The Effect of the Metal Combinations on Wear and Friction in Ultra-High Vacuum Condition

by

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Many studies on the friction and adhesion phenomena under a high-vacuum condition have been done and being continued steadily since the advanced development followed the improvement of the research method.

At present studies many types of metal alloys such as bearing steel, stainless steel and phosphor bronze chosen as the test pieces with a few single metals like nickel and tin.

Though in the ultra high vacuum condition a lot experiments have been done on friction phenomena, the wear phenomena have not been enough clarified in such condition because of being in itself complicated.

As it is most desirable that the change of the worn surface during wear process can be limited within certain extents, the ultra high-vacuum condition are most suitable to clarify the wear mechanism on which a clear explanation has not been made.

The experimental results under such condition can clarify the effect of the compatibility among the material combinations, and of difference of the contact shape, furthermore can make clear also experimentally the larger adhesive force than the ploughing term.

INTRODUCTION

We mainly introduce a few typical examples of the friction and wear on metal surfaces in the ultra high vacuum condition $(10^{-6}$ Pa) as the basic research for the study on wear under the extreme circumstances.

At present studies a lot of types of metal alloys such as bearing steel, stainless steel and phosphor bronze were chosen as the test pieces with a few single metals like nickel and tin.

Though in the ultra high vacuum condition also fairly many things have been well studied on friction phenomena (1) (2), the wear phenomena have not been always clarified in such condition for being in itself complicated.

As it is most desirable that the change of the wear surface during wear process can be reduced within an extent, the ultra high vacuum conditions are most suitable to clarify the wear mechanism on which a clear explanation has not been made.

The present paper reports a few interesting results which we could confirm experimentally, especially about the effects of a compatibility and a hardness between each material combination on the adhesive wear.

The experimental results under such condition can make clear the effect of the compatibility

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among the material combinations, and of the difference of the contact shape occurred by the difference of hardness between both surfaces on friction and wear, furthermore we can observe also an existence of much larger adhesion than ploughing.

EXPERIMENTAL

The test apparatus for friction and wear has been installed in a chamber (Bell Jar) so as to do experiments under a high and an ultra high vacuum condition. The equipment enclosed with a broken line shown in Fig. 1 is set up in the Bell Jar. The lower test pieces 3 are formed of three spheres so that experiments can be done on the each surface of a sphere by means of changing the contact point with adjustable part 8.

The upper test piece is attached to the holder 2. The contact loads are added through the stem 6 and lever 4 by the weights placed on plate 7.

The friction force during sliding can be measured by the strain gauge 5 attached aside lever.

Test Pieces

In the wear and friction test under the condition at 10^{-4} Pa, three types of hollow cylinder are used as upper test pieces shown in the fig. 2. In order to continue the experiments wihtout exposing in the air after having got a vacuum condition the both test pieces are shaped like such forms. Furthermore another shapes of test pieces are used in the experiments at 10^{-6} Pa.

Test Procedure

The schematic system of evacuation to get ultra high vacuum is shown in fig. 3. Each experiment has been done after the degree of vacuum has reached to 10^{-6} Pa at the end of baking the equipement at 130 °C.

The contact condition in these experiments is point contact between sphere and flat surface. The sliding velocity is constant at 1 m/min. and the total distance slid is 15 m as a standard. Both test pieces are set up after having been rinsed in the bath with ultrasonic cleaning for 15 minutes, and the amounts of wear are weighed after taking

Table 1 Dimension of Test Pieces

Materials	Hardness H_V	Remarks
S20C	185	Carbon Steel
SUS304	236	18-8 Stainless Steel
Sn	6.57	99.99%
Ni	149	99.99%
PB	180	Phos. Bronze
Pb	6.11	99.99%
Bs	138	7 : 3 Brass
SUJ	800	Bearing Steel ball
SUS304	196	18-8 Stainless steel Ball
Bs	180	7 : 3 Brass Ball

