoral thesis submitted to the Technische Hochshule, Berlin in 1929. In reviewing the earlier work of Meyer and Nehl on the wear of steel, he believed that atmospheric oxygen had an important influence on the wearing process. To test this he fitted an Amsler machine with a gas-tight chamber around the specimens which could be purged with any desired gas. In an initial experiment with air, Fink found a weight loss of 0.81 grams on one disc after 50,000 revs. When the same experiment was repeated in a nitrogen atmosphere, there was no detectable weight loss of the disc of the same steel. Also the friction torque was a third of the level of the air test. Fink also observed the discs during the test. In air, the surface of the upper disc changed in colour to yellow, red and purple, which Fink ascribed to the growth of an oxide film causing interference patterns with the incident light. When the test was repeated in nitrogen, the disc peripheries took on a

Fink's conclusion was that wear oxidation was an important mechanism of wear, ranking equal with the other processes of cold working during wear and mechanical removal of particles.

The tests that Fink had done were repeated and extended by Rosenberg and Jordan of the American National Bureau of Standards [Rosenberg 1934]. Also using an Amsler machine, they investigated not only the effect of inert gases, but also of heat treatments, on the wear of steels. On the effect of environment, their results were at variance with Fink's. They found that the rate of wear of the steel discs were similar whether they were run in air, nitrogen or hydrogen. In fact close examination revealed that thin films were formed on the discs in all the tests. The film formed in air proved to be oxides of iron: the fact that thinner films formed in the inert gases was ascribed to reaction with traces of oxygen present in the tests cell.

On the effects of heat treating steel, they found that those tempered at low temperatures (260^{o}C) and run in an oxygen free atmosphere, gave a low wear rate and surfaces covered with a film. However when steels were tempered at a higher temperature (400^{o}C) and tested under the same conditions, their rates of wear were vary much higher and the surfaces became rough and free from film.

The experiments of Fink, and Rosenberg and Jordan undoubtedly showed the significant role played by oxidation in the wear of steels. This work was later referred to by Welsh in an extensive study of mild-severe wear transitions of steel carried out thirty years later [Welsh 1966]. although Fink assumed that the temperature of the discs remained at ambient temperature, only a few years later, Harmen Blok demonstrated that the temperature at the points of contact could increase significantly due to the high rate of energy dissipation at asperity contacts [Blok 1937]. This is the so-called "flash temperature" analysis which has been widely used in the investigation of wear mechanisms since 1950.

In 1927, G.A.Tomlinson at the National Physical Laboratory presented a paper to the Royal Society on the rusting of steel surfaces in contact [Tomlinson 1927]. He had investigated the oxidation of steel surfaces in contact which were subjected to vibration. His apparatus consisted of a small steel ball loaded against a slip gauge. The ball was either rotated about its vertical axis or rocked to and fro. What Tomlinson found was that when minute relative slip occurred at the contact, brown brittle debris was produced, and that oiling of the surfaces did not prevent this effect. Tomlinson explained this small scale wear in terms of molecular cohesion. If the surfaces approached and receded from each other normal to their contact plane then molecular cohesion would not be sufficient to pluck out molecules. But with the combination of this and tangential slip, then the cohesive forces could pluck out molecules. Tomlinson also found that as the displacement was decreased from 0.0016 inches down to 3×10^{-8} inches the contact surface degradation diminished and disappeared entirely. Tomlinson concluded that at extremely low slip amplitudes the cohesive detachment of molecules would cease. This paper marks the recognition of a phenomenon now known as fretting corrosion. This now forms a distinct branch of wear studies.

3.7.2 Wear of carbon and graphite.

In electrical generators and motors current is transferred from the stationary to the rotating contact by slip rings or a commutator. In these situations carbons and graphites have traditionally been used as brushes in contact with copper. An investigation into the wear of carbon brushes was reported by Norman Mochel of Westinghouse Electric in 1937 [Mochel 1937]. He had observed that the humidity in the atmosphere had a significant effect on the wear rate of the brushes in electrical generators. If the moisture content of the surrounding air dropped below 2 grains per cubic foot, the wear rate of the brushes became very rapid. Apparatus for testing brush wear in various atmospheres was built by Mochel. This comprised a set of copper rings 9.5 inches diameter rotating at 1725 rev/min with pairs of brushes loaded against the rings, and transmitting a current of 40 amps per square inch. The increase in wear rate found in practice was confirmed in tests, but he also reported that the wear rate was much lower when tests were run in hydrogen as opposed to air. Later the wear of carbons and graphite was studied in detail by R.H.Savage who showed that the normally low wear rate of graphite was not inherent in its structure but depended on adsorbed vapour on the crystal edges [Savage 1946].

3.8 Wear in gears

Gears have been used in machines since well before the Industrial Revolution and the history of their develoment has been traced by Woodbury [Woodbury 1958], who covered not only been traced by Woodbury [Woodbury 1958], who covered not only the evolution of the geometry of gears but also the methods used to make them. The basic problem in the scientific design of gears until the latter part of the last century was to determine the tooth profile to give uniform velocity with minimum friction. The choice centred round two cycloid curves - the epicycloid and the involute. In order to minimise friction, the goalwas that the teeth should roll over each other rather than slide. In practice some sliding takes place whatever the profile, and because of this the teeth are subject to wear.

For ease of manufacture, early examples of gears [Chambers 1779] were of the type known as trundles or wallowers. These comprised circular wooden staves set into discs as shown in Fig 3.12. The meshing gears were either of the peg type if the shafts were at right angles, or the staves engaged in circular slots in a wheel. The staves of the wallower were allowed to rotate in their sockets so that there was no sliding between it and the meshing gear. However as Buchanan [Buchanan 1808] noted:

> "Trundles, in consequence of the surface contact being small, become soon indented by pressure and wear and cease to turn in their sockets".

Before the advent of machined gears, individual gear teeth were made of wood and were fitted into slots in the periphery of iron wheels as shown in Fig 3.13. These wooden teeth were called cogs and were usually made of hard wood such as hickory, mountain beech or hornbeam. This arrangement was described by Willis [Willis 1841] who wrote:

> "... it is found by experience that, if in a pair of wheels the teeth of one wheel be of cast iron and in the other of

wood, that the pair work together with much less vibration and consequent noise, and that the teeth abrade each other less, than if both wheels of the pair had iron teeth".

Buchanan also showed in his "Essay on the teeth of wheels" (1808) the form taken by the "leaves" (i.e. the teeth) of gears after wear and this is shown in Fig.3.14. There is virtually uniform wear on the flanks of the teeth, although, in theory true rolling occurs at the pitch point.

3.9 Classification of wear.

Various writers attempted to identify the wear processes that lead to loss of material during wear. The distinction between types of wear that occur in particular forms of contact and the actual processes that take place within these contacts, were not always clearly distinguished. For example O'Neill, in his book on the hardness of metals [O'Neill 1934] devoted a chapter to "abrasion", and listed three types of wear mechanism with examples;

1) Rolling abrasion	(a) lubricated - e.g. ball races
	(b) unlubricated - e.g. wheels on rails
2) Sliding abrasion	(a) lubricated - e.g. plain bearings,gears
	(b) unlubricated - e.g. wheels brakes
3) Direct abrasion	Metal+abrasive - e.g. grinding machinery

This table infers that there is no distinction to be drawn between the wear that occurs in rolling contact from that in sliding contact. This must be compared with the mechanisms of wear discussed by Gillett [Gillett 1937] in his review. According to him there were two mechanisms of metallic wear, firstly through *asperity contacts* and secondly through *molecular* *contact*. For asperity contacts he quoted Dudley's theory to explain the wear of rail steels, and for molecular contct, Gillett cited the work of Tomlinson [Tomlinson 1929]. However, Gillett also recognised that what happens to the resulting wear debris is important. If the debris is crushed to very fine particles, it may be swept out of the contact and take no further part in the wear process. In some cases the wear particles may become work hardened and embed themselves in one or other of the contacting material and increase the wear rate.

TABLE 3.1

Clamer's Test Results [Clamer 1903]

Bearing alloy composition %wt			Friction lbs	Temperature Rise ^oF	Wear grams
Cu	Sn	Pb			
85.76	14.9	-	13	50	0.28
90.67	9.4	-	13	51	0.177
95.01	4.9	-	16	52	0.0776
90.82	4.6	4.8	14	53	0.0542
85.1	4.6	10.6	18.5	56	0.038
81.3	5.2	14.1	18.5	58	0.0327
75	5	20	18.5	58	0.027
68.7	5.24	26.67	18	58	0.020
64.3	4.7	31.2	18	44	0.013

Test Conditions:

half bearing 3.75"dia. x 3.5" long
steel shaft
1,000 lbf/in^2 bearing pressure
Galena coach oil fed by cotton waste
Wear measured after 100,000 revs.

TABLE 3.2

Mohs Scale of Mineral Hardness

Diamond	10
Carborundum or sapphire	9
Topaz	8
Quartz	7
Orthoclase	6
Apatite	5
Fluorite	4
Calcite	3
Gypsum	2
Talc	1

TABLE 3.3

Bottone's Table of Hardness of Metallic Elements

[Bottone 1873]

Element	Hardness
Mn	1456
Co	1450
Ni	1410
Fe	1375
Cu	1360
Pd	1200
Pt	1107
Zn	1077
Ag	990
Ir	984
Au	979
Al	821
Cd	760
Mg	726
Sn	651
Pb	570

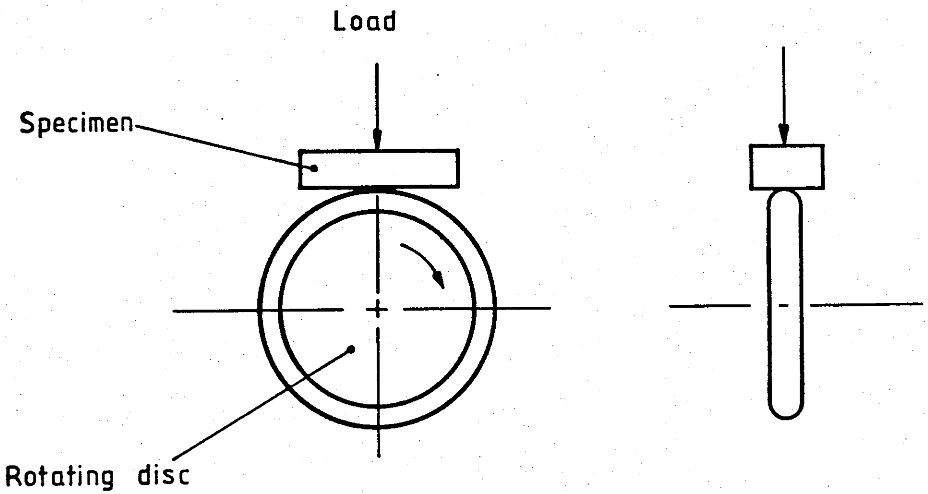


FIG.3·1 BOTTONE - "HARDNESS" TEST

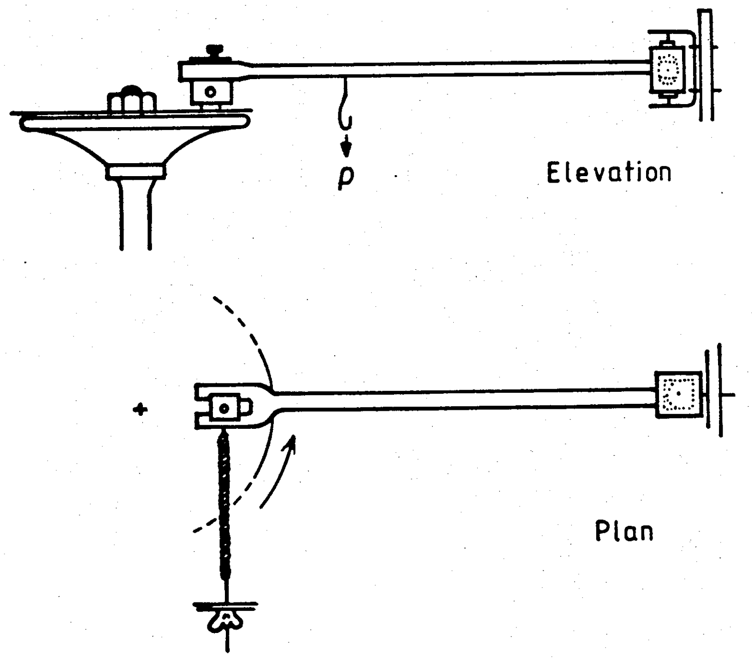


FIG 3·2 ROBIN-PIN ON DISC APPARATUS

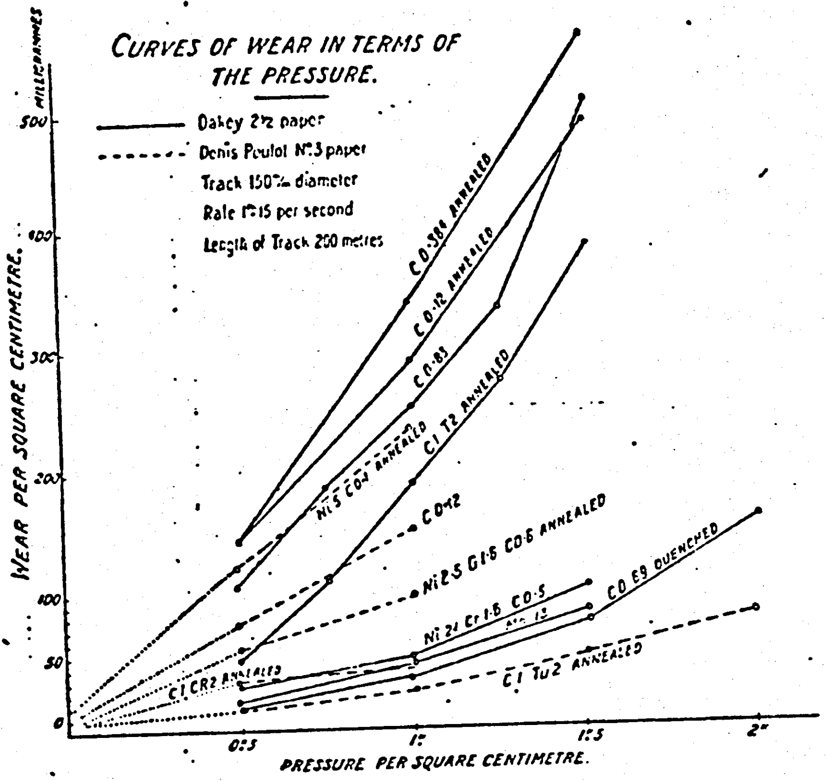


Fig. 3.3 Wear rate vs. Pressure (Robin)

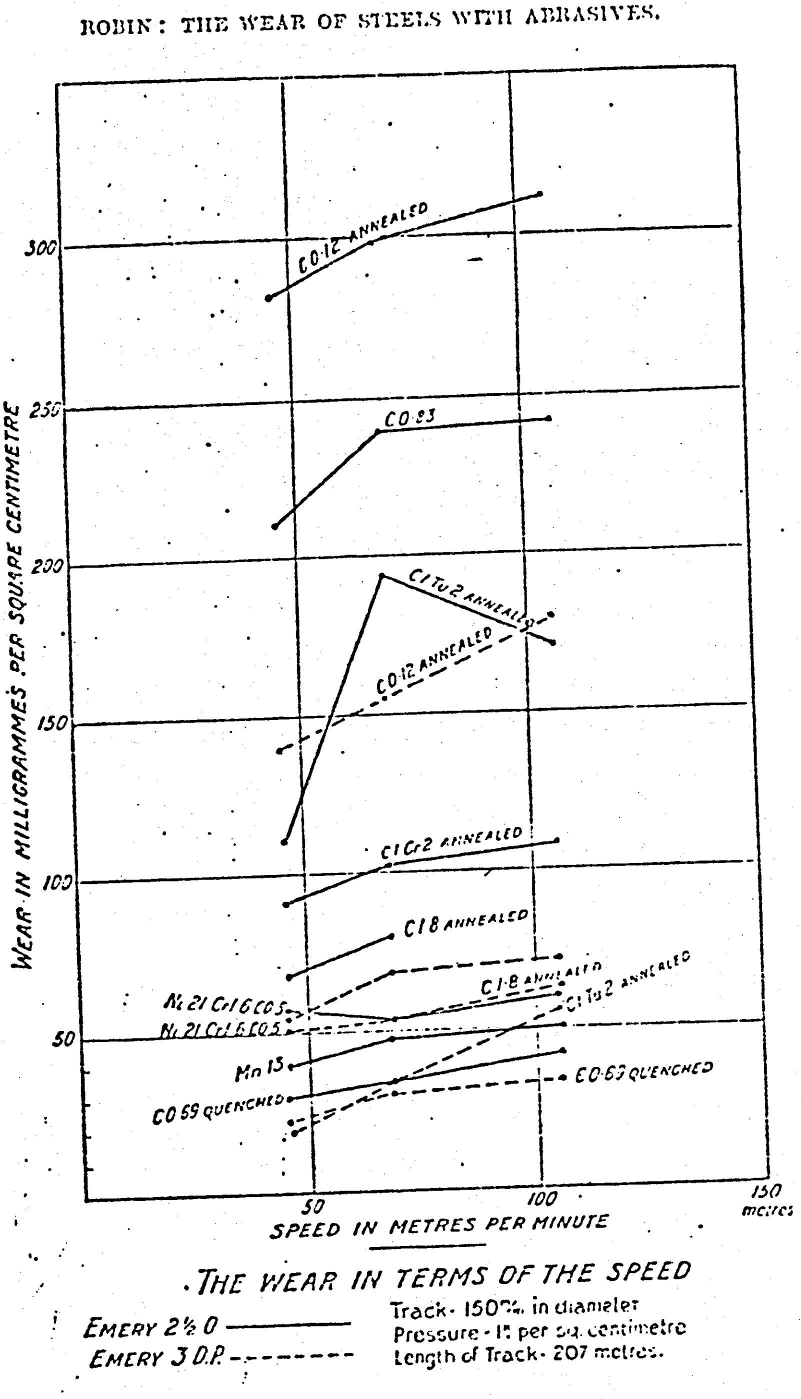


Fig. 3.4 Wear rate vs. Speed (Robin).

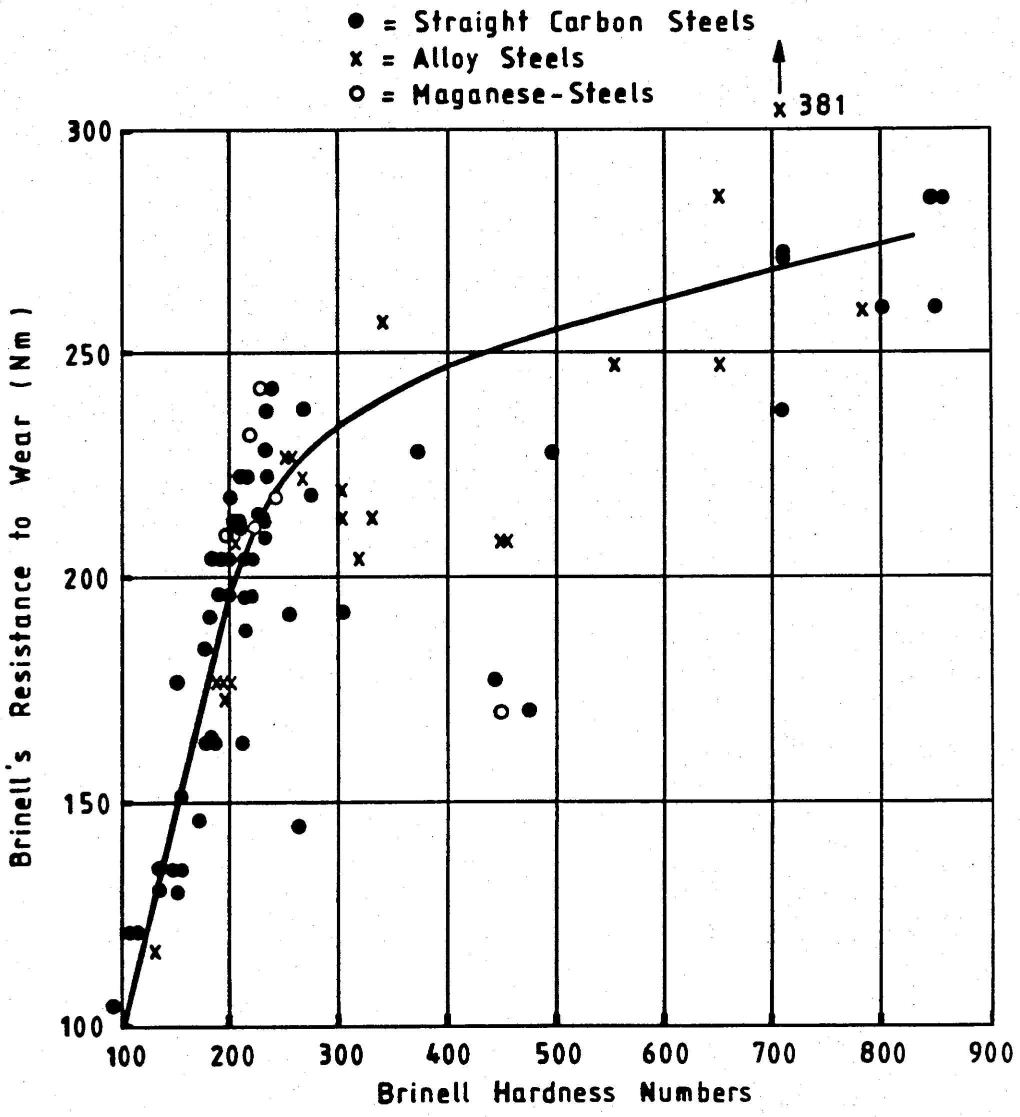
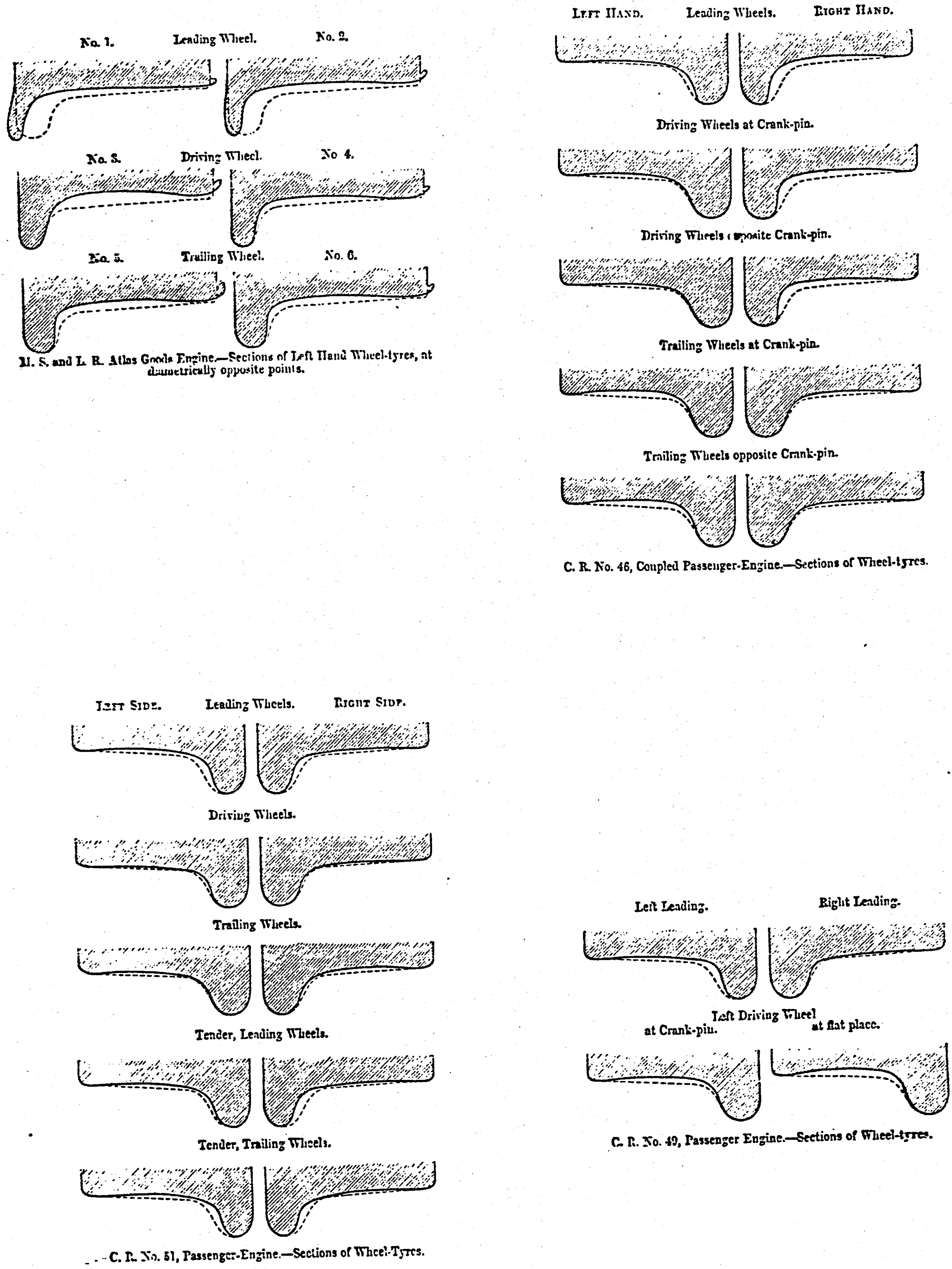


