An Experimental Study of Valve Seat Material Galling Characteristics in Waterworks

Sung-Jun Park[1,#], Young-Tae Kim[2] and Sang-Jo Lee[2]

1 Center for Nano Technology, Yonsei University, Seoul, Korea
2 School of Mechanical Engineering, Yonsei University, Seoul, Korea
Corresponding Author / E-mail: sung-jun.park@samsung.com, TEL: +82-31-218-2576, FAX: +82-31-300-7900

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Environmental contamination creates shortages of potable water. In such situations, the leakage of water due to breakage or aging of rubber valve seats is a serious problem. Rubber is apt to break when it is placed between two materials that contact each other. One way to avoid water leakage due to rubber damage and breakdown is to replace the rubber with metal, which is currently taking place in water distribution systems. In tribology, a severe form of wear is characterized by local macroscopic material transfer or removal, or by problems with sliding protrusions when two solid surfaces experience relative sliding under load. One of the major problems when metal slides is the occurrence of galling. Experimentally, various conditions influence incipient galling, such as hardness, surface roughness, temperature, load, velocity, and the external environment. This study sought to verify the galling tendencies of metal according to its hardness, surface roughness, load, and sliding velocity, and determine the quantitative effect of each factor on the galling tendencies.

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1. Introduction

Environmental pollution and the resulting shortage of potable water due to rapid industrial development has become one of the most serious problems in the world. Many dams have been built to control water shortage problems, but they do not provide fundamental solutions. Recently, the Environment & Labor Committee of the National Assembly proposed a revision of a legislative bill for waterworks. The purpose of this bill is to strengthen the management of water distribution systems because much of the water is currently used inefficiently. One of the proposed solutions to water shortage problems is to replace the rubber seats in butterfly valves, shown in Fig. 1, with corrosion-resistant metal seats because metal is more durable and stronger than rubber. The advantages of such a solution are investigated in this study by examining the galling characteristics of metal. The selected material is to be used in butterfly valve seats for practical industrial applications.

Rubber is apt to break when it used between two materials that contact each other, resulting in water leakage. According to the Ministry of Environment, the leakage of water from water supply facilities to a house is about 16% due to pipe damage. However, metal is more resistant to friction and pressure than rubber. Thus, it can be used longer and will reduce the amount of water leakage. In this study, the galling tendencies of a variety of material combinations were examined to determine whether a material combination exists with fewer tendencies for incipient galling.

Budinski[1] defined incipient galling as the early stages of surface deformation and adhesive interaction in metal-to-metal wear. Various galling experiments for different materials have been carried out. Budinski[1] reported that galling occurs in most metals and proposed using surface polishing and grinding processes to improve the resistance against galling. Schumacher[2] devised a straightforward way to measure galling using a Brinell test. Kawana et al.[3] made efforts to reduce corrosion, wear, and galling using CrN coatings to improve the critical wear, which could be represented when the Cr coating material was exposed to water for long periods of time. However, Sheldon[4] reported that although Cr coatings reduce galling, they can introduce a critical risk of wear in different external surroundings.

Leslie[5] tried to measure galling using a pressure cylinder, but his results were not reliable because of slow reactions and uncertain data. Considering this earlier study, the galling tests performed in this study were carried out using a three-axis machining center.

This study investigated the galling characteristics of different mating materials. The combination of materials most resistant to galling was selected by analyzing the results. The contact pressure and sliding speed were varied in these tests. Austenite series (STS304, STS316), ferrite series (STS444), martensite series (STS410A), and stainless alloys were used. The presence of chrome coatings on the testing material was also compared and analyzed.

2. Galling

The purpose of this study was to select metal mating materials that have anticorrosion properties and use them for practical valve seats. When metal seats contact, one of the possible serious problems is adhesion or wear, known as galling. ASTM defines galling as "a condition whereby excessive friction between high spots results in localized welding with subsequent splitting and a further roughening of rubbing surfaces of one or both of two mating parts.[6]"

Galling is the initial stage of adhesive wear and it can easily occur under non-lubricated or high pressure conditions. Galling causes surface plastic deformation, which is one of the most serious forms of wear. During galling, the magnitude of the load and the shape of the contact area determine the amount of contact between the two surfaces. Thus, galling can be controlled by surface treatments, loading, and the choice of material properties. A surface analysis of each metal material in the tests will help us better understand galling.

In this study, the difference between the static and dynamic friction force is used as the standard to determine the amount of galling. When galling first starts to occur under a given load, the surface pressure due to that load is defined as the threshold galling stress.