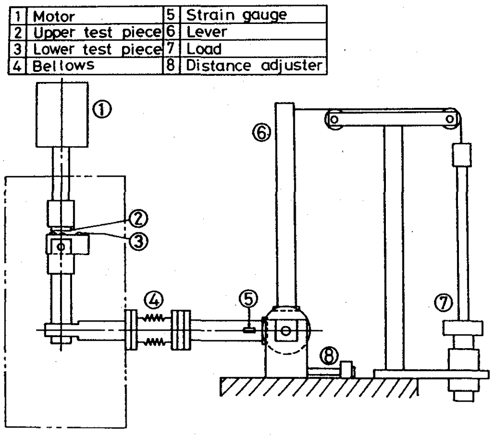
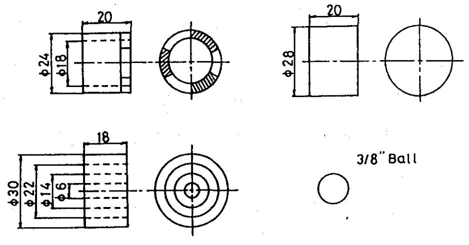


Fig. 1 Schematic Outline of Apparatus



a) Upper Specimens b) Lower Spesimens

Fig. 2 Test Pieces

upper pieces out of the Bell-Jar after sliding.

The experiments are carried out at four steps of the contact loads of 20 N, 30 N, 40 N and 50 N.

1	Belljar
2	Feed through
3	Vacuum manifold
4	Sputter ion pump
5	Titanium evaporation pump
6	Oil-sealed rotary pump
7	Sorption pump
8	Ionization gauge

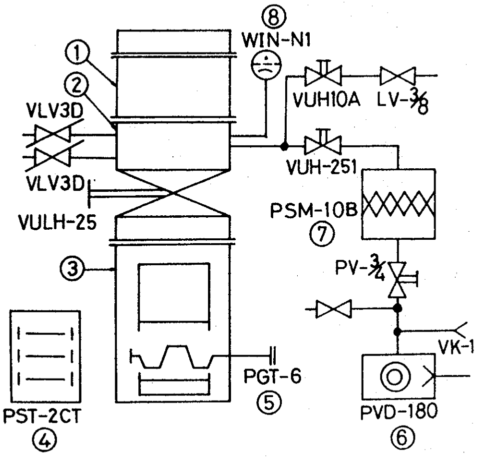


Fig. 3 Schematic System of Evacuation

TEST RESULTS AND DISCUSSION

The effect of a normal load in friction under a high vacuum condition

The adhesive forces under a high vacuum depend very much on the difference of the hardness between the combined metal surfaces, in other words the effect of the load on an adhesive force without sliding is very large. The adhesive force is usually estimated to be not so large even under a high vacuum except very mild metal because of a recovery of the elastic deformation on the adhesive part in a hard metal.

The relation between a normal load and an adhesive force without sliding under an ultra high uacuum such as 10^{-8} Pa has been reported well with fine results by professor D. Tabor et al.

At present we could confirm the dependence of the load on the adhesion force with sliding even at 10^{-4} Pa and also it depends very much on the combination of the materials related with their hardness.

The comparisons of the coefficient of friction between under high vacuum and air are shown in figs. 4, 5, 6 and 7. As the normal loads shown in figs. 4 and 5 are not so large for the hardness of both metals there is not a considerable difference of the friction due to adhesion between two atmospheres even in the combination with good compatibility.

In the combination of a non-steel with a steel shown in fig. 5, there is a considerable difference of adhesion between two atmospheres in spite of their large hardness owing to the elastic behaviour on the adhesive parts (3) (4).