FIG.3.5 RESULTS OF BRINELL'S ABRASION TESTS



M. S. and L. R. Atlas Goods Engine.—Sections of Left Hand Wheel-tyres, at diametrically opposite points.

C. R. No. 46, Coupled Passenger-Engine.—Sections of Wheel-tyres.

C. R. No. 51, Passenger-Engine.—Sections of Wheel-Tyres.

C. R. No. 49, Passenger Engine.—Sections of Wheel-tyres.

Fig. 3.6 Profiles of worn locomotive tyres

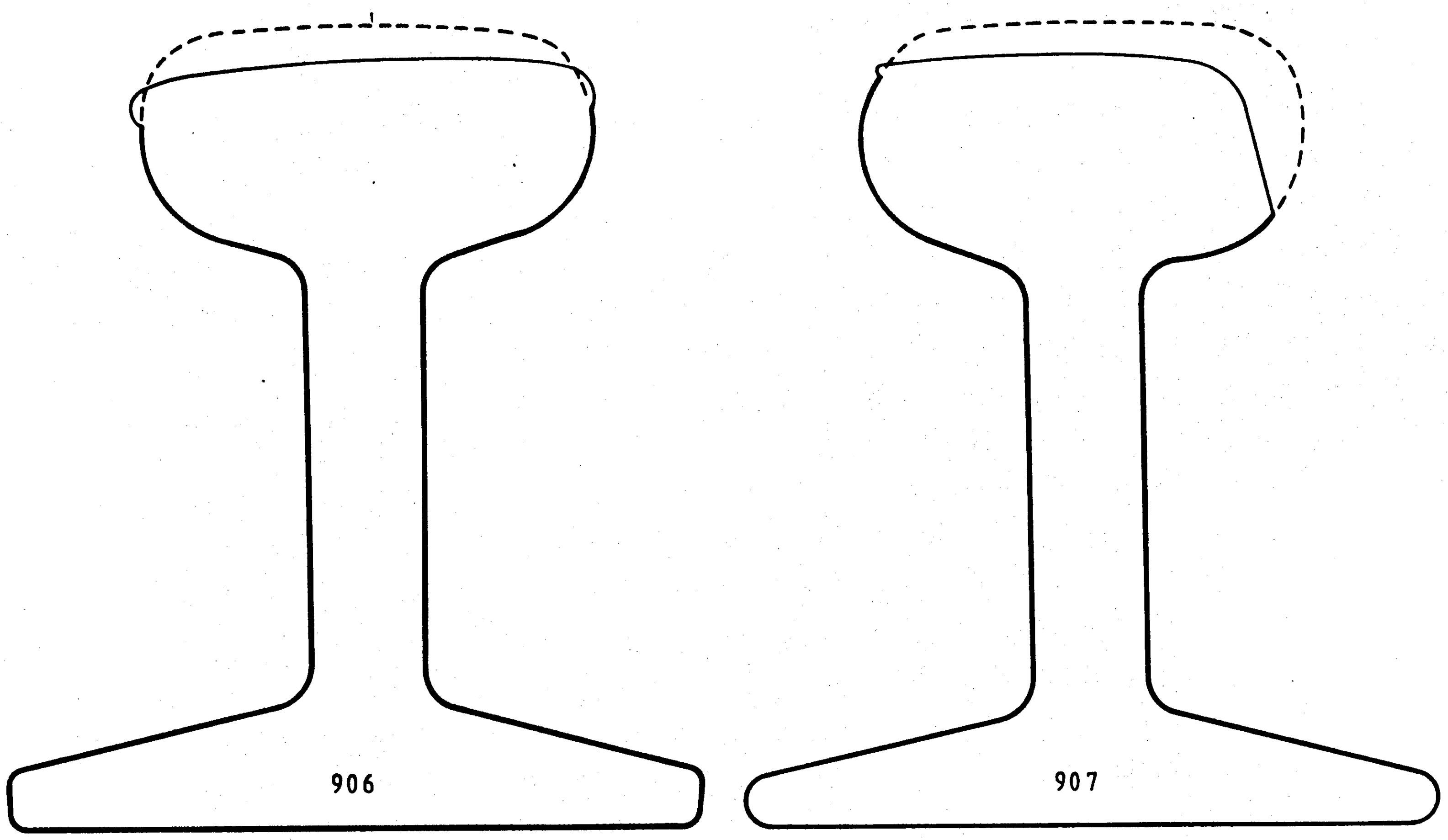


FIG. 3.7 WEAR OF STEEL RAILS (DUDLEY)

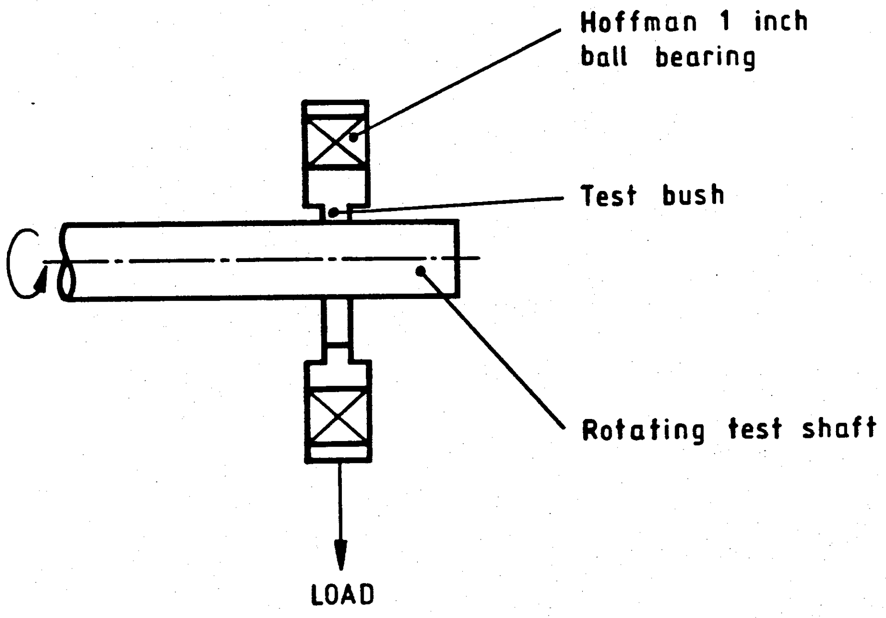


FIG.3·8 SANITER WEAR TEST MACHINE

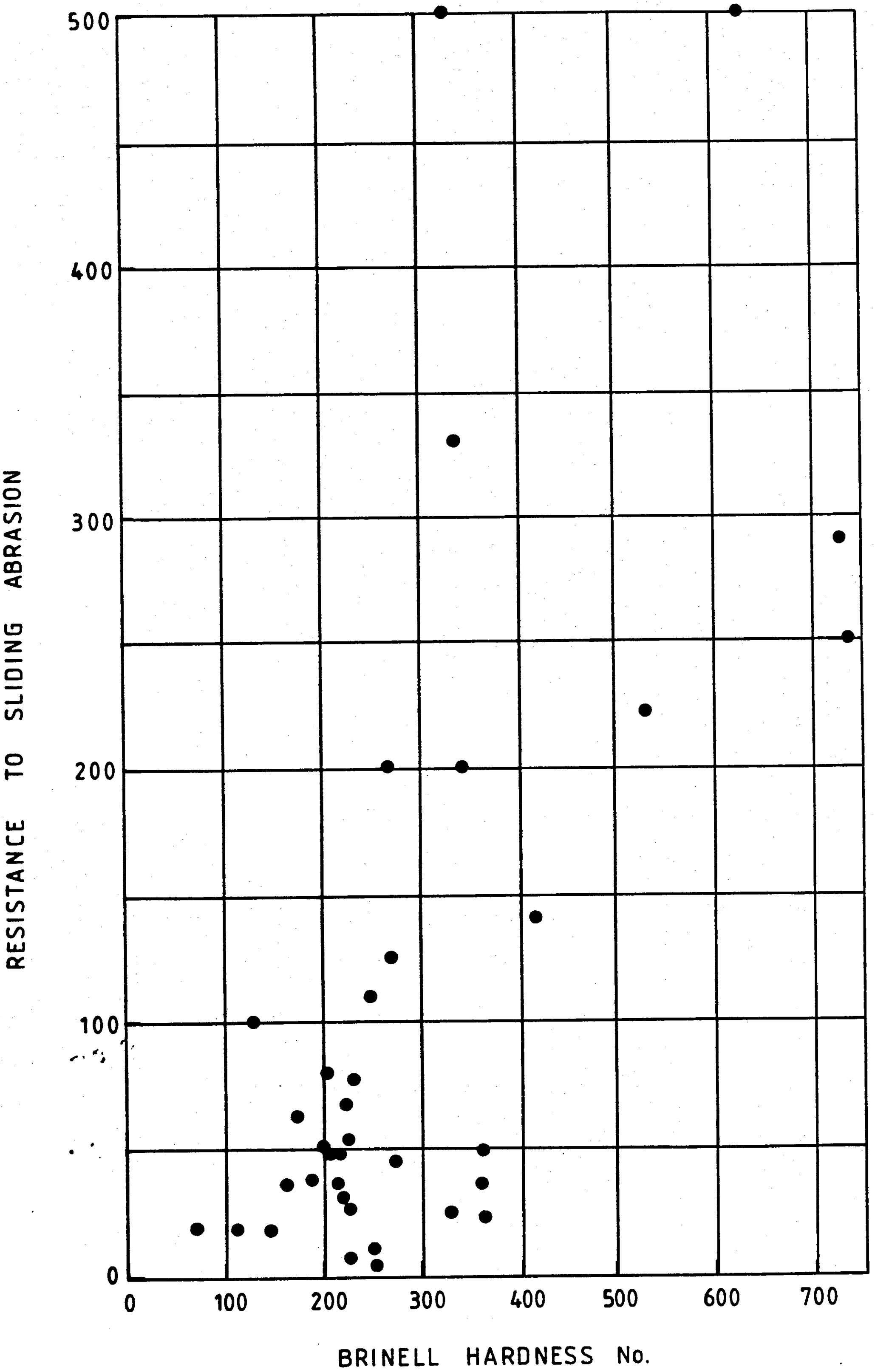


FIG.3·9 STANTON + BATSON WEAR Vs. HARDNESS

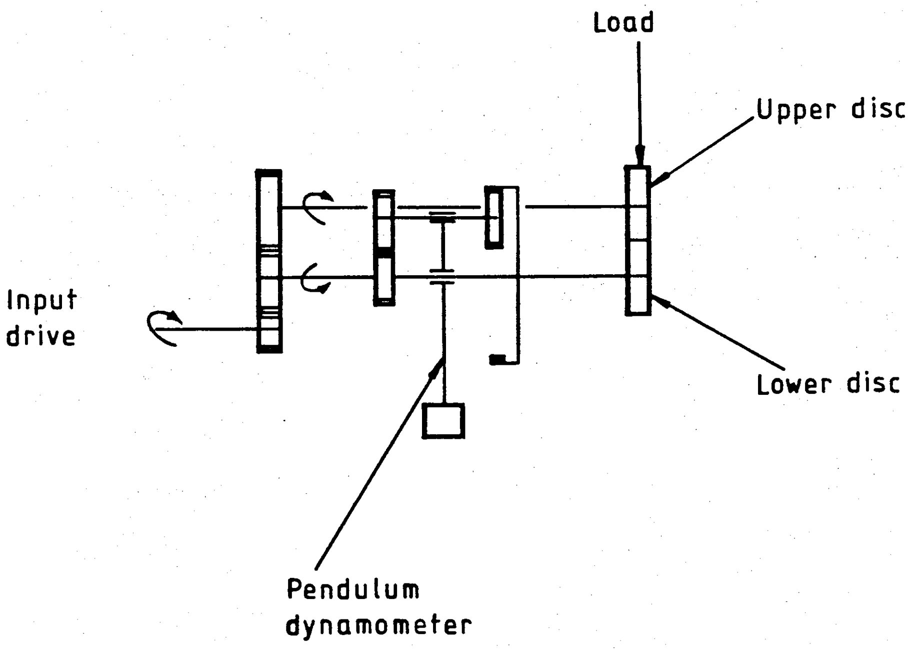


FIG. 3·10 SCHEMATIC OF AMSLER WEAR MACHINE

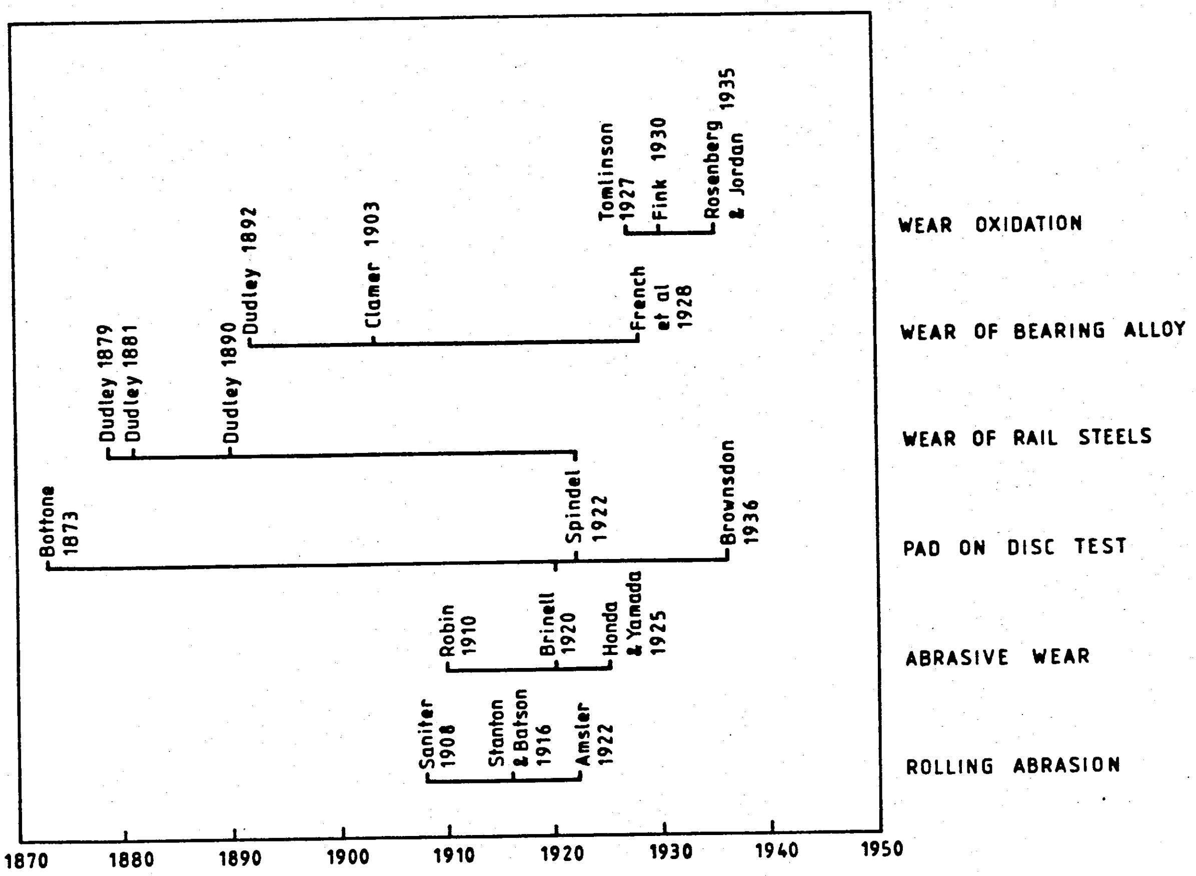


FIG.3·11 CHRONOLOGY

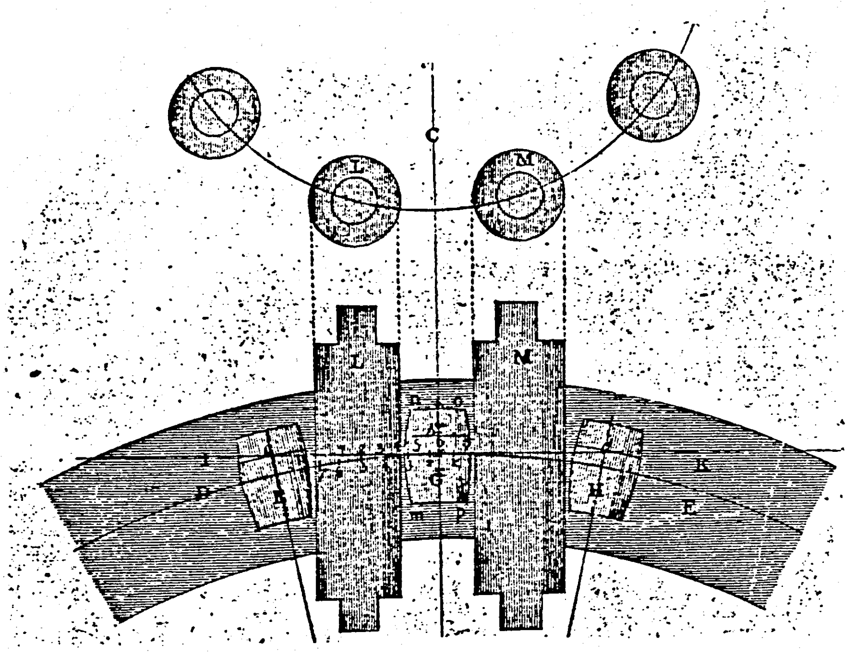


Fig. 3.12 Trundle or wallower gears

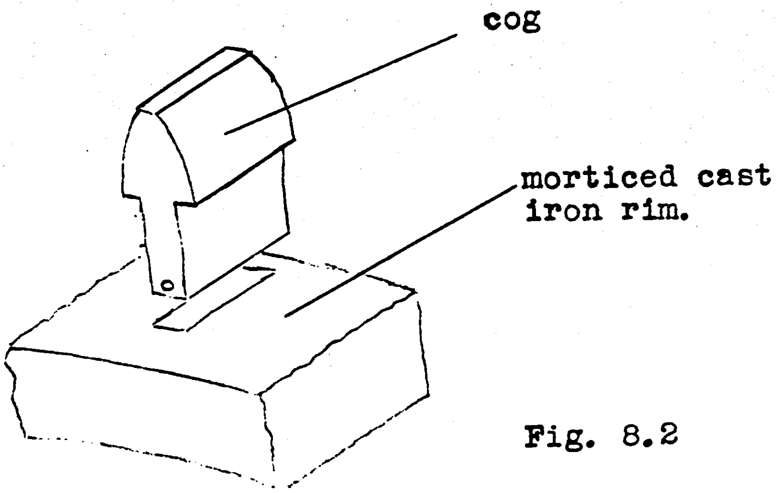


Fig. 3.13 Wooden cog in cast iron rim

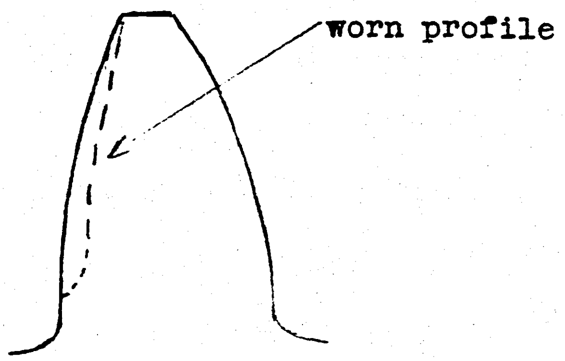


Fig. 3.14 Wear of involute gear teeth

(after Buchanan)

CHAPTER 4

PROFILOMETRY, THE CONTACT OF SOLIDS AND THE DEVELOPMENT OF MODERN THEORIES OF FRICTION AND WEAR

4.1 Models of surface contact.

All those who studied friction in the eighteenth century (Amontons, Parent,Euler and Coulomb) believed that the interlocking of surface roughnesses was the main cause of friction, since during sliding, the roughnesses of one surface would be dragged over those of the other. Surface roughnesses were modelled both by Parent and by Belidor [Parent 1704, Belidor 1737](Fig 4.1). Both represented the roughnesses by hemispheres and used this geometry to calculate the magnitude of the friction coefficient. Assuming closely packed, uniform hemispheres, calculation of the friction coefficient is mathematically tractable. Implicit in this analysis is the assumption that the surfaces were not deformed by the applied normal loads. Euler in the first of his two papers on friction assumed uniform triangular asperities on both contacting surfaces, and the sketch in his paper (see Fig 4.2) indicated that these regular asperities interlock perfectly. The same assumption of perfect fitting of the asperities is also implied in the drawing in Coulomb's memoir (see Fig 4.2). Whilst pertinent objections to this concept were raised no new models were proposed until well into the nineteenth century.

In 1886, John Goodman put forward a modification of the interlocking model [Goodman 1886]. He assumed that the surfaces of all solid bodies were covered with roughnesses that resembled the structure of the pile of velvet. When similar materials were placed in contact the asperities matched exactly whereas for dissimilar materials the difference in pitch of the piles resulted in a mismatch. This accounted for a practical observation that the friction between similar materials was greater than between dissimilar materials.

During the nineteen twenties the nature of surface contact at the molecular level was studied. The work of Hardy [Hardy 1919] and Tomlinson [Tomlinson 1929] showed that considerable cohesive forces could come into play when smooth clean glass surfaces were slid relative to each other. Both demonstrated that, under these conditions, particles of glass were torn out during sliding although contact loads were small. Tomlinson's paper on molecular cohesion is of particular interest. Using sensitive apparatus, he measured cohesive forces of up to 1000 dynes between glass spheres of 0.6 cm radius (contact areas were calculated using Hertz equations). This attraction of cohesion decreased rapidly with separation distance. By experiment he found:

$$F = \frac{K}{d^4}$$

where F is the cohesive force and d the separation distance, and K is a constant. Tomlinson defined cohesion as an electrical force accompanying the structure of the atom. Since, at the surface of a solid, the electrical fields would be unbalanced, adhesion could result when two solid approached close enough for mutual attraction to occur. The concept of high cohesion forces between solids had, of course been demonstrated by Desaguliers as early as 1725 [Desaguliers 1725].