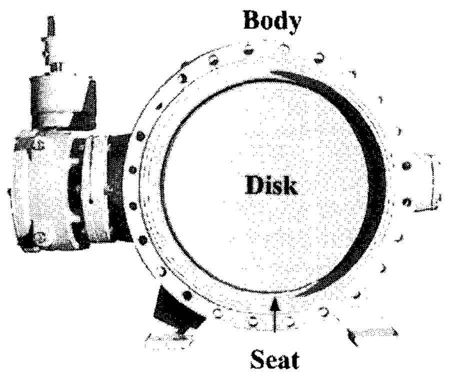


Fig. 1 View of a butterfly valve

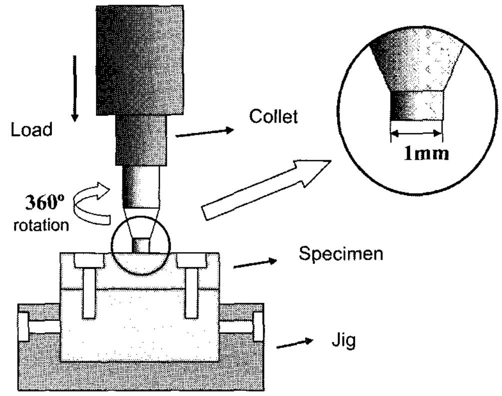


Fig. 2 Experimental setup for the galling tests

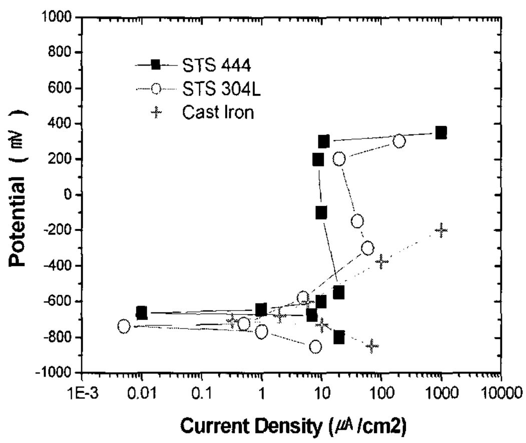


Fig. 3 Electrochemical anodic polarization test results

3. Experimental Procedure

3.1 Experimental setup

The experimental apparatus is shown in Fig. 2. A test plate was machined and fixed on the three-axis machining center. The test plate and pin, which was chucked into the collet of the spindle, were made from either the same or different material, depending on the material combination to be tested. A translation motion was initiated after the pin was rotated for one revolution under the various loading conditions. The tangential force was measured at the starting point and the surface quality of the initial contact area was observed after the relative motion was stopped.

During the sliding motion, static and dynamic friction forces were generated because of the friction and partial melting between the two materials.[7] A difference between the two friction forces generated galling. Thus, this difference was a primary factor when selecting the valve seat material. The test plates used in this experiment were machined by end-milling using the machining center to ensure they had the same roughness. After the experiment, the test plate was cut using wire EDM and the surface quality was analyzed under a SEM and an optical microscope.

3.2 Anticorrosion tests

The materials used in the anodic polarization tests were spherical graphite cast ion, 304L austenite stainless steel (Cr-8Ni-1.0Si-1.5Mn-0.02C), and 444 ferrite stainless steel (18Cr-2Mo-0.6Si-0.6Mn-0.02C). The test piece was ground using 600-grit SiC grinding paper and the concentration of the solution was 3.5 wt% NaCl at 35℃. The electropotential of the solution was increased in the anodic direction at a rate of 60 mV/min.

The results of anodic polarization tests are shown in Fig. 3. The relative electropotential order of the materials was STS 444, STS 304L, and cast iron. Because the seat material has better anticorrosion properties than cast iron, which was used for casting the valve body and disk, and the butterfly valve was rarely operated, every experiment was performed under dry lubricant conditions.

4. Results

4.1 Effect of hardness

4.1.1 Test description

The objective of this test was to apply a contact pressure and observe the amount of galling. The results were used as fundamental data for the effect of the load and sliding speed. STS304, STS316, and STS444 were used for the test pieces. Combinations with high galling tendencies were identified from these tests.

Galling starts when the contact pressure reaches approximately 100 kg/cm^2 (9.8 MPa) for stainless steel.[1] Therefore, these tests were performed under a pressure of 13 MPa while the sliding speed was fixed at 120 mm/min. The hardness of each sample is summarized in Table 1.