In the case that the hardness of one of combined metals is smaller than the other, the junction can

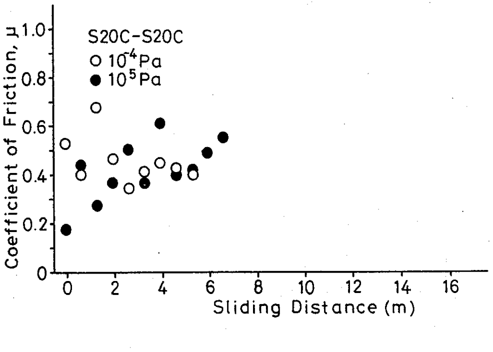


Fig. 4 The comparison of a coefficient of friction between in air and in vacuum at comparably low load, 30N (both specimens flat) S20C; S20C

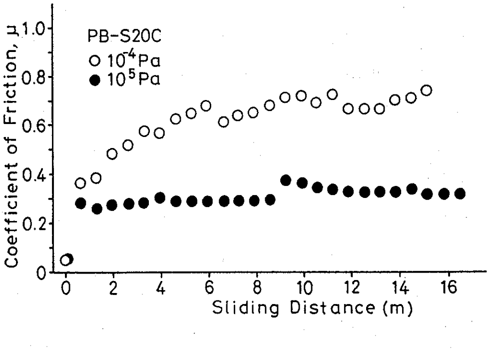


Fig. 5 The comparison of a coefficient of friction between in air and in vacuum at comparably low load, 30 N (both specimens flat) Phos Bronze : S20C

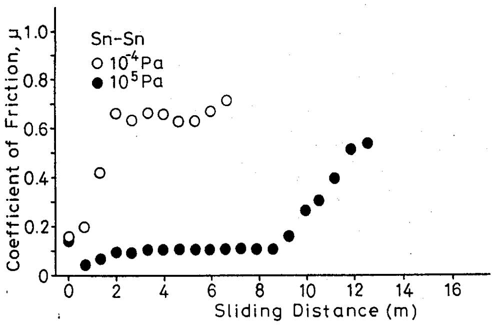


Fig. 6 The comparison of a coefficient of friction between in air and in vacuum at comparably low load, 30 N (both specimens flat) Tin : Tin

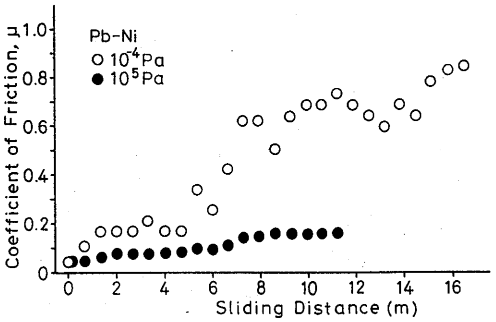


Fig. 7 The comparison of a coefficient of friction between in air and in vacuum at comparably low load, 20 N (both specimens flat) Lead : Nickel

be formed even at small load to bear an equation

$$\alpha\sigma^2+\beta\tau^2=\gamma Y^2 \tag{1}$$

based on the theory of plasticity because of a tangential stress τ being near to normal being near to normal stress σ (5) (6).

In order to get such phenomena the very clean surface to be free from contaminants must be kept as well as having soft hardness in one of two metals.

The effect of the normal load in the combination which can occur a strong adhesion is shown in fig. 8.

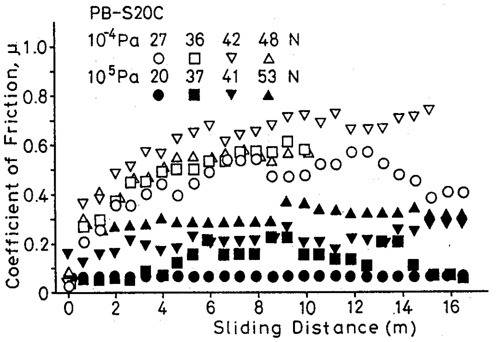


Fig. 8 The effect of the loads on a coefficient of friction under two conditions of air and vacuum (Phos. Bronze vs S20C)

The higher is a normal load, the larger is a friction as shown in fig. 8. We can regard it as the cause that a plastic domain has been increased much more than an elastic one for the higher load. The strong adhesion due to increasing a plastic domain could be shown also in air atmosphere with a similar tendency to vacuum condition.