4.2 Surface topography

Apparatus and methods for assessing and comparing the roughness of solid surfaces began to emerge during the late nineteen twenties and developed quite rapidly in the following decade. By the Second World War reliable, easy to use equipment for measuring surface roughness was available and was being adopted in many workshops. The driving force behind this development was the increasing use of mass production manufacturing methods combined with the closer tolerances to which components could be machined. Given that components were fitted with closer tolerances, some method of comparing roughness was necessary for quality control.

One of the earliest descriptions of an apparatus for measuring surface roughness was given by Gustav Schmaltz[Schmaltz 1929]. The instrument he described translated the surface under examination beneath a spring-loaded styles (Fig. 4.4). The tiny vertical movements of the stylus were amplified optically and thus could be recorded on photographic paper which moved synchronously with the surface. A smaller scale optical instrument was also described by Firestone, Abbot and Durbin in 1932 [Firestone 1933]. In their instrument the best stylus proved to be the corner of a razor blade, although only a few inches of a steel surface could be traversed before the wear of the blade upset the traces. The stylus moved in conjunction with a pilot point over the surface and the movement of the stylus caused tilting of a small mirror which was magnified by an optical lever (Fig. 4.5), so that magnifications of up to 2500 could be achieved.

The paper described measurements made of the teeth of spur gears, where, in addition to the machining marks on the teeth, errors of form were detected by moving the pilot point along a master profile. Whilst the authors were from the Department of Engineering at the University of Michigan, the work on this instrument was sponsored by the Timken Company who used the equipment to study the type of scoring observed on various bearing surfaces in tests on different lubricants. However, no details of this work were given.

Another method of assessing the roughness of machined surfaces was described by Harrison [Harrison 1931]. In this apparatus a phonograph needle and pick up was traversed along the surface. The signal from the pick up was amplified and the output from the amplifier was connected both to a loudspeaker and also to a millivolt meter (Fig. 4.6). Thus both a visual and audible indication of the surface roughness was given. According to the author, a rough ground surface produced a "deep, harsh vibration" in the loudspeaker and a relatively large movement of the needle on the meter. A finely ground workpiece gave a "keen, high note characteristic of minute vibrations" and a small millivolt reading. although this equipment was described in connection with improving quality control in workshops, no indication of how the instrument was to be calibrated was provided. However, some data was given to show that the use of such an instrument could help to reduce the cost of attaining high quality surface finishes.

As Abbot and Firestone (1933) pointed out, the phonograph pickup method yields little detailed information concerning the surface. Unless the dimensions and frequency response of the pickup and the speed of traversal are known, it is uncertain just what characteristics of the surface are measured [Abbott 1933]. They preferred the method of tracing the surface with a stylus and producing a physical record. For standardisation they felt that it would be useful if the roughness of a surface could be specified by a single number. What they proposed was to determine the "bearing area" of the surface from its profilograph. Lines were drawn through the profile from the highest peak to the deepest valley (Fig 4.7). The fraction of the line lying within the metal at each stage was measured. In this way the bearing area curve was built up and the distances for the peak roughness (2%-25% of bearing area), median (25%-75%) and valley (75%-98%) could then be determined. So three numbers (roughness heights) could be obtained for each profile. In mathematical terms the bearing area is the cumulative amplitude distribution of the surface profile.

Development of the surface profilometer was pursued enthusiastically by Abbot and his colleagues, who in fact set up their own company (The Physicists Research Company) at Ann Arbor, Michigan to exploit their product. The outcome of their work was described in a paper of 1938 [Abbott 1938]. By this time they had developed a simple instrument which used a diamond stylus, a sensitive magnetic detector and a valve amplifier. The output was displayed on an oscillograph which could be photographed and a vertical magnification of up to 50,000 x was possible. A portable version was available where surface roughness was displayed as a root-mean-square reading on a meter. Thus by 1939 the forerunners of the present-day surface roughness instruments were already being marketed.

Developments along similar lines had taken place in England. William Taylor, a founder of the firm of Taylor,Taylor and Hobson of Leicester, visited the USA in 1934 and learned of the work of Abbott [Hume 1980]. One of the young designers at Taylor, Taylor and Hobson, Richard Reason developed the concept and also rejected optical magnification technique in favour of electronic amplification. The result was the production of the original Talysurf profilometer which came onto the market in 1937. In addition to providing a measure of roughness amplitude on a meter, this instrument also gave a physical record of the trace which was sparked onto electrically sensitive paper.

4.3 The real area of contact

The previous section described the development of the surface profilometer which gave a physical picture of the roughness of a surface, albeit with an exaggerated vertical scale. When two surfaces touch the points of actual contact are usually only a very small fraction of the apparent, or geometric area. The ratio of apparent to real area of contact was demonstrated by Bowden and Tabor in a paper published in 1938 [Bowden 1938]. To measure the area of real contact they measured the electrical resistance between loaded metal surface. Crossed cylinders, sphere on flat and flat on flat geometries were used. For flats of 21 square centimetres in area, they calculated that the ration of real to apparent area of contact increased from 1/170,000 at a load of 3kg to 1/300 at a load of 300kg. They also found that the real area of contact increased in direct proportion to the applied load.

The earliest of this type of measurement was carried out by Dr. Ludwig Binder in Berlin in 1912 [Binder 1912]. He reported the results of experiments on copper,carbon and steel contacts of cylindrical and spherical geometry in which resistance was measured as a function of load and current density. He quickly realised that the resistance between the contact were considerably higher than they should be if contact was made over the full area. Binder indicated that real contact at discrete points would constrict the flow of electric current and give rise to a significant resistance. A sketch given in his paper of the local contact between two surfaces is reproduced in Fig. 4.8. Support for his view came from the work of Ragnar Holm and his colleagues at Siemens in Austria. They published a series of papers during the period from 1922-1929 [Holm 1922,1925,1927,1929] which demonstrated that the contact resistance between clean metals obeys Ohm's law and is a "spreading resistance", i.e. produced as a result of the constriction of the current through a small contact area. Another conclusion was that, for flat surfaces, contact occurred over a large number of small areas.

4.5 Towards modern theories of friction and wear

The recordings obtained with even the earliest of the surface profilometers clearly showed that, for most ordinary surfaces, the scale of roughness was several orders of magnitude greater than atomic or molecular dimensions. This was seen later to apply even to the most highly polished surfaces. At the same time, theories were proposed to explain the phenomena of friction and wear by reference to the interaction of molecular forces, without reference to surface roughness. For example, G.A.Tomlinson of the National Physical Laboratory published a molecular theory of friction in 1929 [Tomlinson 1929]. Following from his previous work on the cohesion between solids, his concept of friction was based on consideration of the attractive and repulsive forces between atoms. His own observations, coupled with the results of other work, indicated that the rate of change with distance of the repulsive forces between atoms was much greater than that of the attractive forces. So as two bodies move relative to one another, different atoms would come within the range of these forces and then separate. Tomlinson then described how an irreversibility could occur during the approach and separation of atoms. This irreversibility would result in the loss of energy. This loss, summed over all the molecules involved in such processes, represented the work done in overcoming friction.

Tomlinson was concerned only with clean surfaces that were free from contamination and adsorbed films. In a theoretical analysis he demonstrated that the coefficient of friction was proportional to the number of molecular interactions involved and was also related to the elastic constants of the materials in contact. His experimental work, on both sliding and rolling friction, supported this view to some extent. It is also clear that he obtained unusually high levels of friction and even clinging between surfaces such a clean glass and freshly cut lead. At no stage, however, did he consider how the roughness of surfaces might affect their friction although there is an implicit recognition that the local shape of surface contacts would affect the magnitude of the stresses between them.

His observations on wear are also worthy of note. Prior to his paper on friction, Tomlinson had already published a study of what would now be called fretting corrosion between steels contacts [Tomlinson 1927]. During the process of approach and recession of molecules, each has a strong bias to return to its parent body, but the conclusion from his previous paper was that in some cases molecules could in fact be detached, although he noted:

> "It can be shown, however, from our knowledge of the ordinary rate of wear of metals, that only a very small proportion of the molecules can be detached".

He derived an expression to determine the mass of all the molecules involved in the frictional process in relation to the energy or work done in overcoming friction. For the case of a brake on a steel flywheel dissipating 100 kilowatts for 1 hour,the value of the mass involved in friction would be about 10^7 grams. However, the actual mass of metal worn away would be only a very small fraction of this. Taking a not unreasonable value of 1 gram, only about 1 in 10^7 of the molecules effective in causing friction would be detached, and that:

> "wear may be fundamentally only an accidental accompaniment of friction".

Although research after 1950 has shown that wear occurs by detachment of particles on a scale much larger than molecular dimensions, this approach by Tomlinson is of interest since it foreshadowed, to some extent, that of Archard [Archard 1957]. The wear coefficients given by Archard were interpreted as some measure of the probability of detachment of a wear particle.

Ragnar Holm, whose work in connection with the contact resistance of solids has already been mentioned, also concluded that wear occurred by the removal of material on an atomic scale [Holm 1950]. His derivation of a wear coefficient was as follows:

The real area of contact between two solids, A, is equal to the applied normal load, P divided by the hardness of the softer body, H

$$A = P/H$$

Assume a sliding distance d. The moving atoms in one body encounter stationary atoms in the other. The number of encounters will be equal to the number of atoms in the area N_A times the number of encounters N_d which each of those atoms makes in sliding a distance d. If the atomic spacing is s then:

$$N_A = A/s^2$$

and $$N_d = d/s$$

The total number of encounters is

$$Ad/s^3$$

If the worn volume is V it will contain V/s^3 atoms

$$Z = V/s^3 \times s^3/Ad = V/Ad$$

where Z is the fraction of encounters that result in removal of atoms. A, the real area of contact, is given by P/H where P is the load and H is the hardness. Thus:

$$V = ZPd/H$$

This equation indicates that the worn volume is proportional to the load and sliding distance and inversely proportional to the hardness. It is similar to the findings implicit in earlier results (e.g Honda and Yamada) described in the previous chapter. Holm also presented data from wear experiments on a number of material combinations which indicated that the value of $z \times 10^5$ remained relatively constant for a given material couple over a relatively wide range of applied loads (see Table 4.1).

Whilst the work of Tomlinson and Holm is of interest from a theoretical point of view, the practical work of Bowden and Tabor clearly demonstrated that wear and surface damage during sliding occurred on a much larger scale than the atomic level [Bowden 1950]. In their now classical experiments on unlubricated metals, they showed that sliding took place by discontinuous (stick-slip) motion and also that the wear of one surface took the form of removal of relatively large (2 – 20 micrometre) particles.

4.5 Two-term theory of friction

An attempt to quantify the adhesion component of friction had been made by Price [Price 1905] in the USA, in a paper published in 1905. Price's work was concerned with the structure and physical properties of bearing metals. but he also considered the friction between surfaces. although his theory was not fully developed, it was clearly a precursor of later models since he wrote:

> "Recognising the obvious fact that no two surfaces, when placed in contact, can be conceived to fit exactly, except when the normal pressure is made great enough to overcome the tendency toward point contact, or small area contact, and calling the total area of the smaller surface the apparent area, and the summation of all the small areas actually touching, the real area...."

He let A = the apparent area of contact

A' = the real area of contact

P = the applied load

p = the apparent stress

p' = the real stress

μ = the coefficient of friction

f = the friction force

It was assumed that A' varied directly as the load P and thus:

$$p'a' = P$$

and making p' constant with

$$F = \mu P$$

and dividing by A'

$$F/A' = \mu P = \mu p'$$

The interesting aspect of this is the recognition, almost 40 years before Ernst and Merchant and Bowden and Tabor, that for metals the stress at the point of real contact p' was a constant, i.e. the hardness. The step that was missing was that F/A' is equal to the shear stress of the softer of the two contacting materials.

A credible two-term model of the friction process, (adhesion and interlocking), was provided in the work of Ernst and Merchant (1940) [Ernst 1940]. They had in mind the concept of a small true area of contact consisting of discrete contacts distributed over the surface. A pictorial representation of their model is shown in Fig. 4.9, where the forces acting at one such contact are shown. They considered the separate parts played by adhesion and interlocking and the friction coefficient was expressed as follows:

$$u = S/H + \tan\theta$$

The first part of the expression (S/H) is the ratio of the shear strength at the contact (S) divided by the hardness of the softer surface (H) and represents the adhesive term. θ is a measure of the slope of the surface roughness and represents the interlocking term. Ernst and Merchant considered the limiting cases when D tends to 0 and S tends to 0. In the first case when D tends to 0, i.e. when the surfaces are very smooth the interlocking term disappears and the adhesive term dominates, but there is still a finite friction coefficient, as Desaguliers had speculated previously. The other limiting condition (S tends to 0) could be approached with a perfect boundary lubricant which would greatly reduce the shear strength at the contact. Under these conditions the friction would depend upon the smoothness of the surfaces.

The authors went on to propose a method of calculating the interfacial shear strength S for clean metal pairs in terms of their mutual solubility and achieved good agreement between values of u predicted from the equation above and results from carefully conducted experiments on metal pairs in vacuum.

This paper can be regarded as the first statement in English of the "modern" theory of friction and many of the ideas put forward by Ernst and Merchant have become important topics in their own right. Holm, then in Austria, had published a paper along the same lines a little earlier [Holm 1938] and Bowden and Tabor (who moved to Australia during the war) developed similar concepts a little later [Bowden 1942].

TABLE 4.1

Values of Z x10^{5} from Wear Experiments of R.Holm. [Holm 1950]

Harder Member	Softer Member				
	Load grams	Iron	Copper	Silver	Aluminium
Steel	15,000	2.6	–	–	–
	1,100	–	6.8	0.8	–
	100	4	3.4	0.9	64
	15	4	3.0	1.2	66
Glass	530	2	–	0.6	–
	100	1.5	6.8	–	–
	15	2.4	6.6	0.8	98
Silver	100	–	18	20	6–18
	15	–	32	24	3.4

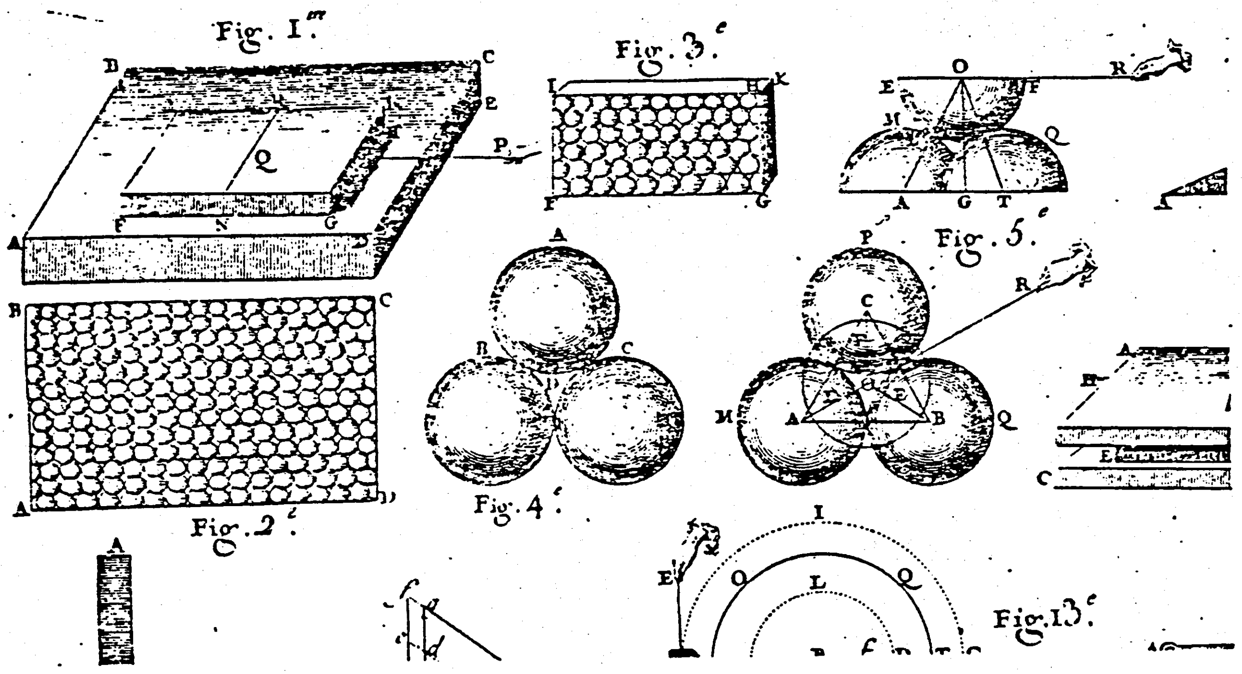
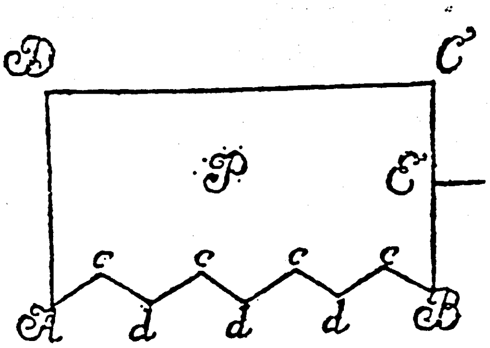
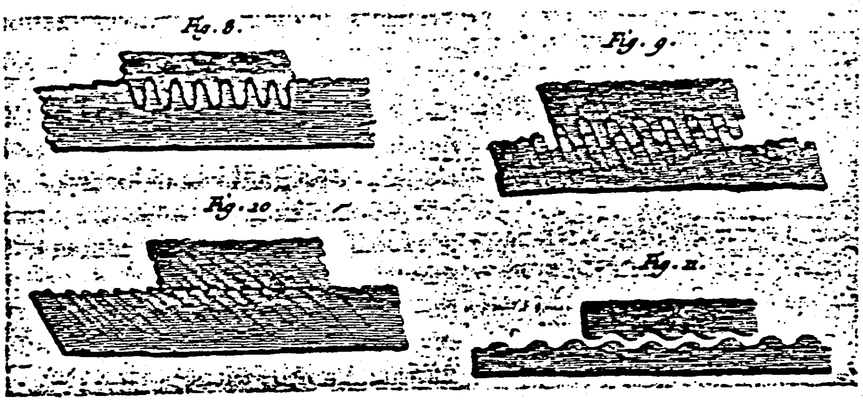


Fig. 4.1 Belidor's representation of rough surfaces with spherical asperities.



Euler - triangular asperities.



Coulomb - interlocking rounded asperities.

Fig. 4.2 Euler's and Coulomb's representation of surfaces roughness.

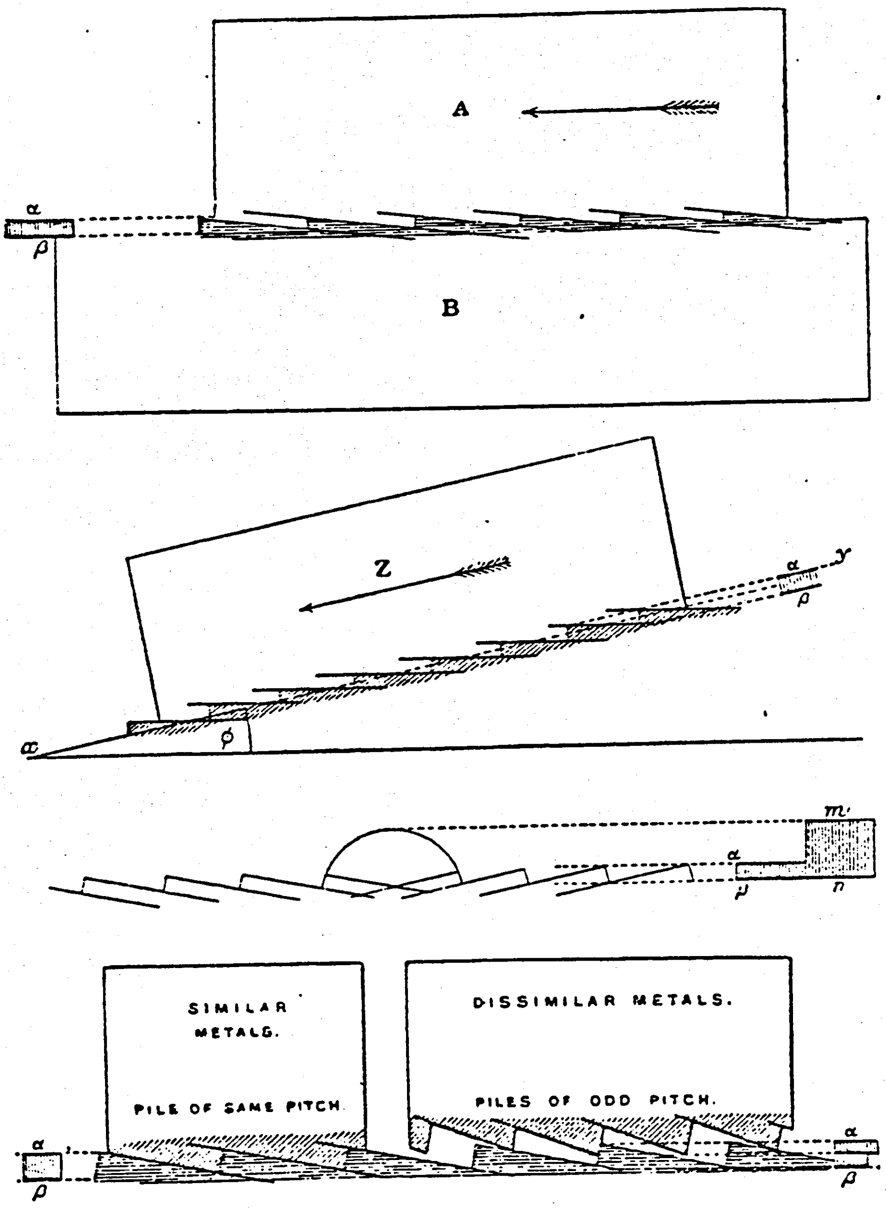


Fig. 4.3 Goodman's analogy of interlocking piles.