Table 1 Brinell hardness of specimens

Specimen	1st test	2nd test	3rd test	Average
STS 304	65.2	77.3	76.2	72.9
STS 316	78.8	80.8	82.4	80.7
STS 444	78.9	82.4	79.7	80.3

4.1.2 Remarks

The galling tendencies are shown in Fig. 4. Each result is the average of three measured data points. Combinations that included STS304, which was the softest material, had a very high galling tendency because its surface had the most cold welding or plastic deformation. Chemical attraction also had an influence when STS304 was used. An optical microscope was used to observe this phenomenon more precisely. The surface of STS 304 magnified 500 times is shown in Fig. 5. An unevenness of the surface is visible at the upper left corner of the photograph while the surface appears damaged at the center. The damaged region appears to have been caused from sticking due to melting. This photograph demonstrates the effect of cold welding.

The combination of STS316 and STS316 had no galling or chemical attraction, although the mating materials were the same. This result indicates that hardness has a greater effect on galling than chemical attraction. In other words, if the hardness of the material is high, galling does not occur because the effects of cold welding and plastic deformation are small.

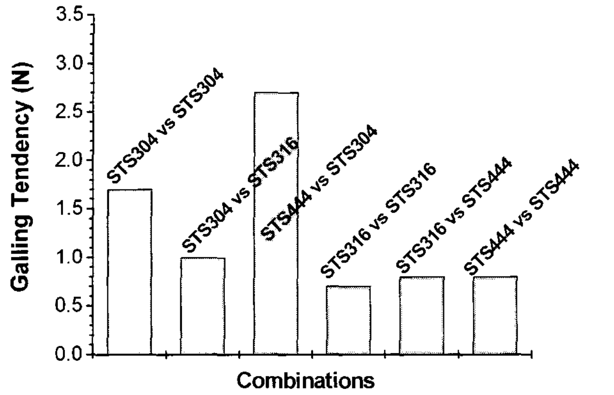


Fig. 4 Galling tendency for different material combinations

A surface that developed a seizure is shown in Fig. 6. As expected, significant deformation occurred, as well as marks that were torn by partial melting; *i.e.*, the hard pin (STS444) tore off comparatively less hard plate (STS304).

Fig. 5 Surface of the STS304 plate (pin: STS304)

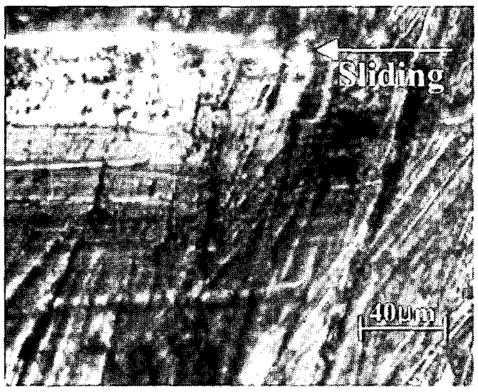


Fig. 6 Surface of the STS304 plate (pin: STS444)

4.2 Effect of surface roughness

4.2.1 Test description

The object of this test was to investigate how the surface roughness influenced galling. The applied load was 13 MPa, and the sliding speed was 120 mm/min. The plate was STS444 and the pin was STS316, the combination that had the smallest galling tendency.

4.2.2 Results

The galling tendency for different surface roughness values is shown in Fig. 7. As the friction force between the surfaces increased, so did the amount of surface galling.

Since the contact area increased, partial melting occurred over a larger area so that the galling tendency had a proportional relationship to the surface roughness.

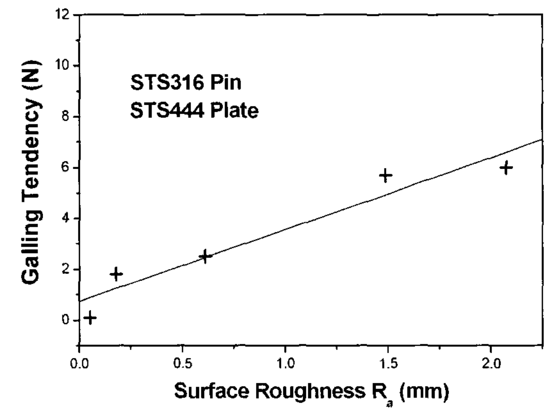


Fig. 7 Galling tendency with surface roughness

4.3 Effect of load

4.3.1 Test description

This test was used to determine which material combination had the largest critical galling stress. The critical galling stress can be used to determine the type of materials suitable for a given application. The samples included STS304, STS316, STS410A, STS444, STS410A (Cr coated), and STS444 (Cr coated) stainless steel alloys.