The effect of a hardness on a friction under an ultra high vacuum condition

As we could keep the vacuum condition nearly at 10^{-6} Pa during whole experiments the surface has been maintained clean so to be free from any contaminants like an oxide layer.

The friction in the combination between a flat surface of S20C and a sphere of SUJ has shown the high friction to be peculiar in the combination of similar materials at first stage of sliding as shown in fig. 9.

After having slid some distance, however, the friction begins to decrease gradually for the cause which seems to be workhardening and to have been occurred on S20C surface by severe sliding. Such phenomena can be indicated in the combination of S20C flat with SUS sphere shown in fig. 10. The friction of bronze against stainless sphere under the ultra high vacuum condition depends on which hardness is much harder than the other's one in spite of the same combination shown in figs. 11 and 12.

Namely, when the flat surface of a brass has a softer hardness than the opposite sphere of stainless, the surface with a soft hardness can be easily penetrated by the harder one and furthermore as the junction is at same time placed under a tangential force by sliding, the front half of the contact area

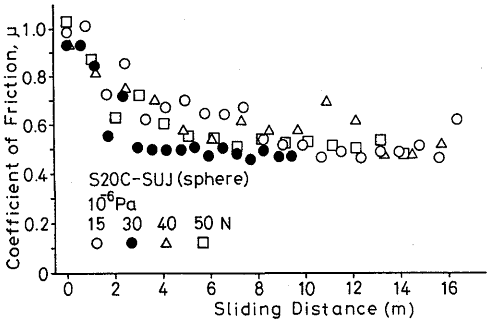


Fig. 9 A coefficient of friction in ultra-high vacuum of the order of 10^{-6} Pa at each load, (S20C ; flat vs SUJ ; sphere)

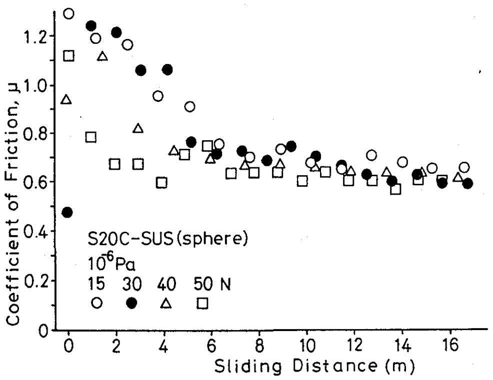


Fig. 10 A coefficient of friction ultra-high vacuum of the order of 10^{-6} Pa at each load, (S20C ; flat vs SUS ; sphere)

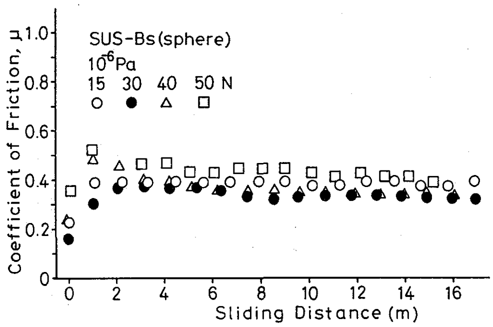


Fig. 11 A coefficient of friction in ultra-high vacuum of the order of 10^{-6} Pa at each load, (SUS ; flat vs Brass ; sphere)

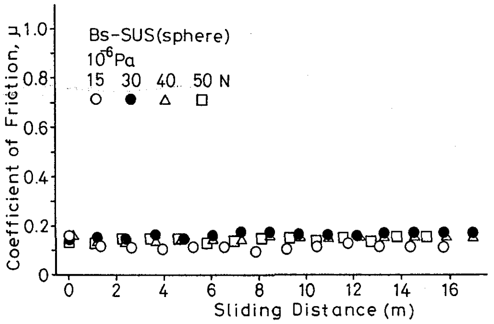


Fig. 12 A coefficient of friction in ultra-high vacuum of the order of 10^{-6} Pa at each load, (Brass ; flat vs SUS ; sphere)

may be in charge of both terms of adhesion and ploughing. In this case the term which may contribute to adhesion should be small comparing with the reverse combination as shown in fig. 13-a and b.