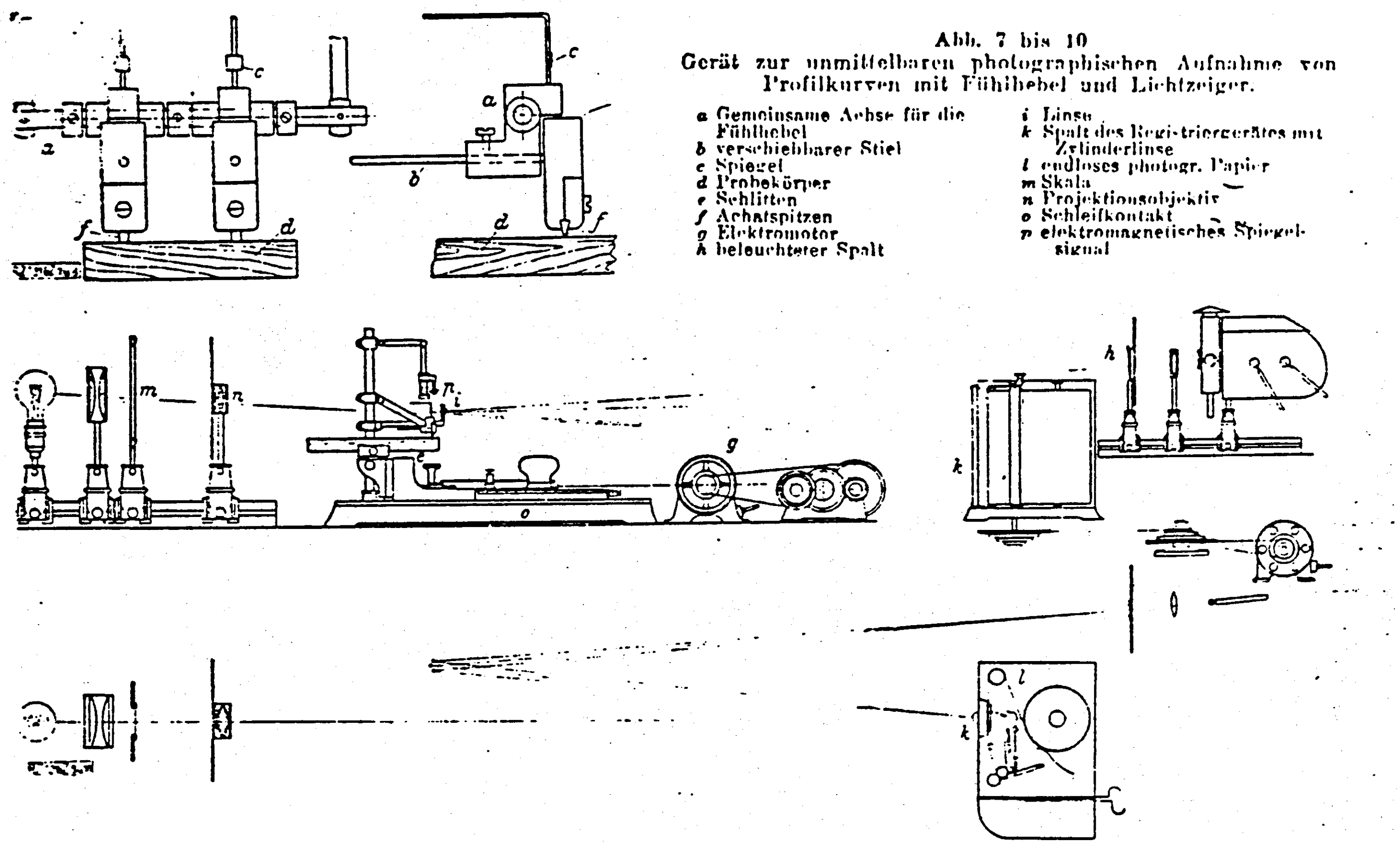
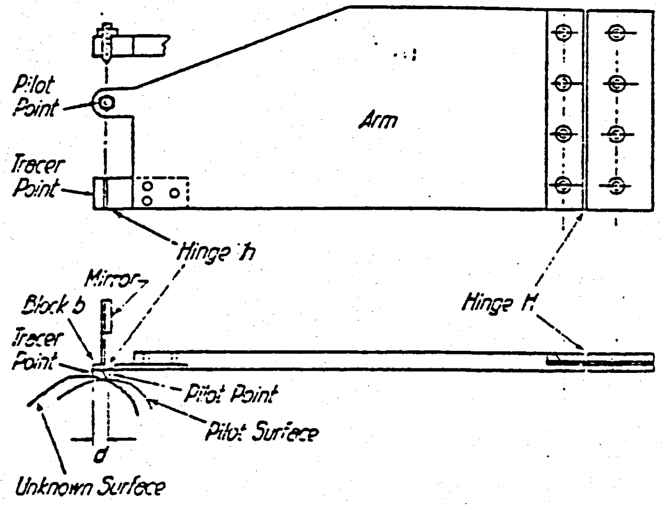


Abb. 7 bis 10

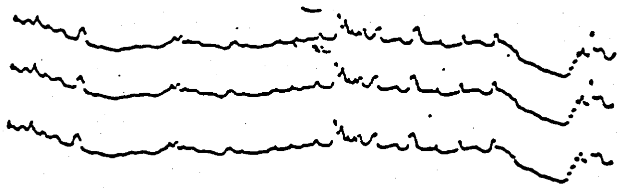
Gerät zur unmittelbaren photographischen Aufnahme von Profilkurven mit Fühlhebel und Lichtzeiger.

a	Gemeinsame Achse für die Fühlhebel
b	verschiebbarer Stiel
c	Spiegel
d	Probekörper
e	Schlitten
f	Achatspitzen
g	Elektromotor
h	beleuchteter Spalt
i	Linse
k	Spalt des Registriergerätes mit Zylinderlinse
l	endloses photogr. Papier
m	Skala
n	Projektionsobjektiv
o	Schleifkontakt
p	elektromagnetisches Spiegelsignal

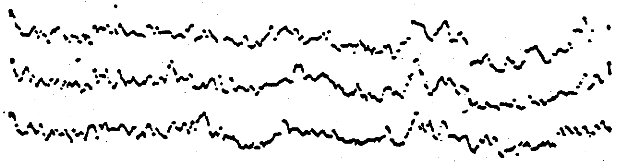
Fig. 4.4 The surface profilometer of Gustav Schmaltz.



Typical Curves Traced on Gear Teeth



Repeat Runs, Same Area



Three Areas on Single Tooth

Fig. 4.5 The optical profilometer of Abbott, Durbin and Firestone.

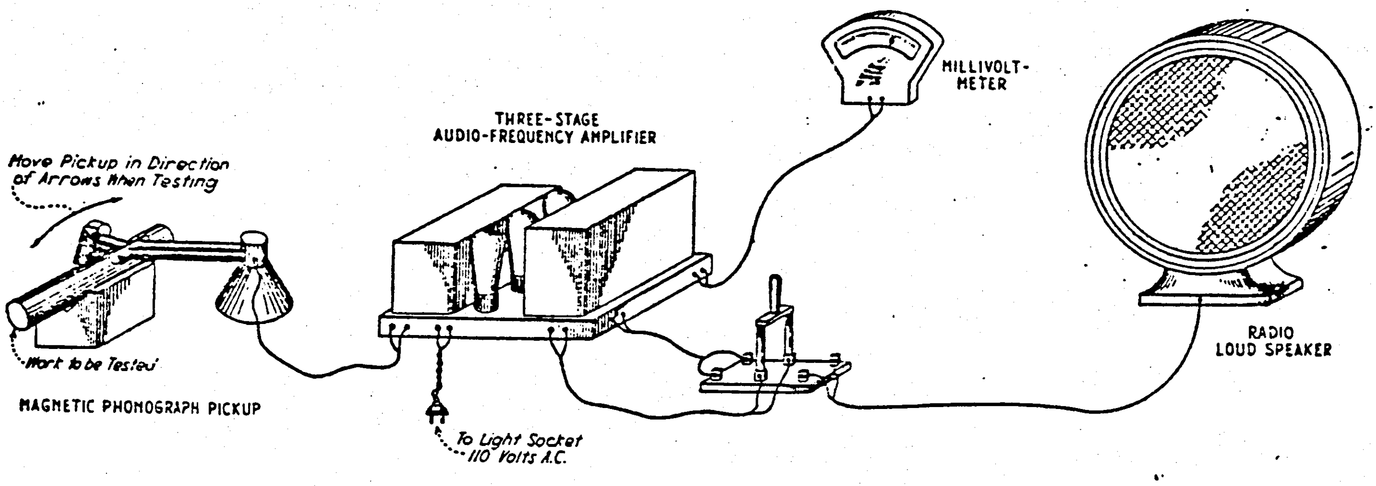
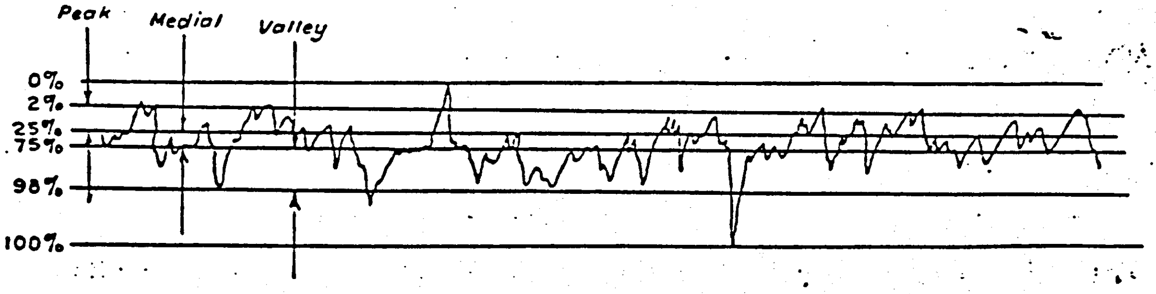


Fig. 4.6 Harrison's acoustic method of comparing surface finishes.



TYPICAL SURFACE PROFILE SHOWING HOW THE DEPTH VS. BEARING-AREA RELATION CAN BE DETERMINED BY THE FRACTION OF THE LENGTH OF A LINE WHICH LIES IN METAL AT VARIOUS POSITIONS

Fig. 4.7 Abbott and Firestone's definition of 'bearing area' of a surface profile.

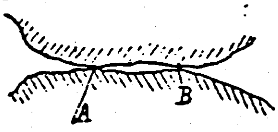


Fig. 4.8 Binder's representation of constriction contact resistance.

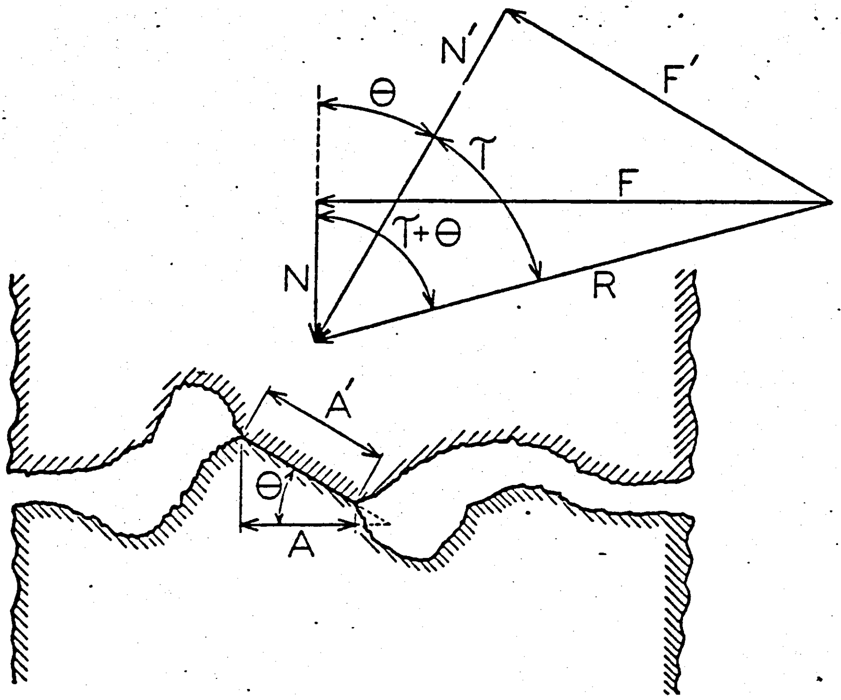


Fig.4.9 Ernst and Merchant's model of interlocking and adhesive friction.

CHAPTER 5

PLAIN BEARINGS

5.1 Plain bearings

A plain bearing is a device that permits relative movement between one surface and another and has always been a constituent part of most machines. A load is transmitted between the moving surfaces and the resulting friction opposes the movement. Plain bearings also serve to locate the relatively moving parts and the concomittant wear reduces the accuracy of location and implies a finite life of the bearing. Historically, the problems associated with plain bearings have been to achieve low friction, since this determines the power needed to drive the machine. Lubrication helps to reduce both the friction and wear. Wear determines the life of the bearing. This chapter shows how, in the between 1700 and 1900, the construction of plain bearings evolved from empirically-based forms to sophisticated types, based on scientific principles.

Renaissance developments in the applications of bearings to simple machines have been described by Parsons [Parsons 1968] and Dowson [Dowson 1979] and the investigations of friction during the eighteenth century have already been described in chapter 1. Yet during this time the construction of practical bearings was the province of the millwright and blacksmith. Timber was the most common material of construction with the increasing used of cast iron later in the century. For example in windmills, the windshaft and vertical shafts were of wood with the shaft being turned down to a smaller diameter to fit a thrust bearing. The neck bearings which supported the weight of the windshaft and sails were generally hollowed out of blocks of hardwood, usually reinforced with iron straps. In some instances blocks of stone, usually marble were used.

In other bearings, such as those for water wheels, iron stub axles or gudgeons were fitted to the wooden axle. The gudgeon was either spiked and driven into the end of the shaft or the shaft was mortised and a gudgeon with flat plate was used. The end of the wooden shaft was usually hooped with iron to prevent splitting [Weisbach 1848] (see Fig. 5.1). With cast iron shafts, gudgeons were an integral part of the shaft.

Where axles or shafts were horizontal, the gudgeons rested on bearing blocks Frequently the block was divided into an upper and a lower half which fitted around the axle. These were called pillow or plummer blocks. (The latter is a corruption of Plumier in reference to Charles Plumier [Plumier 1701]). A variety of materials were used for the bearing surfaces of these blocks. Wood stone and iron have already been mentioned. The most popular timbers were beech, boxwood, oak and in some cases green (unseasoned) thorn proved to be very durable [Buchanan 1841]. In heavily loaded bearings strips of cast iron were used for improved durability, due to the hardness of its chilled outer skin. By the end of the eighteenth century metal bearings were much more frequently used. Brass was widely used, and the term "brass" became synonymous with bearings during the nineteenth century. Eventually, an alloy of 8 parts of copper to 1 of tin was used (gun metal); it was harder and more durable [Buchanan 1841] than ordinary zinc/copper brass.

Whilst such bearings served the millwright and engineer during most of the eighteenth and nineteenth centuries, other forms of bearing were used, mainly where low friction was required. One of the earliest was the friction wheel or disc bearing. Although sketched by Leonardo and Agricola, this type of bearing was patented by Jacob Rowe in 1734 [Rowe 1734]. The principle was that a horizontal shaft rested at each end on two discs or wheels (see Fig. 5.2). This effectively increased the leverage of the axle over the point at which sliding friction occurred. Rowe described and illustrated the application of this idea to wheeled vehicles and how the principle could be extended to multiple friction wheels which would have very low friction. However, as Buchanan later wrote [Buchanan 1841].

> "Friction rollers are sometimes employed to diminish the quantity of friction, but not with much advantage in bearing machinery, because they are liable to get out of order, and require very accurate workmanship. The advantage of friction wheels is very slight".

The eighteenth century work on the friction of sliding surfaces has already been described; wear seems to have been of little concern. yet practical men such as Buchanan were well aware of the effects of wear and that provision should be made for it. The split bearing block usually had some provision for taking up wear. The bearing could be adjusted either by a wedge or by backing plate with screws.

There was a paucity of experimental work on journal bearings during the eighteenth and early nineteenth centuries. Musschenbroek's tribometre [Musschenbroek 1769] consisted of a small wooden roller with steel axles resisting in half bearings. Coulomb [Coulomb 1821] also reported some results on the friction of bearings, but in both cases the scale was small and the loads light. Both Musschenbroek and in particular Coulomb reflected the practice of their time in terms of the materials used: cast iron or steel on copper and brass, and green oak on lignum vitae or elm bearings. The ratio of friction force to load was recorded for each combination of materials either dry or lubricated with vegetable-based substances like tallow, lard and olive oil.

Some new information was contributed by the series of experiments carried out by Morin in 1834 [Morin 1834]. He set up his apparatus in a powder mill at Metz so that it could be driven by a water wheel. Unlike previous journal bearing tests the scale was similar to that used in machines and vehicles. The apparatus consisted of an axle rotating at up to 25 rev/min supported on two bearings of 20 centimetres diameter. The bearings could be loaded up to 1000 kg and the friction was measured with a spring dynamometer. Under these conditions, with cast iron axles resting on either cast iron, bronze or lignum vitae bearings, Morin measured the friction with the bearings coated with oil (unspecified), lard, tallow, asphalt or "cart grease". He found that the coefficient of friction was lowest at 0.05 when the lubricant was "continuously fed" to the bearings as opposed to an initial application only. As with other papers by Morin, the data is given with little or no interpretation.

In 1829 George Rennie [Rennie 1829] reported a series of experiments on the "friction and abrasion of the surfaces of solids" which included experiments with bearings. By applying a load to a cord wrapped around the axle, Rennie measured the friction at various velocities but found it to be independent of velocity. The friction of soft metals such as tin was greater than that of hard metals like steel and the tendency of soft metals to abrade under moderate loads was also noted. He also remarked:

"But when the bearings are properly proportioned to the weights of the parts of the machine, and their surfaces kept from contact by unguents, a much less allowance (for friction) may be made".

Towards the middle of the nineteenth century there was a growing realisation of the limitations of plain bearings, particularly in railway axle boxes, and also in mills and machines. In stating the problems encountered in railway axles, W.Bridges Adams in a paper to the Institution of Mechanical Engineers on the subject (1853) [Adams 1853] wrote of the difficulty of preventing axles and axle boxes from heating, and that the cause of heating was "imperfect lubrication". Another problem was the destructive wear which would be increased by increasing speed.

According to a treatise by Nicholas Wood [Wood 1838] published in 1838, the dimensions of early railway axle bearings were determined from the fixed shafting of factories. With the best grade of oil and the "most favourable circumstances" a bearing pressure of 90 lbf/in^2 gave the minimum friction. Also a viscid soap was substituted for oil "to make up for want of bearing surface". The situation by the 1850's was summed up by Adams as follows: "Road carriage wheels will run 5000 miles on one oiling .... railway axle boxes require greasing every 100 miles or less".

5.2 SPECIAL BEARING TYPES

5.2.1 The anti-friction curve

In 1848, Christian Schiele was granted a British patent (No. 12,338) for "certain improvements in the construction of cocks or valves which improvements are also applicable for rubbing surfaces in machinery in general". The essence of the patent was the application of a particular curved geometry to those rubbing surfaces in order, as the patent puts it "to reduce their friction and consequent wear and tear". An instrument for drawing the curve was illustrated in the sheet of drawings which accompany the patent (Fig. 5.4). A wooden block had a brass rod pivoted on it. A drawing pen slid along the rod and could be fixed at any desired radius. As the block moved along the ruler, the pen traced out the curve shown in Fig. 5.3. As mentioned in the patent, this curve has the property that the length of the tangent between the curve and its axis is always constant. Other drawings in the patent show its application of the curve to the sealing surfaces of a stopcock, regulator valve, a lathe centre pivot and even screw threads. From the wording of the patent it is evident that Schiele was primarily concerned with application of the curve to the sealing surfaces of valves and only secondarily to pivots and bearings.

The granting of the patent was duly reported in Newtons London Journal [Newton 1848] and in the Mechanics magazine [Mechanics Magazine 1848]. However, it was the Practical Mechanics journal (1849) [Practical Mechanics Journal 1848 a] which gave a full account of the invention, devoting a number of articles to descriptions of possible applications. In the first of these articles, it was noted that "Mr. Fairbairn of Manchester has afforded the inventor some important assistance, by permitting trials to be made upon his locomotive engines". Indeed, in a later edition of the Journal [Practical Mechanics Journal 1848 b], a sectional drawing of Fairbairn's tank locomotive, shown at the Great Exhibition in 1851, shows that the steam regulator valve took the form of the "anti-friction" curve. Two subsequent articles in the same Journal [Practical Mechanics Journal 1849 a] described "mechanical applications of the anti-friction curve". Two sheets of drawings show how it could be applied not only to cocks and valves, but also to pivot and spindle bearings and to screw threads (Fig. 5.5). A complete article was devoted to a flour mill where grinding stones were profiled to the curve [Practical Mechanics Journal 1849 b]. "These figures" wrote the Journal, "afford very conclusive evidence of the exceeding slight and uniform wear of the revolving surfaces formed in accordance with the new curve".

Schiele also exhibited some applications of his "anti-friction" curve at the Great Exhibition where the idea "met with the unqualified approval of Colonel Morin, the eminent French philosopher" [Practical Mechanics Journal 1851]. Morin, who was Director of the Conservatoire Nationale des Arts et Metiers, selected a number of examples from Schiele's collection at the Exhibition for purchase by the Conservatoire. A photograph of a two of these examples is shown in Fig. 5.6. These are now part of the collection in the Musee des Techniques, Paris.

5.2.2 The anti-friction curve analysed.

In investigating the development of Schiele's parent, the question which arises is how did he arrive at this particular curved shape. The Practical Mechanic's Journal wrote that Schiele, being aware of the tendency of conical plug valves to wear unevenly and "to stick in its socket like a wedge", considered the truncated cone of the stopcock plug to be divided into a series of infinitely short lengths. He ".. proposed to take a more obtuse cone for each longer portion, and in such progression that it would require equal pressure for every portion of the surface to cause uniform sinking of the plug in the course of wear". In fact, it was reported that Schiele had tested different shapes of pivot made out of cast iron (Fig. 5.7). As the Journal reported "In some instances, the old forms evidenced a less amount of friction than the new one, but this was for a limited period only at the commencement, as very quickly the destructive wear, increasing towards the centre, cause so much friction that the parts adhered firmly together". Schiele's simple demonstration was to revolve a piece of chalk with a conical end in a fitted conical recess in a similar chalk block. (Fig. 5.7). After a period of continued rubbing, the surfaces took on the form of the anti-friction curve. Apparently, the curve was originally called the friction curve by Schiele but, as the Journal reported "in its practical application for the diminution of friction and wear in machinery, the term anti-friction curve, as given by us, is certainly more proper".

Later, it was pointed out that, whilst the name "anti-friction curve" had been used, "mathematically speaking we should term it the Hugenian or equi-tangential tractory". The properties of this curve were described by Christian Huygens in a letter of 1693 [Huygens 1750]. According to Bell's biography of Huygens [Bell 1962] the problem was set by Perrault, "to determine the path in a fixed plane of a heavy particle attached to one end of a taut string whose other end moves along a straight line in that plane". Both Huygens and Leibnitz studied the problem in 1693 and worked out the geometry of the tractrix curve.

By the early 1860's it had been demonstrated mathematically that the term "anti-friction" was a misnomer. Weisbach's analysis of the pivot [Weisbach 1865] (entitled "the so-called anti-friction pivot") showed that, in fact, this type of pivot had a higher frictional torque that flat pivots of equal external diameter in the ratio of 1 to 2/3rds. Furthermore, Weisbach noted that, with flat pivots the friction decreased still further with time "for the exterior portions are more worn than the interior ones, and thus the surface of friction is less".

In "A manual of Machinery and Millwork" 1869, Rankine [Rankine 1869] also mentioned Schiele's "anti-friction" pivot "whose longitudinal section is a curve called the tractrix". Its moment of friction is the coefficient times the load times the external radius. Whilst noting that this was higher than for a flat pivot of equal radius, Rankine pointed out its advantage of uniform wear.

Within a few years of the issue of Schiele's patent, its initial enthusiastic reception was tempered by subsequent analysis which demonstrated the disadvantage of a high friction moment. There must also have been the practical problem of translating such a curve into a manufactured product. No guidance on how this was to be achieved was published either by Schiele or anyone else. That it was in fact achieved is borne out by the surviving examples. From the 1860's onwards the anti-friction curve became merely a text book example.

In the United States, R.H.Thurston [Thurston 1903] referred to, and analysed the properties of "the tractory or Tractorix pivot of which the generatrix is Huygens' curve the tractrix... which was proposed for pivots by C.Schiele, by whose name it is often known."

The American "Machinery's Encyclopaedia" (1917) [Machinery 1917] wrote that "experiments carried out by Schiele show that the wear is theoretically along a curve called the tractrix. If an end thrust bearing is made of a form corresponding to the Schiele curve, then wear in the direction of the axis ... will be uniform at all points ... it has been shown in practice that nothing is to be gained by the used of bearings having this complicated shape". An interesting point is that editions of Machinery's Handbook up to 1966 have all included essentially the same paragraph.

In 1923 Shaw [Shaw 1923] described the properties of the "Schiele Bearing" and its possible application to machine tool spindles. Another "text book" reference is Green's "Theory of Machines", although without reference to Schiele. Recently, Pascovici [Pascovici 1976] has shown that the segment joint of the pincers in crabs have evolved on the principle of "uniform descent", that is the joint surfaces have a tractrix shape.