In the hardness tests, material combinations that included STS304 generated galling at pressures less than 13 MPa. Therefore, a pressure range from 6 to 32 MPa was used for the load tests. The maximum pressure condition was almost three times greater than the general critical galling stress of metal. The sliding speed was set to 120 mm/min.

4.3.2 Results of each combination

4.3.2.1 Combinations with STS304

Fig. 8 shows the galling tendency of various loads for combinations of STS304 plate and various pin materials. The STS304 pin and plate combination showed little galling up to 19 MPa, followed by a sharp increase in galling between 19 and 26 MPa. The STS410A pin combined with the STS304 plate exhibited a very strong tendency to generate galling.

This tendency increased sharply between 6 and 19 MPa and then increased more slowly between 19 and 26 MPa, so the surface was expected to change during the later range. To verify this result, the surface at 16 MPa, shown in Fig. 9, was analyzed under the SEM. An irregular deposit of material that differed from the original material was observed. Because Si, P, Cr, and Mn are common between the two materials, while Mo only exists in STS410A, whether a transition between the two materials occurred can be verified by analyzing the Mo content on the STS304 plate.

An EDS analysis of the plate surface is given in Table 2, which indicates that a combination of STS410A and STS304 will produce fatal damage at about 19 MPa.

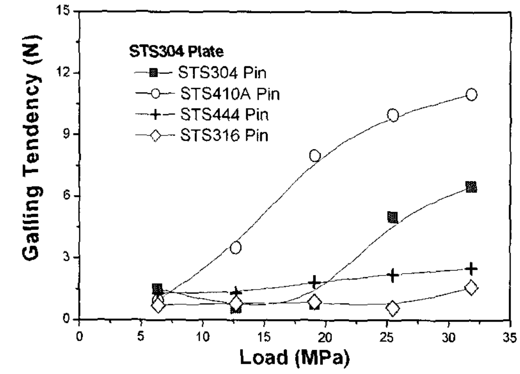


Fig. 8 Test results for the STS304 plate

Fig. 9 SEM image of the STS304 surface at 19 MPa

Table 2 EDS analysis of the STS304 surface at 19 MPa (pin: STS410A)

Element	Si	P	Cr	Mn	Mo	Total
Weight Percent	3.77	0.01	38.42	18.54	39.26	100

4.3.2.2 Combinations with STS410A

The test results for STS410A plate are shown in Fig. 10. The galling tendency was low at 19 MPa for all combinations because the melting material caused by the high partial pressure reduced the static friction force by providing a melting lubricant effect.

EDS analyses for STS410A at 13 and 19 MPa are listed in Table 3. The results indicate that the transition of N from STS444 to STS410A increased suddenly between the two loads.

SEM images of STS410A at 13 MPa and 19 MPa are shown in Fig. 11. The material is uniform in Fig. 11(a), but irregular deposits of a different material are visible in Fig. 11(b).

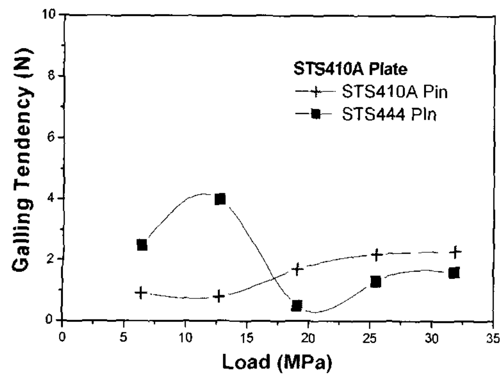


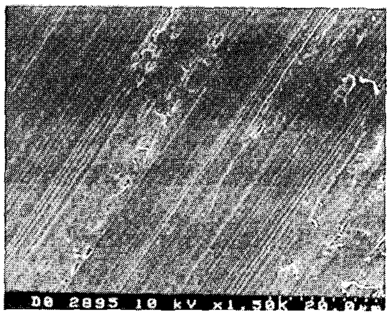
Fig. 10 Test results for the STS410A plate

Table 3(a) EDS analysis of the STS410A surface at 13 MPa (pin: STS444)