If the front half of the contact area along sliding direction may be in charge of whole load, the contact area of the half must be necessarily increased. The contact area, however, has not been increased as shown in photo 1. The cause may be that when the softer metal gets a tangential force simultaneously with a normal load a successive ploughing might occur within a softer one owing to the lack of an allowable shear stress. We can find it on the photo. 1-B which shows a rather diminution of the contact width with beginning of the sliding from static contact.

The leading edge along a sliding direction shows a fine semi circular dent and there remained a few adhesive points across the diameter after having slid for about 3 cm. However, there are the contact parts left in the both sides of initial semi circle by the wide groove worn away on the photo. 1-D after having slid 40 rounds (nearly 120 cm).

On the other hand, when a hardness of sphere is softer than flat surface, the considerable deformation occurs mainly on the soft surface of a sphere and consequently forms a flat contact between two surfaces shown in fig. 13-b. If the tangential force is added them in such contact condition, a large friction force can be generated because of a junction growth. That is just the fact that a tangential stress increases necessarily accompanied with decrease of normal stress due to junction growth.

In the conditions of the air atmosphere or with contaminant layer on surface, of course such strong adhesion can not exist between two surfaces. Photo. 2 shows the comparison of the wear debris between in air and under an ultra-high vacuum.

Although the coefficients of friction shown here are a little bit small as the friction under ultra high vacuum condition, its cause might be according to a weak shear stress of the combined metals. Fig. 14 and 15 show the coefficient of friction in the combination of a single metal tin as a flat surface with harder ones stainless and brass as spheres. In these cases the friction is not high since the break down of the junction occurs on the surface of tin of which shear stress is weak. Furthermore, it may be due to a soft hardness of tin as a flat specimen comparing with a sphere as well as a poor compatibility of tin against steel.

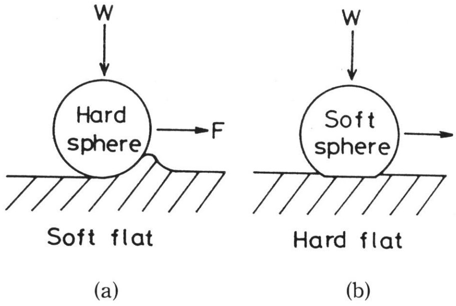
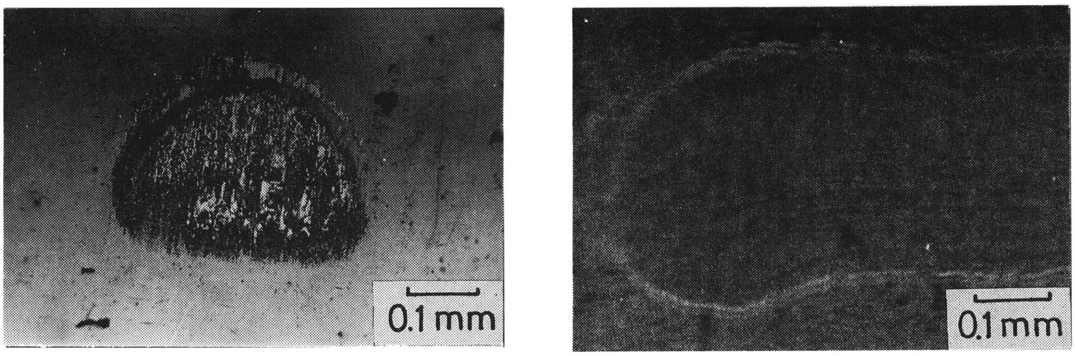
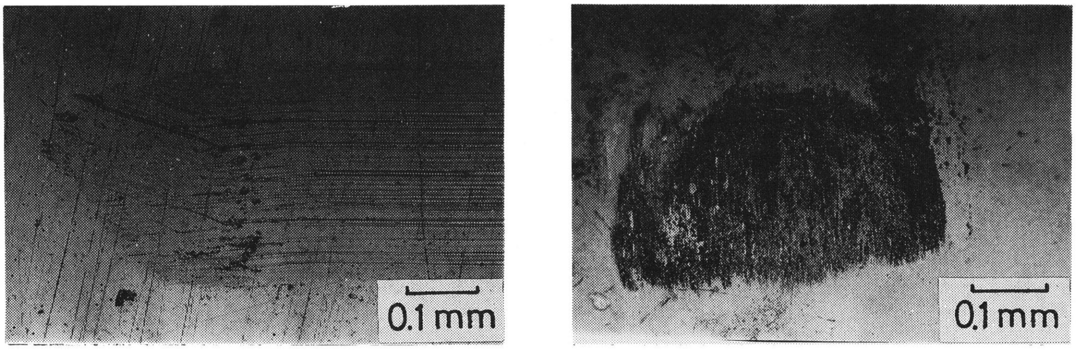