5.2.3 Marine bearings

Particular problems arose in marine bearings in connection with the transmission of the propulsion force from the screw to the ships hull. The change from paddle wheel to screw propulsion in ships meant that, not only did the speed of rotation of drive shafts increase (see Table 5.1) [Seaton 1883], but also the bearing type changed. With paddle wheel vessels the drive shaft lay across the vessel and conventional journal bearings were used. However, with screw propellers, having the drive shaft parallel to the axis of the vessel, meant that thrust bearings were needed to transmit the thrust to the ship. also the shaft needed to be effectively sealed. These were problems that hindered the adoption of the screw [Storr 1982] and it took some time before effective solutions were found. To quote an article in "Engineering in 1866 [Engineering 1866] :

> "as soon as large propellors came to be regularly worked ... the bearings of the screw shaft were rapidly worn away".

This necessitated regular replacement of the stern tube bearing, and the out-of-balance forces caused intolerable thumping. Occasionally stern tubes split, resulting in leaks. In some cases where brass bearings were used the wear was very rapid. This problem was ultimately solved by the use of lignum vitae strips in the stern tube bearing.

John Penn, the Thames shipbuilder, read a paper to the Institution of Mechanical Engineers in 1856 [Penn 1856] entitled "On wood bearings for screw propeller shafts". Penn noted that where brass propeller shaft bearings had been used on steam ships "the wear was so great that repairs had frequently to be made at great expense after a run of 2000 or 3000 miles". In a series of experiments he found that wear resistant bearings could be made by inserting staves of wood axially in the bearing. As in all propeller shaft bearings, the bearing was flooded with sea water since the sealing gland was inboard of the bearing. Under these conditions, lignum vitae showed very little wear at bearing pressures as up to 4000 pounds per square inch in salt or fresh water. Hornbeam, boxwood, elm and pine all gave good results, although at 2500 pounds per square inch. Penn took out a patent for wooden stern tube bearings in the same year. The validity of the patent was questioned but following a court case, was upheld [Engineering 1866]. So successful was Penn's solution that the numbers of Naval craft equipped with screw propellers more than doubled between 1854 and 1866 [Engineering 1866]. The use of lignum vitae in these bearings remained common practice until after the Second World War, when asbestos/polymer composites began to replace them.

For transmitting the thrust of propellers collar bearings were used up to the early part of this century. A typical bearing was described by Gaudry in 1857 [Gaudry 1857], which comprised three or four collars on the propeller shaft which fitted into a simple split bearing block. The bearing surfaces of the block were "of bronze or similar alloy", and as for lubrication:

> "It goes without saying that these ... must be constantly lubricated with oil, grease or even water. The nature of the anti-friction metals used today even allow the use of sea water".

Various empirical rules were devised for the design of these bearings. Examples of such rules are given by Seaton [Seaton 1883] where the bearing pressure in pounds per square inch, that is the thrust load divided by the combined area of the discs, should not exceed

$$\frac{2{,}700}{Rd + 100}$$

where R is the shaft speed in revs/min, d is the shaft diameter in inches. The diameter of the collars was given by

$$P = 47n(D^2 - d^2)$$

where n is the number of collars, d is the shaft diameter and D the outer diameter of the collars.

For naval purposes

$$n = 1 + \frac{d-5}{1.25}$$

and for mercantile engines

$$n = 1 + \frac{d-5}{1.8}$$

Seaton also recommended that the thrust faces of the collars were lined with white metal, with a carefully turned steel shaft and that the bearings must be well lubricated. As a rule of thumb, the power lost in this type of bearing was about 1.5% of the indicated horse power (i.h.p.) of the engine. Storr [Storr 1982] indicates that the i.h.p. for compound marine engines of the period ranged from 450 to 800. The loss due to friction in the thrust block would thus be 6.7 to 12 horse power, all of which would be dissipated as heat. The requirement for good lubrication (i.e. an adequate supply of oil) would be as much to remove the heat as to lubricate the bearing surfaces.

Under the auspices of the Institution of Mechanical Engineers Committee on Friction, Tower [Tower 1888] had carried out a series of tests on lubricated thrust bearings in 1888. The results were presented in the third report to this committee. The previous two reports by Tower [Tower 1883,1885] had elucidated the complete separation of journal bearing surfaces by a film of oil, and had shown the substantial pressure generated in the film. No such results were observed with thrust bearings and it was reported that "complete lubrication" was not achieved. The reason was that flat thrust faces cannot take on the required wedge shape in which hydrodynamic pressures are generated.

The solution to the hydrodynamic lubrication of thrust bearings was to use pivoted thrust faces which could take up the required geometry and this idea was conceived almost simultaneously by Michell and Kingsbury. The story of this development has been told in detail by Dowson [Dowson 1979]. Tilting pad thrust bearings were used in ships from about 1913 and were used by the British Navy from 1914 onwards, and a little later by the U.S. Navy.

The principle feature of these bearings was that titling pads adjusted themselves to give optimum hydrodynamic lubrication between the surfaces virtually at all times and resulted in a decrease in the friction coefficient by a factor of ten compared with well lubricated plain thrust bearings.

5.3 Bearing loads and speeds

Figures 5.8 and 5.9 show the range of loads imposed on, and speeds of rotation of, plain bearings for the years from 1700 to 1900. the data has been compiled from those who reported current practice, such has Buchanan and Fairbairn [Buchanan 1841, Fairbairn 1861], as well as from the principal experimentalists such as Tower, Petrov [Petrov 1900] and Thurston [Thurston 1879]. The indication is that bearing loads and speeds increase rapidly after about 1850 and also that a broad range of loads and speeds was covered in bearing test machines.

TABLE 5.1

Comparative shaft speed data for paddle and screw driven vessels [Seaton 1883]

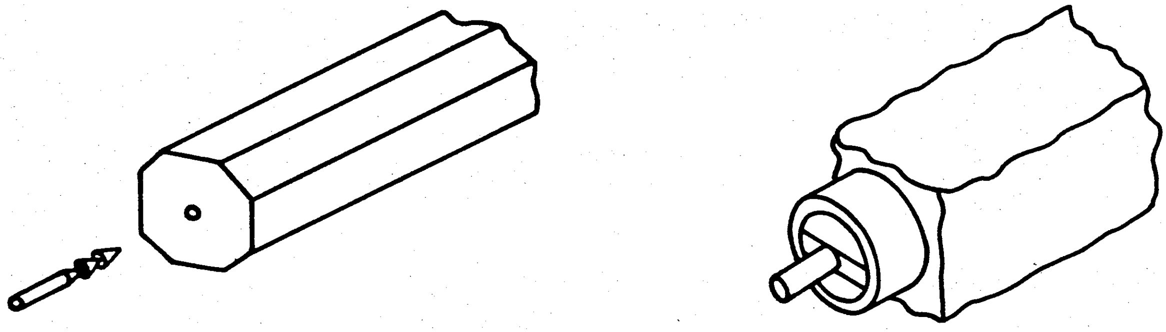
PADDLE WHEELS

Paddle diameter ft	Shaft speed rev/min.
13.5	42
27	28
21	32.7
15	38
8.75	63
15	35.8

SCREW PROPELLERS

Screw diameter ft	Shaft speed rev/min.
18.1	58.6 (11.3 knots)
18.5	91 (16.5 knots)
19.2	72.6 (15.2 knots)

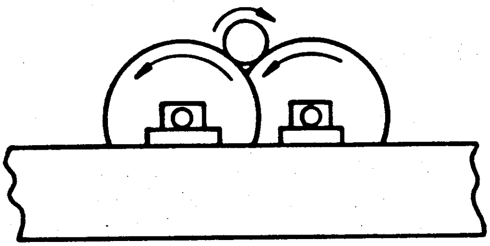
Each of the above figures refers to a different vessel.



Spiked Gudgeon

Morticed Gudgeon

FIG. 5·1



Friction Wheel (disc bearing)

FIG. 5·2

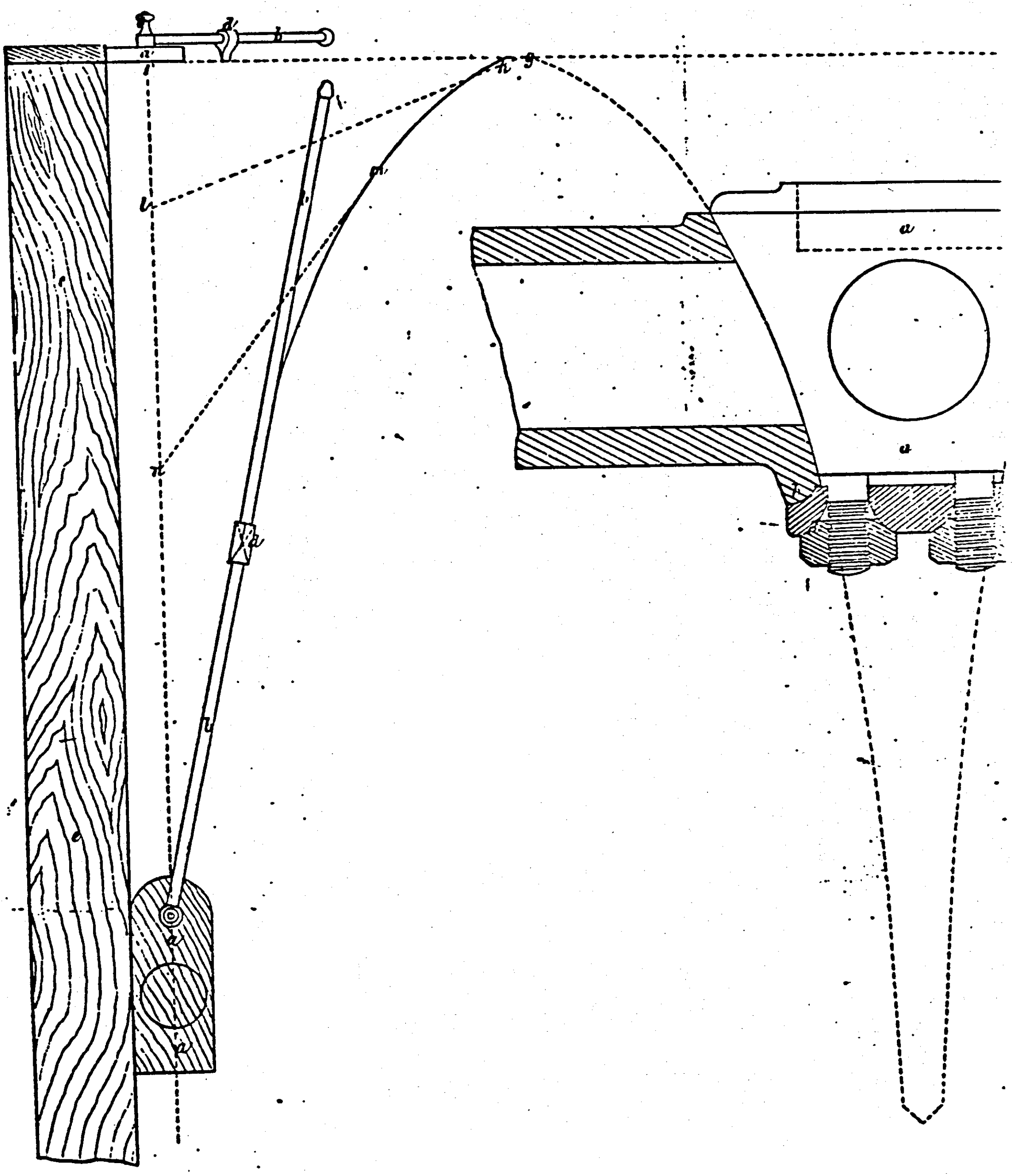


Fig 5.3

Fig 5.4

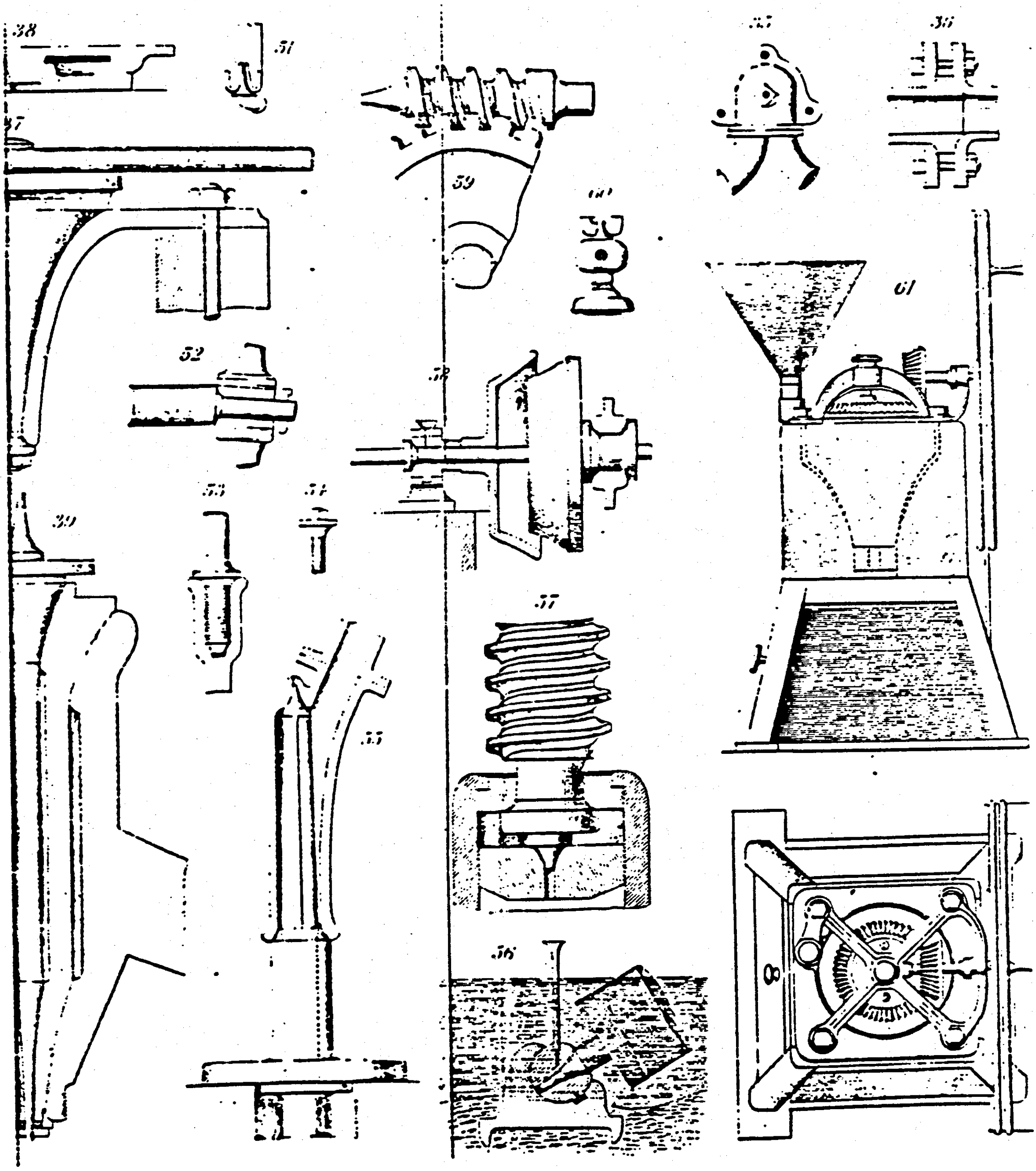


Fig 5.5 Examples of the application of the "anti-friction curve

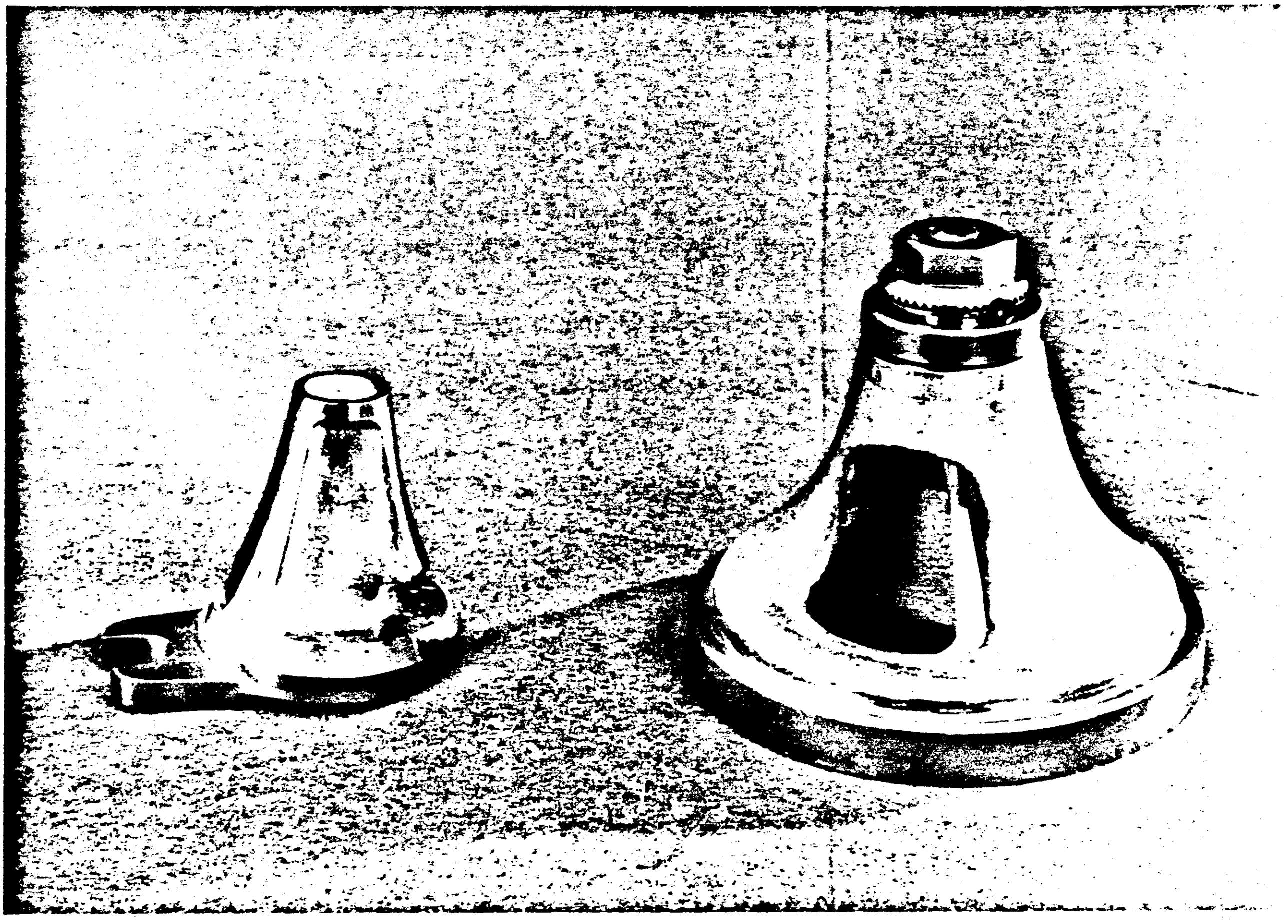
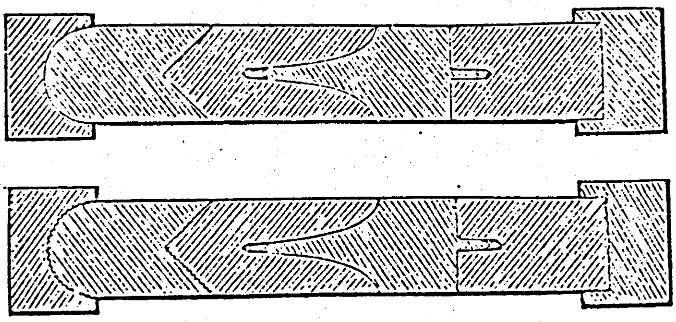
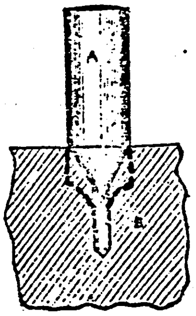


Fig. 5.6 Two valves with "anti-friction" curve surfaces made by Schiele.

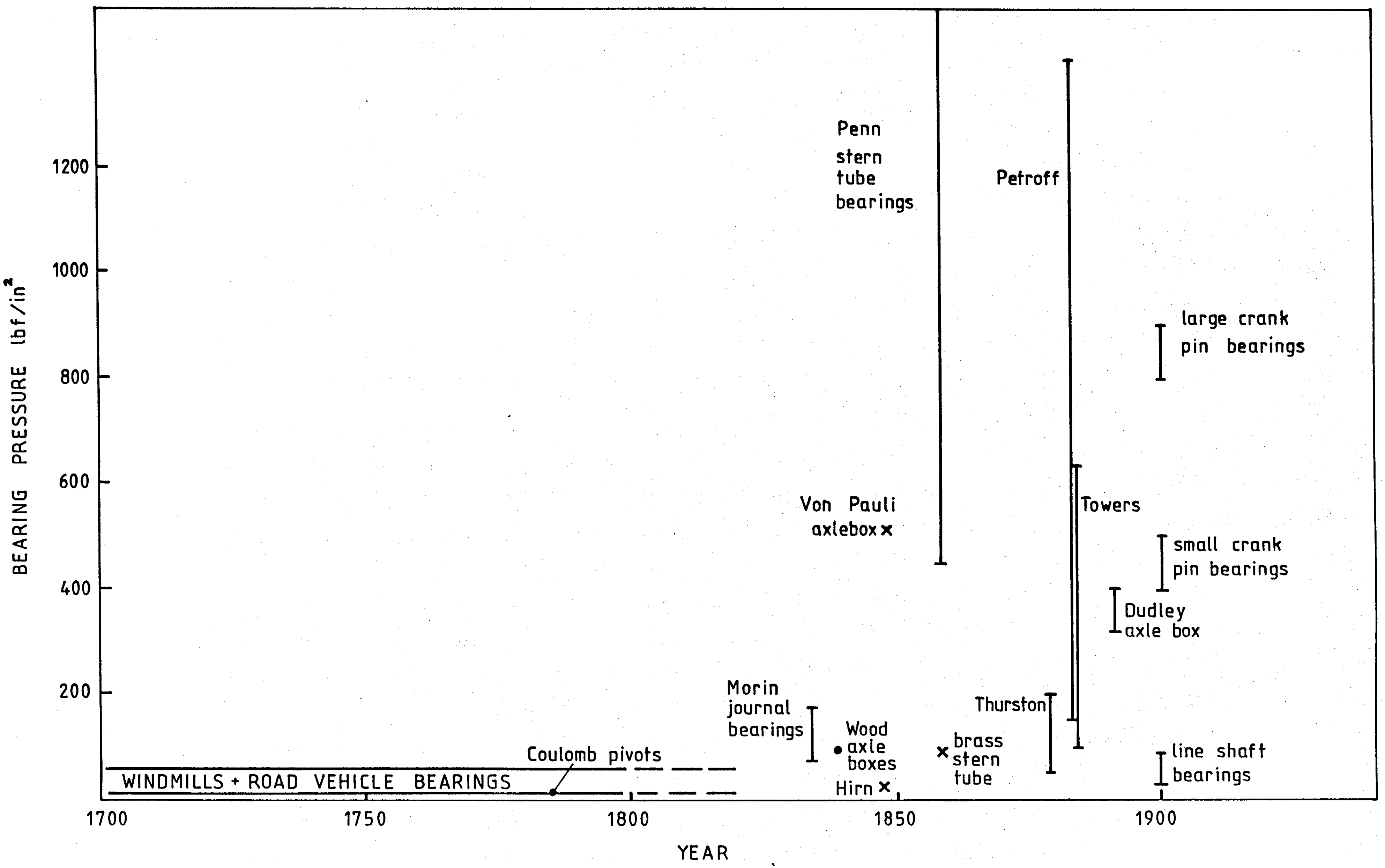


Cast iron bearings of different profiles.



Schiele's chalk experimemt.