Fig. 13 The contact models in the combination ;
(a) hard sphere on soft flat
(b) soft sphere on hard flat



(A) A semi circular scar on a sphere surface at beginning of sliding (after having slid 3 cm)

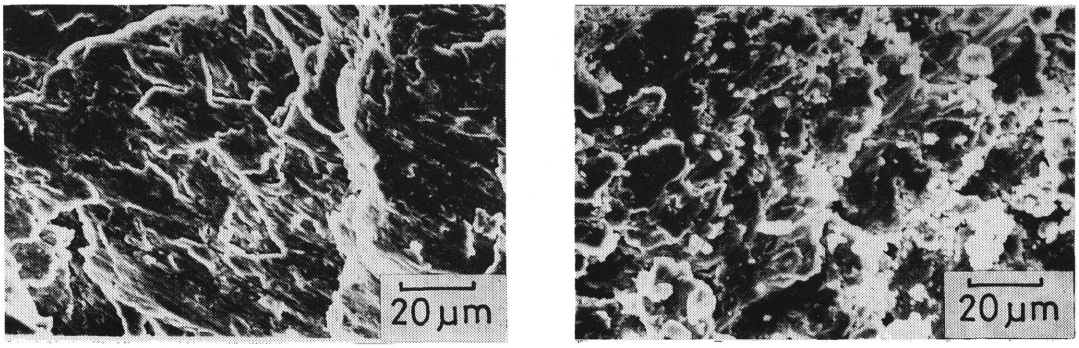
(B) The trace on a flat surface which shows a contact width at beginning



(C) Some adhesive traces (scattered black ones) found on a flat surface after having removed a sphere

(D) A semi circular scar with bands at both sides on a sphere after having slid long distance (120cm)

Photo 1 The scar traces on a sphere surface and a flat surface



(A) Wear debris under a vacuum by SEM

(B) Wear debris in air by SEM

Photo 2 Wear debris after sliding

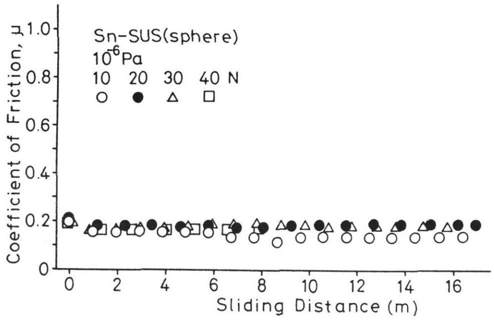


Fig. 14 A coefficient of friction in ultra-high vacuum of the order of 10^{-6} Pa at each load (Tin ; flat vs SUS ; sphere)