Fig. 5.7



BEARING PRESSURE lbf/in²
1200
1000
800
600
400
200
1700
1750
1800
1850
1900
YEAR
Penn stern tube bearings
Petroff
large crank pin bearings
Von Pauli axlebox ×
Towers
small crank pin bearings
Dudley axle box
Morin journal bearings
Wood axle boxes
Thurston
brass stern tube
line shaft bearings
Coulomb pivots
WINDMILLS + ROAD VEHICLE BEARINGS
Hirn ×

FIG. 5.8

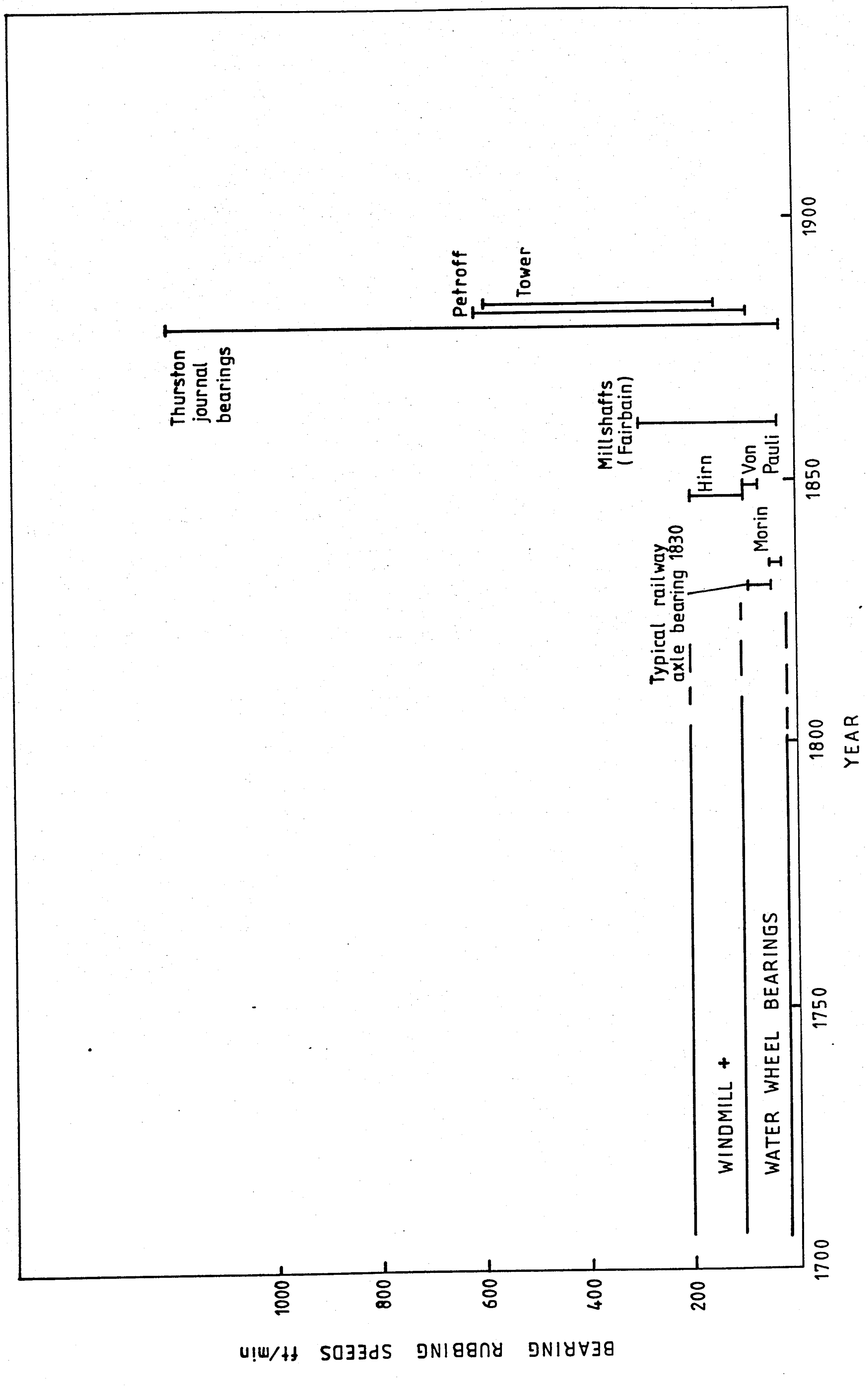

Thurston journal bearings
Petroff
Tower
Millshafts (Fairbain)
Hirn
Von Pauli
Morin
Typical railway axle bearing 1830
WINDMILL +
WATER WHEEL BEARINGS
1000
800
600
400
200
BEARING RUBBING SPEEDS ft/min
1700
1750
1800
1850
1900
YEAR

FIG. 5.9

CHAPTER 6

LUBRICATION AND WEAR PREVENTION

6.1 Fluid lubrication

The single most effective method of wear prevention, both in sliding and rolling contacts, is to ensure adequate lubrication of the surfaces with a suitable fluid. Correct fluid lubrication, of course, reduces the friction between surfaces and also the wear. In the limit, wear can be eliminated if the surfaces are completely separated by a fluid film. In reality, however, surfaces come into contact when machines are started or stopped and there is a transition through "semi-fluid" or "boundary" lubrication when fluid thicknesses are similar to the combined roughness of the two surfaces.

That journal bearing surfaces could be fully separated by a self-generated fluid film was discovered during the latter part of the last century. The history of this discovery and the subsequent mathematical analysis of the hydrodynamics has been traced in detail by Dowson [Dowson 1979]. The experiments of Beauchamp Tower [Tower 1883], undertaken for the Institution of Mechanical Engineers, received considerable attention after their publication, but an equally interesting series of tests, carried out by Hirn in France, pre-dated those of Tower by almost 40 years. It is therefore appropriate to record in some detail the results obtained by Hirn, and the events surrounding their accomplishment.

Gustav Adolphe Hirn was born at Logelbach near Colmar in Alsace on the 21st August 1815. His maternal grandfather and his father were partners in a cotton mill and textile printing business there. Owing to delicate health, Hirn did not attend school. However, he studied chemistry and was permitted to work in the chemical laboratory, and took charge of the mechanical department of the business. He was a practical man as well as a theoretician and he had in his charge several different types of machine with the time to study them [Colmar 1890]. He began a series of experiments with different lubricants in 1846 with the purpose of determining the best and cheapest lubricants for his machines. Friction was to be studied in relation to the nature of the two bodies in sliding contact, with their "extent of contact" and with pressure and speed.

Hirn distinguished between two types of friction which he termed "mediat" and "immediat". Mediate (or mediate) friction applied to cases where a lubricating material was interposed between the surfaces which "not only prevents too rapid wear, but also diminishes the necessary displacement effort". In immediat (or dry) friction no lubricant was present, as for example in brakes. Hirn's experiments were only concerned with mediate friction, because this applied to the majority of sliding contacts in machines. Hirn was also aware of the economic aspects where, for example, "the force absorbed by a cotton spinner can vary between 100 and 65 according to the more or less judicious combination of rubbing pieces. The possible reduction of 35% of the moving force is an economy of the first order".

In order to test lubricants, Hirn constructed a simple piece of apparatus based on the principle of the beam balance (Fig. 6.1). A rotating drum 9 inches in diameter supported a half bearing of eight parts copper and one part tin. This was at the fulcrum of a beam at the ends of which weights were added. As the drum rotated, the imbalance due to friction was corrected by adding further weights to one end. The bottom of the drum dipped into a bath of the lubricant being tested. The drum was also hollow and was cooled by water flowing through it. The temperature of the bearing was measured by a thermometer. Hirn's apparatus was in essence a simple friction balance – a concept widely used by later researchers. The weight of the bearing and lever arm amounted to 50 kg and the drum was rotated, by belts and pulleys, at speeds up to 100 rev/min. This arrangement was thus fortuitous in that it combined a low bearing pressure with a reasonable speed – conditions which were bound to give full film lubrication with almost any fluid.

The requirements of the lubricants were summarised as follows:

1. They must be capable of wetting the surfaces.
2. They must not evaporate or alter too quickly.
3. The temperature at which they were used must give the highest possible fluidity.
4. But at this fluidity they must have a certain viscosity.

Hirn tried a number of vegetable and animal oils including olive oil, calves foot, three types of refined spermacetti oils and tallow, as well as a mineral oil which it was reported [Colmar 1890] was derived from a nearby lake.

Hirn summarised his principal findings as follows:

1. When surfaces are abundantly lubricated with good quality lubricant, sufficiently viscous, the pressure is not too great to expel the oil, and the temperature is constant:

> "The loads equilibrating friction are very nearly proportional to the speeds". (i.e. The friction coefficient is proportional to the speed).

2. With little lubricant or when working a long time with the same ration of lubricant:

> "Loads equilibrating friction are proportional to speeds to a certain power, less than unity and approaching the square root of these speeds".

Hirn was certainly aware that it was the viscosity rather than the density of the lubricant that played the vital role in determining the friction of a bearing at a particular speed. This may well have arisen from the work of Charles Dolfus whose interest in the viscosity of lubricants had resulted in a paper to the Societe Industrielle on this subject in 1831 [Dolfus 1831]. It is also evident from a footnote in Hirn's paper that Charles Dolfus had also taken an active interest in Hirn's researches.

For good lubrication, Hirn stated that the lubricant must have sufficient fluidity and a certain viscosity which would compel it to "remain between the two surfaces". In other words for good lubrication, the moving surfaces were separated by a film of lubricant. This was forcefully demonstrated when, at sufficiently high speed, water, or even air, would serve as a lubricant and the load to equilibrate friction decreased from 3 or 4 kg to 10 grams in the case of air. But "when the speed decreased to a certain extent these two non-viscous fluids were expelled by the pressure, the two surfaces came into contact and the friction at once became enormous".

Thus Hirn established, on an experimental basis, the fundamentals of fluid lubrication and his work provided the impetus for those who followed.

Whilst the original motive for the work was to find the best lubricant for machinery, Hirn also dealt extensively with the balance between the work expended in overcoming friction and the conversion of this work into heat. For each of the tests, Hirn measured the rate of flow, and temperature rise, of the cooling water in the drum, the temperature rise of the oil and the bearing, and the work expended. The ratio between the number of kilogram calories of heat produced and the work done, he found to be reasonably constant at 0.0027 whatever the speed, temperature or lubricant. In other words, every 370 kilogram metres of expended work gave rise to 1 kilogram calorie of heat*. an appendix to the memoir, which was probably written after the original work on lubrication was completed, dealt with the relationship between work and heat. Hirn wrote: "At the time when I was carrying out this series of experiments on the production of heat by friction, I was completely ignorant of that which had been done on the same subject ... by Mayer of Heilbronn and by Joule in England and Regnault in France. I had completed my memoir and has already given it to M.dolfus when an article by M.Foucault (Journal des Debats 8th June) appraised me that that which concerned the law of heat in my test had been forestalled by other physicists and thus put me at the risk of an unmerited assertion of plagiarism".

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* 370 kilogram metres is equivalent to 3629.7 Newton metres. 1 kilogram calorie is equivalent to 1000 calories or 4200 Joules. Thus, on this basis, 1 Newton metre was equivalent to 1.157 Joules, an error of 15.7%.

Based on the results of this work, Hirn submitted a memoir to the French Academy of Sciences in 1849, but withdrew it later the same year [Dowson 1979]. It has also been stated that he submitted a paper to the Royal Society, which rejected it. It was not until 1854 that Hirn was invited by Emille Dolfus, President of the Societe Industrielle de Mulhouse to present a paper to this Society. This he duly did at the session of the 26th June 1854 [Hirn 1854]. (He had already read two papers to this Society).

The apparent rejection of Hirn's paper by the Academy of Sciences has been the subject of some speculation. One possibility is that, like Dupuit before him, Hirn experienced opposition to ideas which ran counter to those of Coulomb and Morin, even when the conclusions were supported by results from carefully conducted experiments.

During the remainder of the century many experiments to measure the friction of lubricated bearings were carried out, in many cases to provide practical data. Robert Henry Thurston, who later became Professor of Engineering at Cornell University, devised and built his own lubricant tester in which the bearing under tests acted as the fulcrum of a pendulum [Thurston 1879]. The friction torque in the bearing, which caused an offset from the vertical in the pendulum could be read off on a suitably calibrated scale. This machine, a second version of which was constructed for testing railroad bearings at realistic loads and speeds, was essentially a variant of Hirn's friction balance. Thurston was aware of Hirn's work and the value of his contribution since he not only quoted Hirn's results but also dedicated his book "Friction and Lost Work in Machinery and

Millwork" (1887) [Thurston 1887] to Hirn.

Like Hirn, Thurston found that the torque of a lubricated bearing increased with speed but that at very low speeds the torque passed through a minimum and then increased rapidly as the speed tended to zero. The large amount of data on lubrication collected by Thurston, and the practical information published by him served practical engineers well for many years.

The work of Nicolai Petrov [Cameron 1966] in Russia applied the theoretical work on viscous flow of Poiseuille [Poiseuille 1846] to a straight cylindrical bearing and showed how the torque of such a bearing was related to viscosity. In the same year, 1883, Beauchamp Tower reported his well known experiments on lubricated bearings. Tower's main contribution was to show that considerable pressure was generated in the oil film that separated the shaft and the bearing. He showed how this pressure was distributed over a partial bearing and that the maximum pressure was more than twice the average pressure due to the load.

Tower's results attracted the attention of both Professor George Gabriel Stokes of Cambridge University [Stokes 1884], and also of Professor Osborne Reynolds, Professor of Mechanical Engineering at Manchester University. Both sought to apply the equations of motion of a viscous fluid in bearing lubrication. Both recognised that, in a cylindrical bearing, the shaft took up an offset position with respect to the bearing thus creating a tapered wedge between the relatively moving surfaces. It appears that Stokes did not pursue the theoretical analysis. reynolds did, and the outcome was his celebrated paper entitled "On the theory of lubrication and its application to Mr

Beauchamp Tower's experiments" which was published in the Philosophical Transactions of the Royal Society for 1886 [Reynolds 1886]. In this long paper, Reynolds derived the differential equation relating the thickness of the film separating the surfaces with speed and viscosity of the fluid. It was this paper, perhaps more than any other, which established the mathematical basis of fluid lubrication.

Full separation of bearing surfaces is only maintained with an appropriate combination of lubricant viscosity, relative speed and bearing pressure. Stribeck [Stribeck 1902] and Hersey [Hersey 1914] both demonstrated how friction coefficient could be plotted against the dimensionless parameter, ZN/P, where Z is the viscosity of the lubricant, N the rotational speed and P is the bearing pressure. A typical curve is shown in Fig. 6.2 in which friction decreases to a minimum and then increases. Generally speaking, fluid film lubrication exists to the right of the minimum friction point. Data from a number of papers, mostly published in the last century, has been analysed in terms of ZN/P and the results are shown in Table 6.2. Also included is a range of data for a railway axle bearing operating at various speeds. Hirn's experiments ran at by far the highest ZN/P values and he, fortuitously, achieved conditions which favoured full fluid film lubrication, as also did those of Tower. Railway bearings operated with much lower ZN/P values, and often in the regime now known as "mixed" lubrication where some metallic contact occurs with resulting wear. Given that many researchers simulated practical operating conditions in their experiments, many bearings must have run with incomplete separation of their surfaces.

6.2 Oil film thickness

A simple method of measuring the thickness of the oil film between a journal bearing and shaft was used by Goodman [Goodman 1886]. This consisted simply of a micrometer rigidly connected to the bearing, which completed an electrical circuit when it touched the shaft. The micrometer was read with the shaft stationary, and when at full speed and the difference in the readings was a measure of the oil film thickness.

The electrical resistance of the bearings of a dynamo was also measured by Kennely and Adams [Kennely 1903]. The resistance was practically zero when the machine was at rest, whereas at speeds above about 100 rev/min the resistance of the two bearings in parallel rose to 4.4 megohms, each bearing being 5 inches diameter by 1.125 inches long. A little later, A.V. de Forest [de Forest 1916] measured the electrical resistance between a rotating 2 inch brass disk and a cast iron plate. The resistance increased when a high viscosity oil was used and decreased with applied load, but the oil film formed was sensitive to vibrations. Essentially, measuring the electrical resistance of an oil-lubricated bearing indicated whether or not the surface were separated by a fluid film. It was not a practical means of determining the fluid film thickness. However, Vieweg in Germany (1927) described a method in which the electrical capacitance of a bearing was measured [Vieweg 1927], using the oil as the dielectric. In this case the capacitance is proportional to the film thickness so that, with suitable calibration, a thickness measurement is obtained.

6.3 Lubrication methods.

Both Hirn and Tower ensured a constant supply of lubricant in their experiments by simply letting the rotating shaft dip into an oil bath. This however can only be used when the axis of the shaft is horizontal and a partial bearing is used as was the case in railway axle boxes. In many other journal bearings the complete bearing encircles the shaft and lubricant was fed to the surfaces through an oil hole (Fig. 6.3). Where there was an oil bath below the bearing, various methods were used to convey oil upwards to the bearing. These included loose rings, cotton pads acting as wicks, or even, as patented by Schiele, a gear which was rotated by a thread cut in the shaft.

Aside from journal bearing lubrication, various methods were devised to provide an effective and controlled supply of lubricant for the cylinder and sliding components of steam engines. Devices were evolved which used either the steam pressure or the partial vacuum resulting from steam condensation, to provide a controlled flow of lubricant. One of the earliest of these devices was patented by James Roscoe [Roscoe 1862] and is shown in Fig. 6.4. The principle was that steam was taken from the delivery pipe to compress the air above the oil in a reservoir and so provide a flow of oil through a regulator valve. One feature was that the oil flow stopped when the steam pressure was cut off. Lubricators had to be fixed to the moving parts of machines such as connecting rods and big ends. In these cases the oil supply was controlled by ball valves which were thrown off their seats by the oscillation, allowing the lubricant to escape but seating themselves again when the machine stopped. Two examples of this type are shown in Fig. 6.5.

TABLE 6.1

SOME SELECTED RESULTS FROM HIRN'S EXPERIMENTS

Experiment Number	Lubricant	Rev/min	Time (mins)	Friction load kg	Bearing Temp degC	Total Work kg. m.	Calories	$\frac{\text{Calories}}{\text{Work done}}$
1	Olive oil	45	31	6.1	18.1	29931	80.8	0.0027
10	" "	93.3	60	2.15	31.2	42336	114.3	0.0027
12	Spermacetti	48.4	60	1.57	16	16056	43.3	0.00276
20	"	98.3	25	1.77	25	15307	41.3	0.00262
23	Whale oil	89.6	35	5.1	46.1	56284	152	0.00267
26	"Fat"	91.3	30	3.73	35.4	35950	97.1	0.00278

TABLE 6.2 ZN/P VALUES

Source	Viscosity,Z centipoise	Speed,N rev/min	Pressure,P lf/in^2	ZN/P
Morin	43	11–25	65–150	3.15–16.5
Hirn	43	45–90	3	645–1290
Tower	43–54	100–450	100–625	6.88–193.5
Clamer	40	525	1000	21
Railway	20–60	168(15mph)	200–400	8.4–50.4
axle	20–60	280(25mph)	200–400	14–84
box	20–60	448(40mph)	200–400	22.4–134.4

Notes: 1. Viscosity of 43 centistokes for olive oil.

2. Viscosiy of 54 centistokes for rapeseed oil.

3. R.Gunther, "Lubrication", Bailey Bros 1972 indicates minimum friction coefficient at ZN/P values of about 40 in the above units.(see Fig. 6.2).

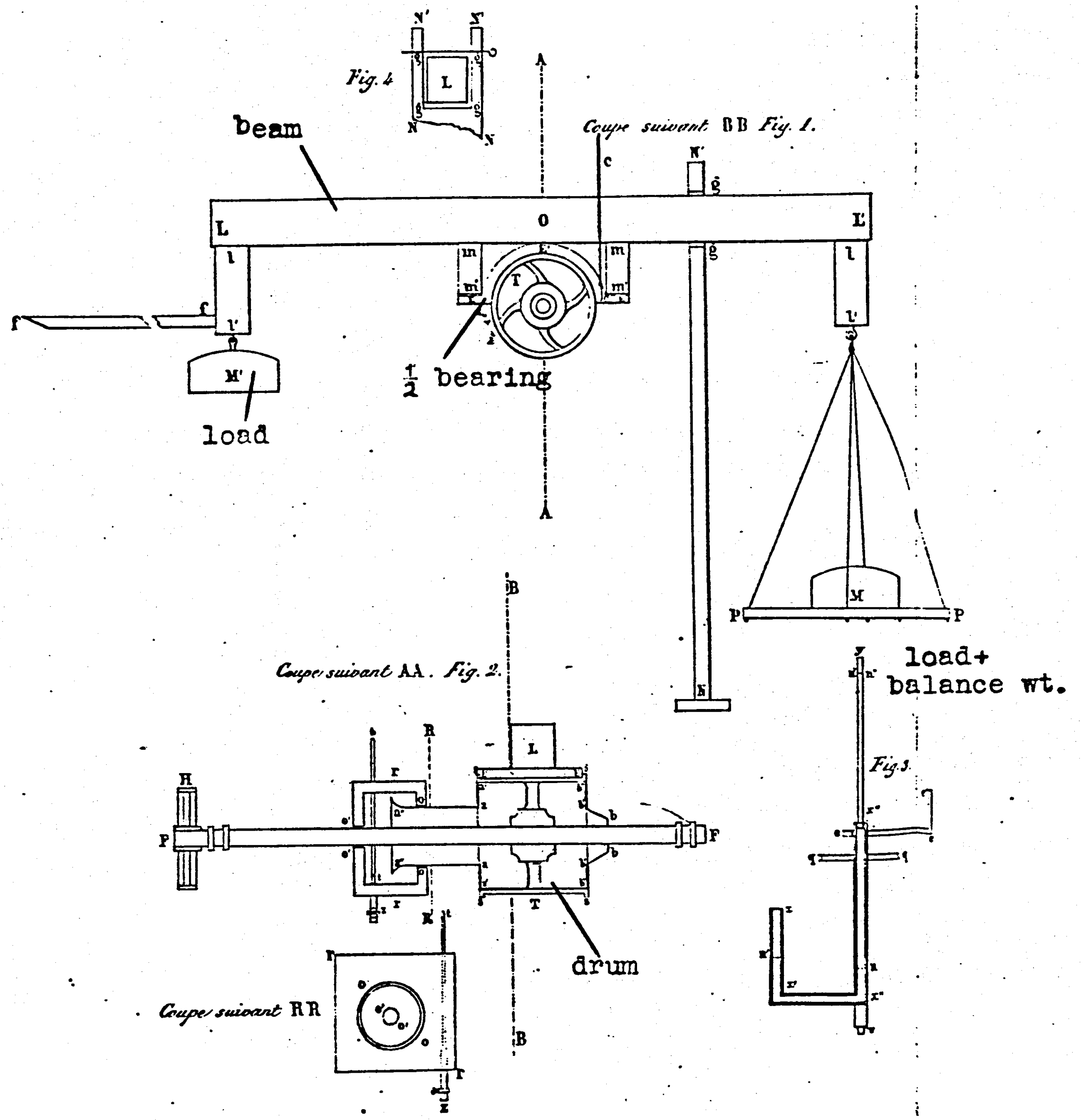


Fig. 6.1 Hirn's friction balance

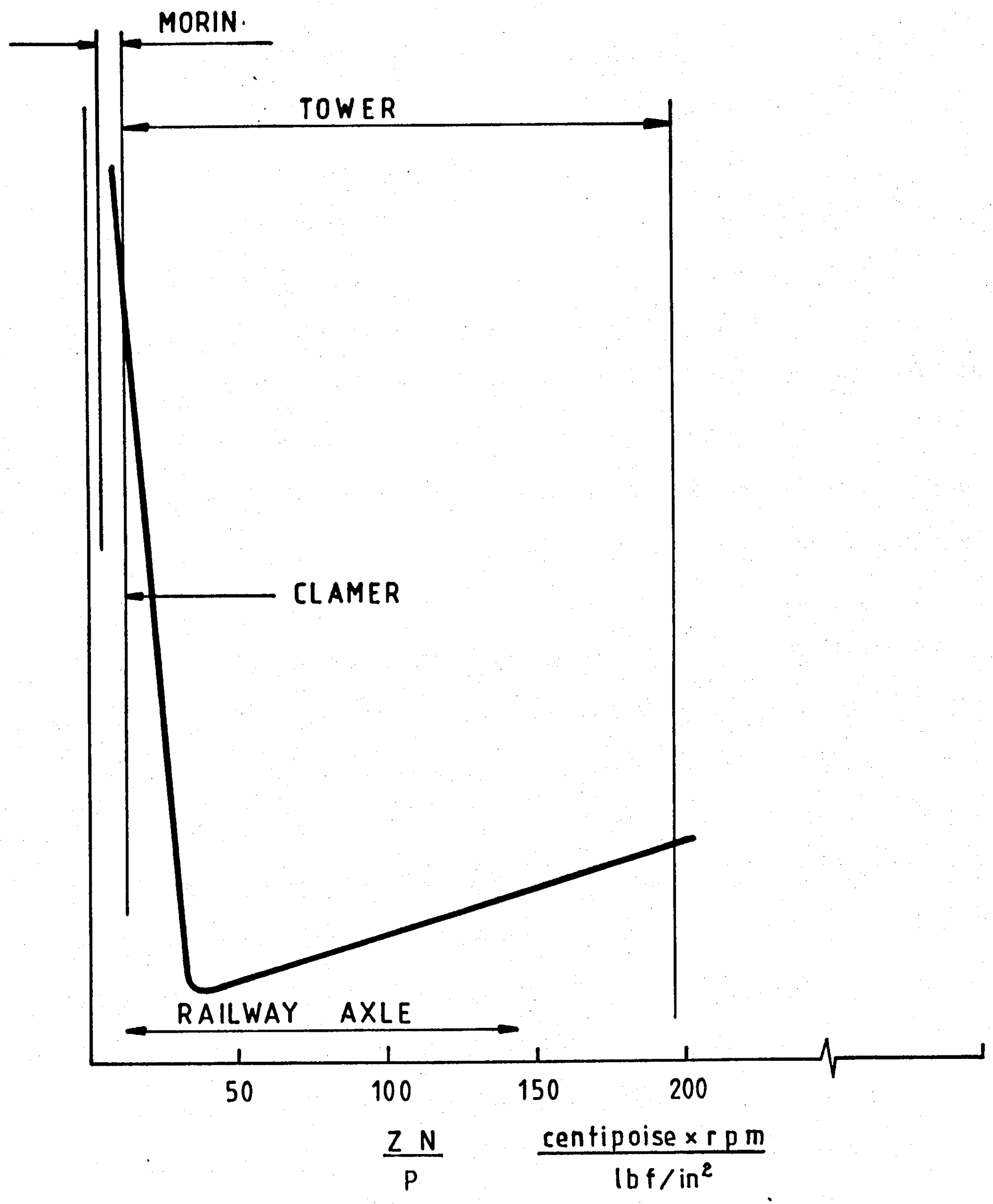

MORIN·
TOWER
CLAMER
RAILWAY AXLE
50
100
150
200
$\frac{Z\ N}{P}$
$\frac{\text{centipoise} \times \text{r p m}}{\text{lbf/in}^2}$