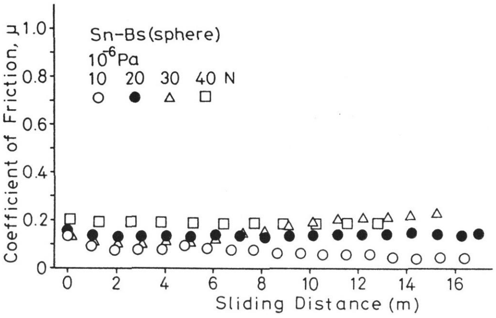


Fig. 15 A coefficient of friction in ultra-high vacuum of the order of 10^{-6} Pa at each load (Tin ; flat vs Brass ; sphere)

The comparisons of the friction in an ultra-high vacuum with one in an air are shown in figs. 16, 17, and 18. In the air even the combination like stainless against stainless to possess a good compatibility shows at first a low friction following a comparable high friction of the order 0.4–0.6 after much sliding. One of the reasons why the friction in the air reaches to one in an ultra-high vacuum with increase of sliding distance may be owing to the fresh surface generated by rubbing.

In the case that a hardness of a sphere is smaller than one of a flat specimen there is little difference of the coefficient of friction between two atmospheres after much sliding as shown in fig. 18.

Wear in an ultra-high vacuum

The wear in an ultra-high vacuum have been shown in fig. 19 and 20.

The wear amounts of flat specimens against a bearing steel and a stainless steel as sphere specimens have been measured by weighing. The combination such as a nickel against a stainless or a bearing steel, which showed a high friction as mentioned before, have shown also high wear rate because of good compatibility of a nickel to an alloy steel.

On the contrary, in the combinations with poor compatibility such as a brass against a stainless or an alloy steel they have not been worn out so much irrespective of their low hardness.

Accordingly we may say that the wear in an ultra-high vacuum will be governed mainly much more by the strength of an adhesive junction than by a hardness, and it seems to be one of the important factors to explain the wear mechanism. Rigid marks in fig. 20 show the results at air atmosphere.

CONCLUSION

Although we can not necessarily fully explain all the phenomena obtained here on friction and

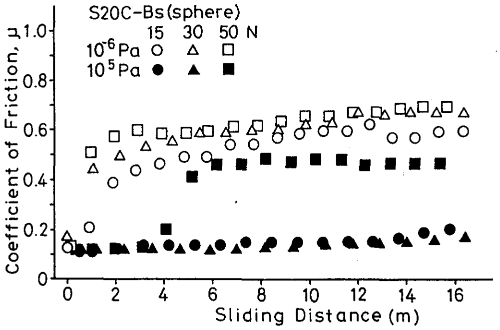


Fig. 16 The comparison of a coefficient of friction between in air and in vacuum of the order of 10^{-6} Pa at each load, (S20C ; flat vs Brass ; sphere)

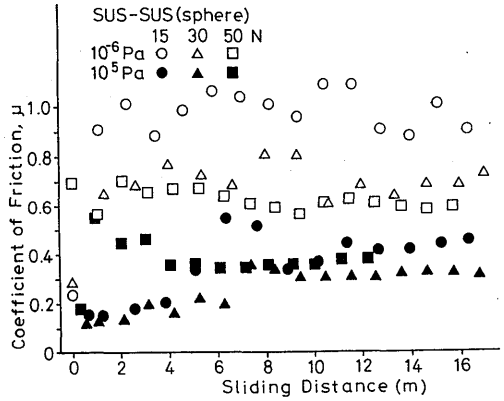


Fig. 17 The comparison of a coefficient of friction between in air and in vacuum of the order of 10^{-6} Pa at each load, (Stainless ; flat vs stainless ; sphere)