FIG. 6.2

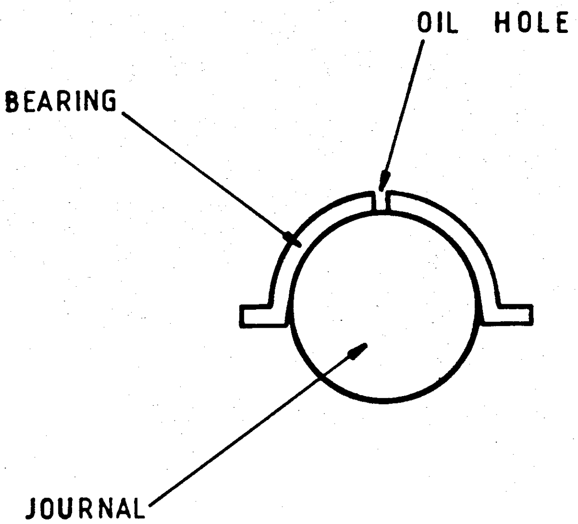


FIG. 6.3

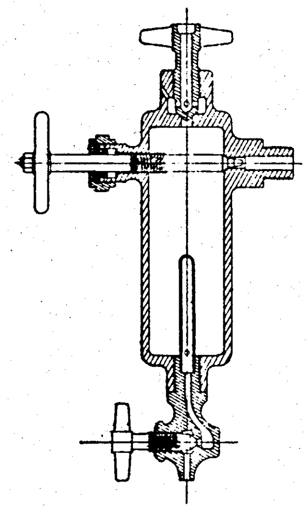


Fig. 6.4 Roscoe's Lubricator.

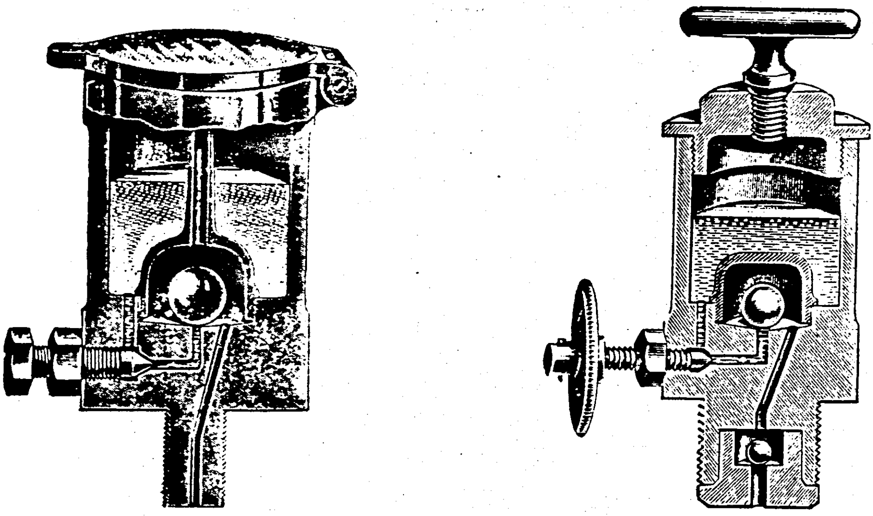


Fig. 6.5 Two examples of "oscillating ball" lubricators.

CHAPTER 7

BEARING METALS AND ALLOYS

7.1 Bearing metals

By the middle of the last century, metallic bearings had largely replaced non-metallic bearings. There were notable exceptions such as the use of lignum vitae for stern tube bearings in ships. Non-ferrous materials, in particular bronzes, were developed for many applications. Indeed the term "brass" and "bearing" were practically synonymous, but one of the most commonly used materials was an alloy of copper and tin - typically in the ratio of eight parts copper to one of tin. Other compositions were used, for example Muntz metal (a copper/zinc alloy) [Clark 1855].

Two conflicting requirements, however, apply to plain bearings. They require adequate strength in the direction in which the load is applied, whilst having low shear strength parallel to the direction of motion for low friction. This cannot be achieved effectively in a homogeneous material since a low strength (soft) material will tend to squeeze out under load. One way of overcoming these difficulties is to line a hard bearing shell with a thin layer of a soft material at the sliding surface. This idea was originally covered by Isaac Babbitt's patent of 1839. Later the idea was tried by D.F.Hopkins in about 1870 [Corse 1930] who first lined bronze bearings with thin sheet lead. This was found to be too plastic and antimonal lead (usually 85% Pb, 15% Sb) proved to be more satisfactory. This became one of the materials used in railway axle bearings, particularly in America.

7.2 Bearing bronzes

In his pioneering work on the wear of bronzes, Charles

Dudley, [Dudley 1892] compared the in-service wear of a number of alloys against a "standard" phosphor bronze which had the composition 80.7% Cu, 10% Sn, 9.5% Pb, 0.8% P. The high-lead bronzes, which wore more slowly than the standard, (see Chapter 3, Section 3.2) were composed as follows:-

"K" bronze Cu 77%, Sn 10.5%, Pb 12.5%

"B" bronze Cu 77%, Sn 8%, Pb 15%

Details of the compositions of the other materials tested by Dudley are given in Table 7.1.

In preparing high lead bronzes for these trials, Dudley found that 15% lead seemed to be about the limit. Increasing the lead content further resulted in lead segregating out of the alloy during casting. (The rate of cooling is the critical factor here. If slowly cooled the lead solidifies out of the melt first). Yet less than a decade later high-lead bronzes were being produced commercially, based on a better knowledge of the copper-tin system.

Practical data on the freezing points of binary alloys based on either silver or copper was given in a paper in 1897 by Heycock and Neville [Heycock 1897]. Using a platinum resistance pyrometer, they measured the freezing points of several binary alloys (including copper-lead and copper-tin alloys) of various proportions, and indicated the eutectic points. These data were compared with estimations derived using the theory of mixtures put forward by Le Chatelier in France. The equation used to determine the freezing point, T, of an alloy of metal A in metal B was:

$$2\log_e X = L(1/T_A - 1/T)$$

where X is the percentage of b, T_A is the freezing point of the pure metal A, and L is the latent heat of fusion of A.

In the United States, Two patents were granted to clamer and Hendrickson covering methods of producing lead bronzes without segregation of the lead. The first of these described the use use of a small proportion of nickel, the effect of which was to produce a mixture which solidified quickly, thus holding the lead evenly distributed throughout the alloy. The subsequent patent indicated that lead segregation could be avoided by limiting the amount of tin to less than 7%. This meant that all the tin was in solid solution in the copper.

Clamer and Hendrickson sold their product as "Plastic Bronze", having formed their own company, the Ajax Metal Company, for this purpose. However, in 1903, they brought a legal suit for infringement of their second patent against the Brady Brass Company of Jersey City, which also sold a high-lead bearing metal under the trade name of Allan Red Metal [Allan 1909]. A.Allan Jr. of the Brady Company claimed that his father had invented a process of alloying copper and lead in any proportion, without segregation, in 1876. A decision in favour of Ajax was given in 1907, but was reversed on appeal to the U.S. Circuit Court of Appeal [Clamer 1909], which found that the Clamer and Hendrickson patent covered a product rather than a process. The matter did not end there, and after a further four years of legal argument, the U.S. Commissioner of Patents granted a re-issue patent which corrected six errors in the original [Clamer 1909].

It later transpired that Allan's method involved the addition of sulphur to the molten copper-lead alloy which diminished the temperature range in which copper and lead are immiscible. It seems that the knowledge of the effect of sulphur was arrived at accidentally [Corse 1930].

Another problem in the preparation of bronzes of uniform quality was the rapid formation of oxides on the surface of the melt. this was overcome by Montefiori, who added phosphorus which virtually eliminated the formation of oxides. He obtained a patent for this in 1870 [Montefiori 1870], which was on the point of lapsing in England in 1878 when it was acquired by Alexander Dick, founder of the Phosphor Bronze Company Ltd. For many years his company produced an alloy of 80% Cu, 10% Pb, 9% Sn and 1% P, which became a standard railway axle bearing material. Zinc could also be added as a mild deoxidiser, but although it hardened the resultant alloy, it also tended to increase its wear rate. Rigid bronzes, most favoured in England, were harder and carried a greater load than the so-called plastic bronzes. They also tended to cause more wear of the mating shaft or axle and resulted in higher bearing temperatures [Corse 1930].

The wear performance of various bronze alloys continued to be evaluated both in the United States and in Britain. for example Portevin and Nusbaumer [Portevin 1912] tested bronzes in a Derihon mill, in which the edge of a polished steel disc rotated against the specimen. They found that the wear of the bronzes was proportional to the tin content, or more exactly to the amount of the delta phase, and that the introduction of phosphorus decreased the rate of wear of high tin alloys, but increased that of low tin alloys. They also noted that a skin of cold worked metal was produced on the rubbing surface of the bronze and that when this layer was formed, the wear rate decreased.

The Brinell hardnesses of various bronzes are given in Table 7.2. This table is adapted from data given by Corse. Mechanical properties of alloys for railway bearings are given in Table 7.3. This data is taken from the table given by Clamer in 1916 [Clamer 1915]. The reason for including this data is to show how the composition of bronze bearing metals affects their properties.

7.3 White metals

The term "white metal" refers to low melting point alloys based on tin or lead. There is, therefore, no single "white metal" but rather two classes of alloys based on these metals. Babbitt's original specification was for an alloy of 89% Sn, 9% Pb and 2% Cu. Usually antimony was added to harden the resulting alloy. a good review of the types and applications of white metals was given by Hague [Hague 1910] in 1910. He listed some of the desirable properties that good bearing metals should have:

1. They should have a compressive strength above 9000 lbf/in^2
2. It is important for a bearing metal to have a low coefficient of friction and a high degree of durability. The slowest wearing metal may have the highest coefficient of friction.
3. Bearing metals should have a low specific heat and high thermal conductivity to give low running temperatures. High tin alloys were believed to be better than high lead alloys in this respect.

4. Bearing metals should cause minimum shaft wear. Hague believed white metals to be good in this respect, since they do not score the shaft if the lubrication is poor.

Hague categorised classes of white metals as follows:

Lead - antimony. The useful range of antimony was 13-25% and the friction decreased with increasing antimony content whereas the converse was true for wear. Wear, according to Hague took place by "splitting of the harder grains".

Tin - antimony. In the course of an extensive study of white metals in 1901, Georges Charpy [Charpy 1901], ascetained that alloys of tin and antimony in certain proportions contained in cuboids of the compound SBSn, in a tin-rich matrix. He produced the equilibrium diagram shown in Fig.7.1. If the antimony content was less than 4% the cuboids were not formed. These cuboids were much harder than the surrounding metal and preferentially carried the load and gave the alloy high compressive strength. According to Hague, however, such alloys were rarely used in practice because they were no more satisfactory than some of the cheaper ternary alloys.

Tin-antimony-copper. These alloys included Babbitt metal, which had the highest compressive strength of any bearing material and ran at a lower temperature. Charpy found that these alloys contained crystals of a copper-tin compound, SbSn cuboids and a tin-rich matrix. He also discovered that if considerable pressure was applied the cuboids stood out in relief and that the Cu-Sn needles disintegrated. If the percentage of Cu was greater than 10% or the Sb greater than 15%, the alloys were brittle.

7.4 Graphited bearing metals

By the turn of the nineteenth century, various attempts had been made [Corse 1930], notably in Germany, to produce an anti-friction metal that would contain graphite. The problem was that in conventional casting processes the graphite was either lost due to oxidation or it segregated during casting. In onemethod a mass of coarse graphite crystals were placed in a mould and a layer of copper was electro-deposited over them using an acid copper plating solution. Another layer of graphite was then placed over the copper and another layer of deposited. The metal was built up in layers to the required thickness. In 1910 Clamer reported [Clamer 1910] that he had produced graphite bearing metals by subjecting a mixture of graphite and metal particles to heat and pressure. This was an early example of the application of powder metallurgy techniques to bearing metal production. Whilst some difficulties were experienced in producing metal alloys containing graphite, a method was developed to impregnate graphite with various metals in order to produce a bearing metal capable of operating at relatively high temperatures. This material (trade name Graphalloy) was first produced by theGraphite Metallizing Corporation of New York in about 1918 by the following process. Graphite bars, which contained a small proportion of amorphous carbon, were first machined to the required shape ans size and then heated in a crucible. Molten copper of Babbitt metal was poured in and the crucible placed in the chamber of an hydraulic press. The chamber was evacuated and the press applied pressures of up to 5000 lbf/in^2 whilt the material was superheated. The pressure was gradually released and the specimen slowly cooled. In this way, metal-impregnated graphite materials, capable of withstanding moderate bearing duties were made, and they were tolerant of adverse conditions including lack of liquid lubrication.

7.5 Manganese steel

Although manganese steel is not used in bearings, its origin should be mentioned because it has been widely used for its outstanding resistance to abrasion. The development of this type of steel was due to the work of one man - Robert Abbot Hadfield (1858-1940) who, in the late 1870's was inspired by the work on improving steel that was being carried out in France. The French had found that manganese was useful in producing sound material, free from cavities. Hadfiled tried adding ferro-manganese in various proportions to decarburised iron and found, initially, that with a manganese content of between 2.5 and 7.5%, the steels were brittle. Only when manganese was present at above 8% was a tough steel produced. He obtained a patent [Hadfield 1883] in 1883 for manganese steel containing between 7 and 20% manganese. Certain production problems plagued early attempts, but by 1887 manganese steels were produced commercially containing 12.5% Mn and 1.2% carbon. Hadfield presented a paper to the Institution of Civil Engineers in 1888 [Hadfield 1887] describing the properties of manganese steel, including its resistance to wear. Those who compared its wear resistance withthat of other metals also found it to be superior.

Hadfield himself advocted its use in conditions of harsh wear and in particular as a rail steel, where it soon found favour. Although the hardness of manganese steel, as produced, lies between 200 and 300 Brinell hardness, abrasion raises the hardness of the surface layer to around 600, as a result of the cold working involved.

Table 7.1 List of bearing alloys quoted by Dudley

(% composition)

Name	Cu	Pb	Sb	Sn	Fe	Zn
Camelia metal	70.2	14.7		4.5	0.55	10.2
Anti-friction metal	1.6			98.13	trace	
White metal		88	12			
Metal for lining car brasses		85	15	trace		
Slagee metal	4	1		10		86
Cornish bronze	78	12		10		
American anti friction metal		78	19	0.6		1.4

Table 7.2 Brinell Hardness of Lead Bronzes

(B.H.N. = Brinell Hardness Number in kg/mm^2)

%Sn	%Pb	BHN
4.5	0	49
8.8	0	63
16.3	0	77
25.9	0	230
0	10	27.2
0	20	23.8
0	40	13.8
4.1	0.95	57
8.1	1.1	67
14.1	1.15	83
3.9	3	46
7.8	3.2	61
13.9	3.1	83
3.99	5.0	46
8	5	61
13.7	5.1	93
4	6.9	46
8	6.9	59
13.9	7.0	80
2.4	10.6	39
8	10.4	48
13.9	10.4	86
4.1	14.12	39
9.2	15.3	57
19.8	5.0	130
20.4	8.8	130
21.5	8.05	150
11	5	70
17	5	109
5	20	44
24	5	182
12	20	70

Table 7.3 Properties of Alloys for Car Journal Bearings

%Composition Cu	Sn	Pb	Zn	Tensile strength p.s.i	%elongation	Compressive proportional limit p.s.i
95	5	0	0	41,800	34.5	18,000
90	5	5	0	40,500	34.5	19,000
90	10	0	0	39,000	15	25,000
85	5	5	5	38,150	36	18,000
85	10	5	0	32,700	9.5	22,000
80	5	5	10	28,100	15	18,000
80	5	10	5	34,700	23	16,000
80	5	15	0	23,300	15.5	16,000
75	5	10	10	29,800	13	19,000
75	5	20	0	23,300	15.5	15,000
70	10	20	0	27,000	6	21,000
70	10	5	15	27,500	1.5	40,000
65	5	30	0	19,800	12	15,000

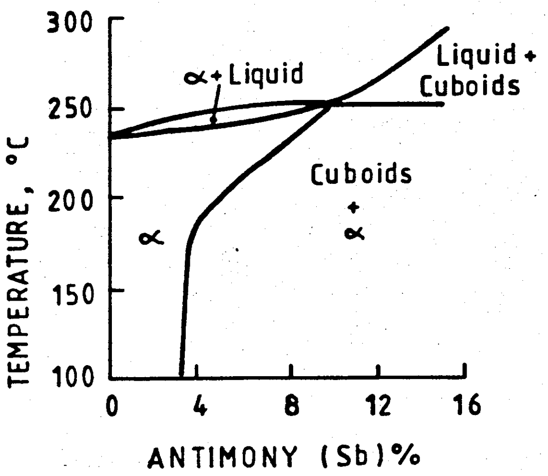


FIG 7.1 PART OF THE TIN-ANTIMONY PHASE DIAGRAM (AFTER CHARPY)

CHAPTER 8

CONCLUSIONS

8.1 Sliding and rolling friction.

The first 2 chapters of the thesis describe the work on sliding and rolling friction. Sliding friction was mainly of academic interest during the eighteenth century, although Coulomb's work was carried out with a practical purpose. The principal issue was whether the area of contact of surfaces influenced the magnitude of friction. Amontons original assertion that it did not was questioned both at the time of his memoir and by later workers. Yet those who contended that the area did influence friction coefficient do not appear to have put forward convincing demonstrations (e.g. Nollet). Coulomb's lengthy study of sliding friction settled the matter. He demonstrated with large scale experiments that friction is, for all practical purposes, independent of the area of contact.

Amontons' results are often quoted as the two "laws" of dry friction, yet in all cases the surfaces he used were greased with pork fat. So it is not surprising that he obtained the same coefficient of friction for all the combinations of materials that he tried. A more significant, but less publicised, contribution on sliding friction was that of Camus, who published a table giving friction coefficients for various combinations of materials.

The interlocking of surface roughnesses was seen as the primary cause of friction by most of those who wrote on the subject, although Desaguliers recognised that cohesion between two surfaces (which he had demonstrated with lead spheres) could play a part in the friction of smooth surfaces. Whilst the lifting of surface asperities over each other could account for the initial static friction, it could not account for the work lost in sliding surfaces together, as Leslie pointed out.

The study of rolling friction in the late eighteenth and first part of the nineteenth century had a practical purpose in connection with the traction of wheeled vehicles and the effect of wheeled vehicles on the state and upkeep of roads. Chapter 2 recounts the work of Morin and Dupuit and the debate between them on the relationship between the radius of a wheel and the traction force. Morin's results indicated a direct inverse relationship whereas those of Dupuit led him to conclude that the traction force was related to the inverse square root of wheel radius. A similar conclusion was also drawn by Helsham from his experiments on model carriages, carried out a century before Dupuit's work.

Even a detailed analysis of Morin's and Dupuit's results as given in the Appendix to Chapter 2 does not show up an error on either side which might call into question the results. What does emerge is that Dupuit was concerned with the cause of energy loss during rolling although he termed it "lost work". Implicit in Dupuit's analysis is the concept of hysteresis loss, although neither Morin nor Dupuit had a satisfactory means of relating depth of impression of a wheel or roller to the applied load.

8.2 Wear.

8.2.1 Significance of wear

Wear in plain bearings began to have serious consequences towards end of Industrial Revolution, that is from about 1840 onwards. The data on bearing loads and speeds given in Chapter 5 on bearings shows that at this time they began to increase significantly. It is in the second half of the last century that wear began to be studied in detail, although most studies were aimed at selecting materials for improved wear resistance.

8.2.2 Wear testing

The evidence presented in Chapter 3 shows how data on the wear of materials up to 1940 was gained in one of two ways. In the case of Charles Dudley's pioneering studies, materials were tested in-service, that is tried in the actual application as in his trial of different railway axle bearing materials. In the case of rails, the original profile of the rails was compared with their profile after a specific period in service. The other, more commonly used method, was to do comparative tests; that is to measure the wear of different materials under indentical conditions in a test machine. For example Clamer obtained broadly similar results to those of Dudley (i.e. increasing lead content in bronzes yielding a reduced rate of wear) but from tests under identical conditions on a wear testing machine. No doubt the "in-service" trials took considerably longer than the laboratory tests and required accurate records to be kept of miles run and was probably more suited to a user of bronze bearings (the Pennsylvania Railroad Company). Whereas a supplier of bronze bearing material, represented by Clamer, would have required quick results from laboratory tests to indicate the most promising alloy compositions.

Robin's study of the wear of steels is interesting, not only for the results he obtained, but also for the fact that it was probably the earliest use of a pin-on-disc type of wear test, now perhaps the most widely used type of laboratory wear test.