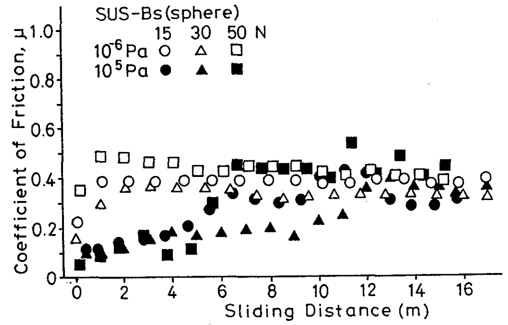


Fig. 18 The comparison of a coefficient of friction between in air and in vacuum of the order of 10^{-6} Pa at each load, (SUS ; flat vs Brass ; sphere)

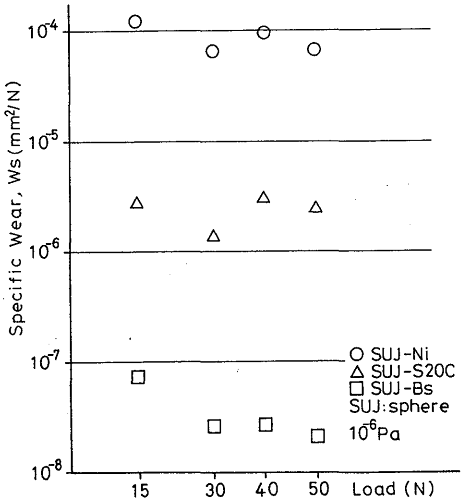


Fig. 19 Specific wear rate Ws (mm²/N) of Ni,S20C and Bronze against sphere SUJ at each load under a vacuum of the order of 10^{-6} Pa

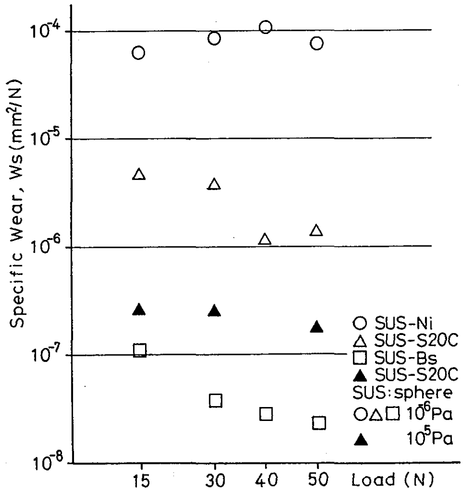


Fig. 20 Specific wear rate Ws (mm²/N) of Ni,S20C and Brass against sphere SUS at each load under a vacuum of the order of 10^{-6} Pa (a rigid mark only is one in air for comparison)

wear in an ultra-high vacuum, we summarize from the some experimental results above-mentioned as follows;

(1) If one hardness of the combined metals is much harder than the opposite one's, the high friction occurs by the junction growth due to a tangential force simultaneously with a normal load even in a vacuum of the order of 10^{-4} Pa.

(2) In the combination of metals with the high hardness in a vacuum of the order of 10^{-4} Pa the friction is not much harder than air atmosphere.

(3) Even in the combinations of metals with the high hardness the combination such as a steel against a non-steel of which elasticity modulus differ from each other shows a dissimilar friction between two atmospheres, namely in air and a vacuum so as to indicate the effect of elasticity and plasticity on the adhesion.

(4) In a vacuum of the order of 10^{-6} Pa the combinations of a steel against a steel and of a nickel against a steel with a good compatibility show high friction.

(5) In the case that one hardness differs from the other, the effect of the contact condition due to the shapes of both specimens on the friction is not negligible for a remarkable junction growth on flat surface and a ploughing term on a leading edge.

(6) Wear seems to be occurred extensively much more in a combination with a good compatibility than by the difference of the hardness.

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