Most wear test machines were custom made for specific wear tests, but the Amsler wear machine, first produced in 1922, was quickly adopted by many experimenters.

8.2.3 Theories of wear

The study of wear was empirical up to 1940. Conclusions were drawn directly from experimental results, and in many cases no clear connection with any one mechanical property was established. Wear was traditionally explained in terms of the breaking off of asperities from a surface. Tomlinson attempted to explain friction and wear in molecular terms and later Holm developed a molecular theory of wear. Although later work showed that wear occurs by detachment of fragments on a scale much larger than atomic dimensions, Tomlinson seems to have recognised that there was an element of probability in the formation of a wear particle whatever its size.

The crucial concept in present-day studies of friction and wear is that of the real area of contact, and the fact that this is a much smaller fraction of the apparent area of contact. The realisation that small areas on intimate contact were formed when two bodies touched emerged from studies of the electrical resistance of contacts. This idea was initially used to explain the constriction in the electrical path between two conductors, and was used by Bowden and Tabor to measure the ratio of real to apparent contact area. The concept of real area of contact is alluded to in Price's paper of 1905, but was not fully developed until the work of Ernst and Merchant thirty five years later. Although Euler, Coulomb and others pictured the interlocking of asperities in models of surface contact, their pictures implied that the surfaces meshed together perfectly.

The development of the surface profilometer, which give a magnified picture of surface roughness has been traced. The driving force behind its development was the need to categorise the surface finish of engineering components. In the space of a decade, during the nineteen thirties, profilometers evolved into instruments that were robust, simple to use and which gave a quantitative measure of surface roughness. It is only in the last forty years that these instruments have played a significant role in friction and wear studies.

8.3 Wear prevention.

The latter Chapters in the thesis deal with some aspects of wear prevention, specifically in relation to bearings. The demonstration by Hirn, and later by Tower that journal bearing surfaces could be completely separated by a film of oil was a significant revelation. Yet for complete separation a certain combination of lubricant viscosity, rotational speed and bearing pressure is required. The analysis in Table 6.2 shows that, for example in railway axle box bearings, complete separation would not always have occurred. The consequence of this was metallic contact and wear.

The geometry of the journal bearing provides a natural converging "wedge" which is a pre-requisite of hydrodynamic lubrication. Reynolds' 1886 paper provided the mathematical basis which enables the thickness of the film to be calculated. However the thrust bearing does not have this inbuilt advantage, and Chapter 5 describes the origins of Schiele's "anti-friction" pivot. The name "anti-friction" turned out to be a misnomer, since it was quickly shown that the only benefit of this unusual geometry is that the wear is uniform at all points on the surface. The tractrix curve, to which the surfaces were formed, was originally analysed by Huygens.

With the advent of the screw propeller, a large thrust bearing was required to transmit the thrust to the ships hull. Multiple collar bearings were used and various empirical formulae were devised for their design. Care in their construction and attention to their lubrication was required if they were to work reliably. A great advance in thrust bearing technology was the tilting pad concept conceived by Michell and Kingsbury (see Dowson 1979). In this type of bearing the tilting pads automatically created a wedge and thus promoted separation of the surfaces by a film of oil.

As bearing loads and speeds increased during the second half of the last century, improved bearing metals were developed to meet the demands imposed. In particular a better understanding of the metallurgy of bronze alloys enabled sound alloys with a high content of lead to be produced. Testing both in the laboratory and in service proved the better wear resistance of these alloys. The composition of tin-based white metals was investigated and by the turn of the century specific categories of bearing metals were established, each with its own particular advantages and disadvantages. The production of specialised bearing alloy such as graphited bronze also date from the early decades of this century and the ability to produce them rested on the better knowledge of non-ferrous metallurgy.

APPENDIX 1

Biographical note on Christian Schiele

Christian Schiele was born in Frankfurt on the 18th September 1823, the son of Georg Schiele. Georg Schiele (1975-1861) was a Frankfurt businessman who, with Johann Knoblauch, founded the first gas-works in Frankfurt in 1828. I have not been able to trace Schiele's education, but it is clear from his later work that he must have received good training in mechanical engineering. By 1847 he had settled in Manchester, where he set up as a "mechanician" with an address at 5 Corporation Street.

In the following year he obtained his patent for the "anti-friction" curve and had moved to Granby Row in Manchester, setting up as an "engineer and brass founder" [Slater 1848]. After only a brief period in Manchester, he moved to Oldham in 1851 establishing himself at the North Moor Foundry there. He evidently felt himself well established for on the 1st November 1851 he married Joanna Kay, daughter of one John William Kay of Bury. He remained in Oldham for some eight years during which time four of his six children were born.

After a short period of residence at Bebbington on the Wirral, from 1858 to 1860, Schiele returned to Manchester in 1861 where he founded C.Schiele and Company in Booth Street [Slater 1862] which specialised in the manufacture of water turbines, the first of which was installed at Scout Mill, Mossley near Stalybridge in 1863 [Manchester Examiner and Times April 30th 1863]. However it seems unlikely that the company was a success for in 1865, Schiele and his family moved to Frankfurt where in the same year he set up a company to make ventilators. This venture was to be his last, for he died in Frankfurt on the 1st July 1869 at the age of 45.

Schiele's patents

In all Schiele obtained 17 letters patent (see Table A1), of which the one that received most attention was undoubtedly that for the anti-friction curve. Most of the others were concerned with machines of various sorts, and prime movers in particular.

His first patent in 1847 was for a steam condenser. This comprised a vessel with two compartments partly filled with water, immersed in a tank of water. Steam from an engine, entering one compartment depressed the water level which, acting on a flap valve, expelled colder water from the second compartment through a pipe with a large number of fine holes. The water thus trickled back into the first compartment condensing the steam. In effect this arrangement was a refinement of the water injection method of condensing steam.

Another of his patents also deserves particular mention. In 1856 Schiele patented a machine for cutting "toothed wheels" i.e. gears. The drawing which accompanied the specification shows what was essentially a gear hobbing machine (Fig. A1). The teeth on the blank gear were machined by a profiled cutter in a worm and wheel arrangement. The gear was indexed by a series of change wheels and the arrangement of cutter and change wheels enabled a range of tooth pitches to be machined. This machine tool would have produced gear teeth of accurate pitch but it is not known whether any machines were produced to this specification. However, it was certainly a forerunner of the present day gear hobbing machine.

Two year later in 1858, Schiele patented a method of lubricating axles or shafts. The shaft to be lubricated had a helix machined into it. A gear wheel fitted into the helix in a worm and wheel arrangement. The wheel was partly immersed in an oil bath (Fig.

A2). The idea was that oil, conveyed up on the teeth of the wheel, was fed to the bearing along the helix. One of the figures in the patent shows the application of the idea to the lubrication of railway axle boxes. At about this time several methods of lubricating such axles boxes were proposed, reflecting the efforts to improve their lubrication and extend the interval at which bearings had to be replaced.

Schiele's other interest was in water and steam turbines. In 1855 he obtained a patent for a "rotary steam engine" (Fig. A3). The specification describes a turbine in which jets of steam impinge upon curved blades on a runner. The turbine is reversible by having two runners with blades of opposite curvature on them and the steam can be valved from one to the other. In many respects this design is similar to the impulse water turbine, however as a steam turbine it would probably have been inefficient.

During Schiele's stay at Bebbington, close to the sea, he patented various ideas for "obtaining and applying motive power from ocean of other ways" including a piston rising and falling in a cylinder, and an endless belt with buckets and other, rather impratical devices. Still on the subject of prime movers, he patented a radial flow water turbine in 1863 (Fig. A4). The design was similar to Jonval's turbine but adjustable inlet guide vanes were used to admit the water to the vanes "without shock", that is tangential to the vane tips.

In summary his patents show a variety of interests, but lack the combination of true originality and practicality required for success.

Advice to his brother inventors in England

After Schiele's return to Frankfurt he privately published his only book [Schiele 1866] which was entitled "Advice to his brother inventors in England" with a sub-title of "his experiences with numerous patents for fans, turbines, the anti-friction curve etc.". This slim volume reflects the bitterness felt by Schiele regarding the patent laws of England. He claimed that their wrong administration "has become a fearful oppression on inventors tempting moneyed persons to rob them of just reward". There is also a indication that he had been subjected to patent litigation but in what connection is not made clear. The theme of the book is advice to inventors as to how best to make a profit out of their inventions and to avoid exploitation by capitalists. "could I have found such advice in former years", wrote Schiele, "it would have been of great value to me; may others now benefit by this attempt to assist them".

In fact, English patent law had been revised and a new Patent Law Amendment Act came into force in 1852. Under this Act the submission of a provisional specification and the payment of five pounds stamp duty secured six months provisional protection. Before expiry of the six months, a complete specification had to be filed and considerable fees were charged for the upkeep of the patent; 25 pounds for the first three years, 50 pounds for the following four years and 100 pounds for the last seven years. The obtaining and upkeep of a patent thus represented a considerable outlay of money. Schiele recorded in his book a number of cases of inventors who had been deprived of rewards by unscrupulous practice.

TABLE A1
List of Schiele's Patents

Patent No.	Date	Subject
11,717	27/5/1847	Machinery for condensing steam
12,338	23/11/1848	Construction of cocks or valves(anti-friction curve)
13,784	22/10/1851	Machinery for the preparation and manufacture of fibrous materials
13,965	12/2/1852	Obtaining and applying motive power
1,383	4/6/1853	Pressure indicators
2,892	13/12/1853	Preventing undue oscillation in engines, carriages and other apparatus
1,693	26/7/1855	Obtaining and applying motive power
2,896	6/12/1856	Machinery for cutting nuts, screws, bolts or toothed wheels
1,723	30/7/1858	Hydro-extractors or drying machines
2,019	3/9/1859	Weighing machines
475	22/2/1860	Machinery for hammering or crushing
594	3/3/1860	Obtaining and applying motive power from ocean or other waves
1,317	29/5/1860	Manufacture of lubricants
1,309	3/5/1862	Machinery for cutting or dressing stones
1,681	7/7/1863	Turbines
2,008	14/8/1863	Fans, pumps and machinery for propelling air
2,581	21/10/1863	Governors

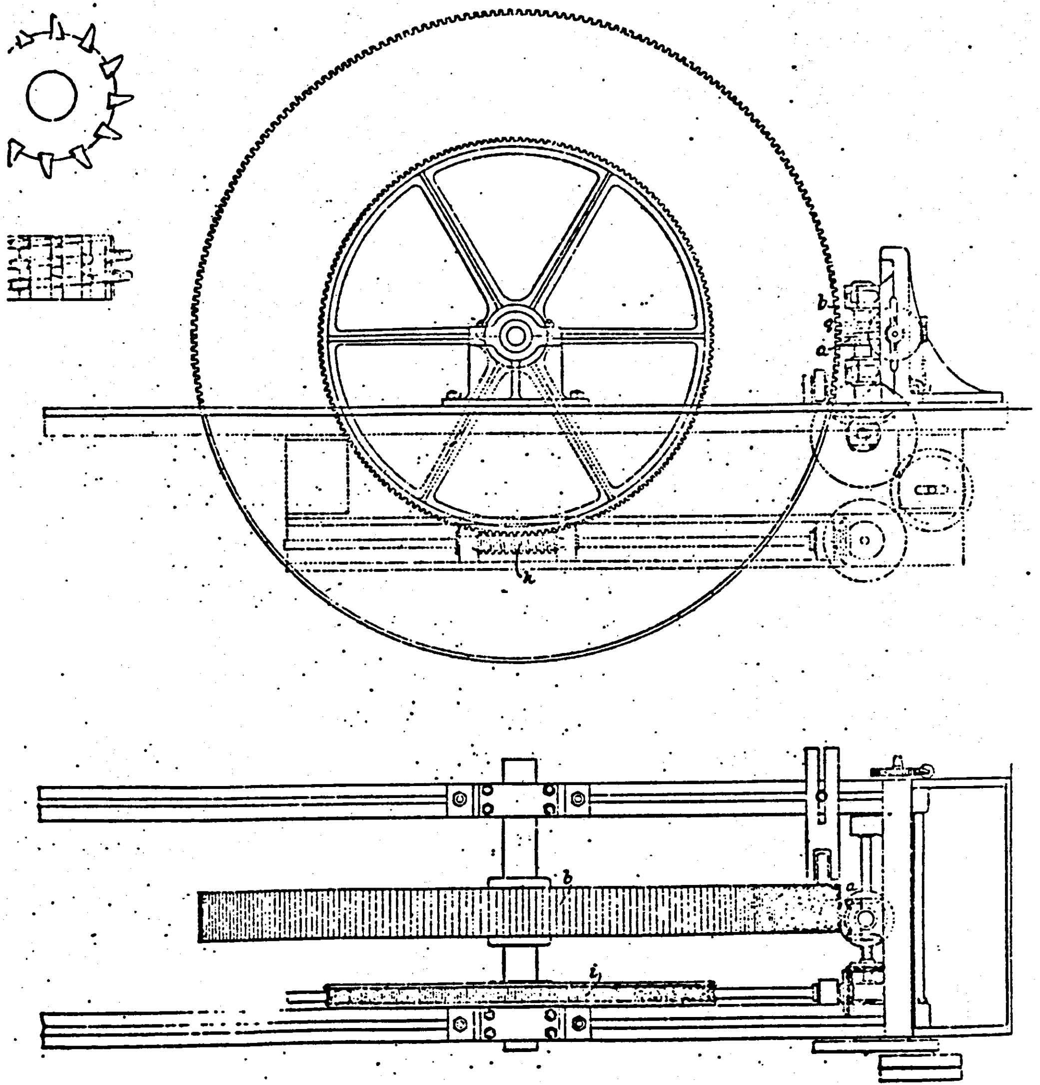


Fig. A1 Gear cutting machine

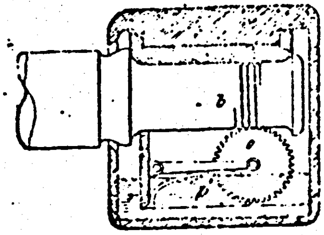
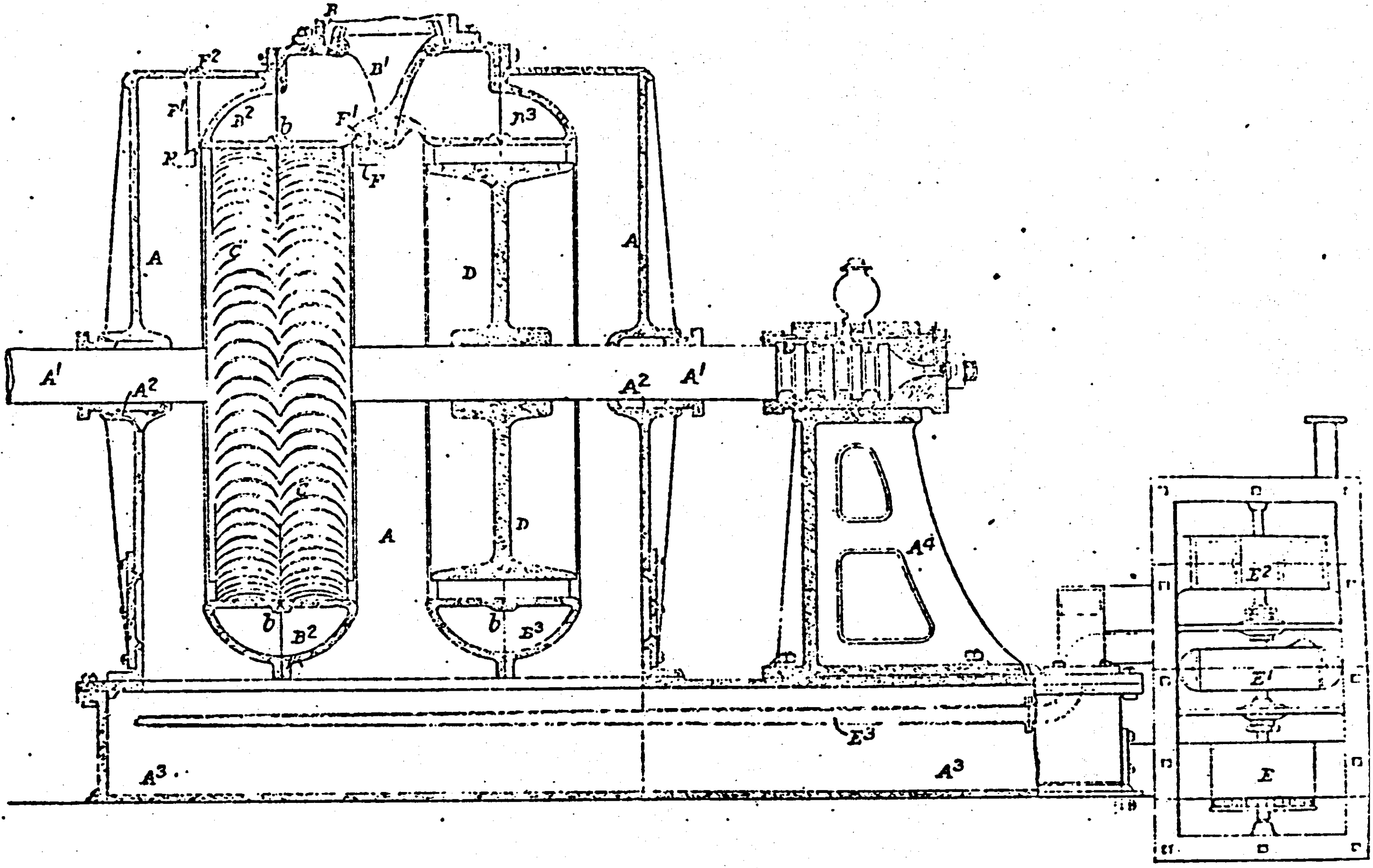


Fig. A2 Oil bath axle lubricator



- - Fig. A3 Steam turbine

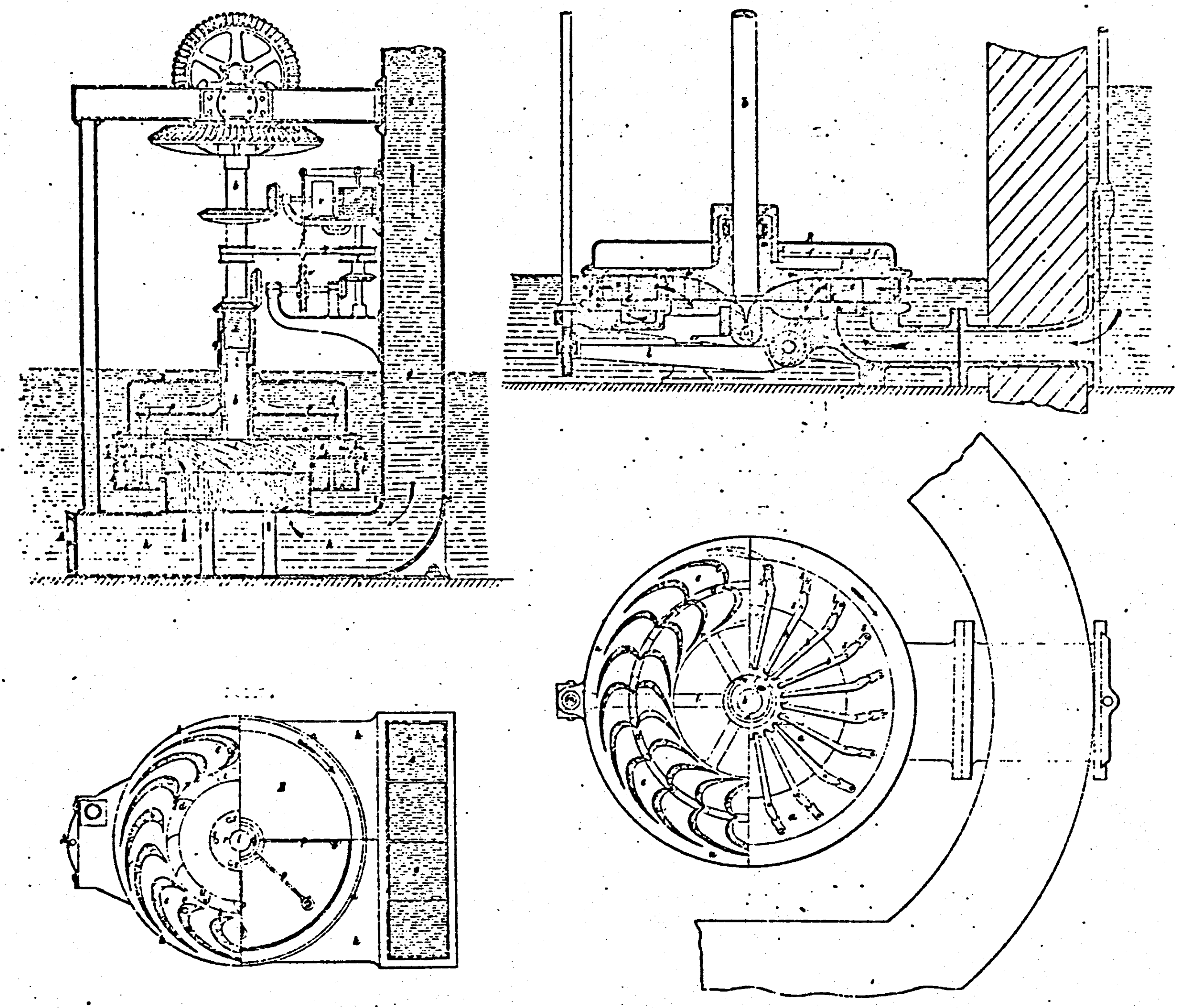


Fig. A4 Water turbine

APPENDIX 2

BIOGRAPHICAL NOTE ON CHARLES BENJAMIN DUDLEY

Charles Benjamin Dudley was born on July 14th 1842 in Oxford, Chenango County, New York. He attended the local school and Academy and instead of embarking on a college course, he enlisted in the Union forces in 1862, during the early stages of the Civil War. During the next three years he took part in seven battles and was wounded in the leg during the battle of Opequon Creek in September 1864, a wound which left him partially crippled for life.

After his discharge from the army in 1866 he enrolled for a degree at Yale in 1867 and graduated with honours in 1871. Already in debt for the expenses of his degree course, he took various journalistic jobs on local newspapers for over a year. The money earned enable him to pay his debts and to pay for a postgraduate course in chemistry. He attained his Ph.D. in 1874 with a thesis on lithium and its compounds. After two posts as university assistant, he applied for, and obtained, the post of Chief Chemist of the Pennsylvania Railroad in 1875, which he held until his death. At this time the establishment of a chemical analysis department within a company such as the Pennsylvania Railroad was an innovation, necessitated by the large quantities of all kinds of materials which it purchased, but having no means of scientifically checking their quality.

Dudley discovered and perfected tests, and prepared specifications for, all the important materials used by the company, such as coal, water, lubricating oil paint and steel. He built up the staff in the laboratory to 27, which included a bacteriologist who examined the water supplies and administered the tests required in the medical diagnosis required for the company's Relief Fund. Dudley joined various learned societies, including the Institute of Metallurgical and Mining Engineers, in whose Transactions his papers on the wear of steel rails were published. His passion was the formulation of standards for materials testing, both national and later international. He was an instigator in the founding of the International Association for Testing Materials, and attended as the United States representative at the Copenhagen meeting of the Association in 1909. At this meeting he was elected President of the Association. The next meeting was to be held in the United States in 1912 and Dudley promised that the sessions would be conducted in French and German, as well as English. Thereafter he devoted himself to improving his fluency in both languages, although he could read and translate both with some proficiency.

In December 1909, not long after his return from Europe, pneumonia developed from a severe cold and he died on the 21st.

His main contribution was his work on the establishment of standards both for test methods and materials. In the context of this thesis he should be remembered for his pioneering work on the wear of metallic materials, deriving his results from carefully conducted field trials on rail and bearing materials.

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