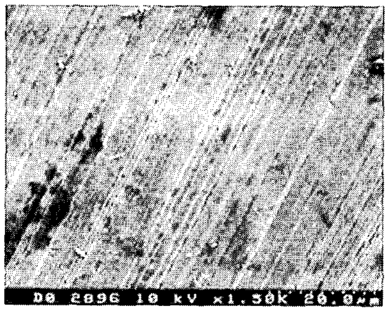
Element	N	Si	P	Cr	Mn	Total
Weight Percent	1.78	3.31	2.27	77.21	15.43	100

Table 3(b) EDS analysis of the STS410A surface at 19 MPa (pin: STS444)

Element	N	Si	P	Cr	Mn	Total
Weight Percent	10.57	5.19	2.29	67.98	13.97	100



(a) 13 MPa



(b) 19 MPa

Fig. 11 SEM images of the STS410A surface

4.3.2.3 Other combinations

Galling was not observed in other combinations except those examined in previous experiments. In particular, the coating material had a low galling tendency. Material transition was not observed when analyzing the surface.

4.3.2.4 Summary of results

The threshold galling stress for various combinations of material is shown in Fig. 12. If the galling tendency was high, the surface of the test sample showed similar changes.

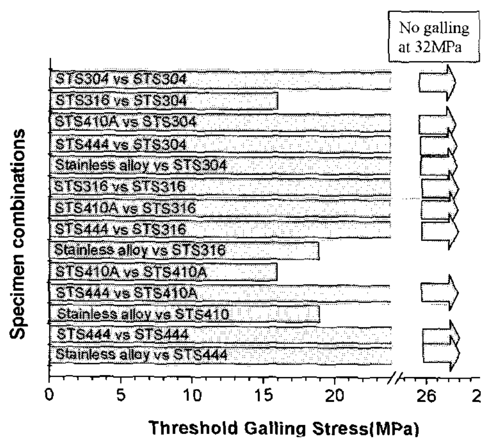


Fig. 12 Threshold galling stress

Thus galling, as defined in this study and the galling tendency were related to each other.

4.4 Effect of relative speed

4.4.1 Test description

Galling is affected by the sliding speed as well as load when water valves are opened and closed. This can influence the corrosion and transition of the materials. Therefore, the galling phenomenon was observed for various sliding speeds at constant load. The speed ranged from 60 to 2010 mm/min while the pressure was set at 26 MPa. This value is much higher than those found in practical applications. However, if no galling occurs under adverse conditions, the lifetime of the valve will increase under normal conditions. The load test results indicated that the test sample experienced substantial changes if the load exceeded 5 N. Thus, the threshold galling stress was set to 5 N in the speed tests.

4.4.2 Combinations with STS304 and STS410A

The tests were performed using 6 test samples and 18 combinations. The effect of the sliding speed on galling for the STS304 plate is shown in Fig. 13, while that for the STS410A plate, which contains a coating material, is shown in Fig. 14. The galling tendency for the STS304 plate combinations increased and then decreased with the sliding speed. However, for the STS410A plate, some combinations exhibited a continuously increasing galling tendency with sliding speed.

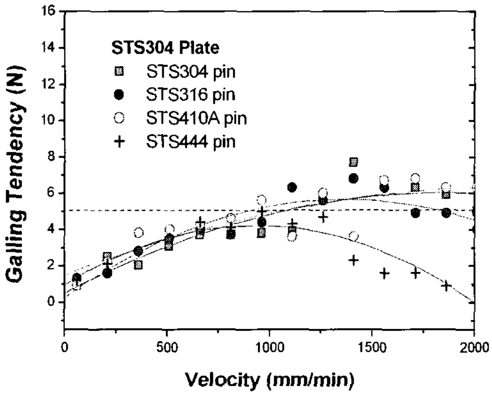


Fig. 13 Velocity effect on galling for the STS304 plate

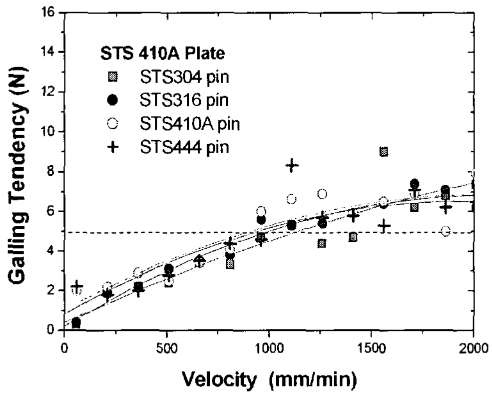


Fig. 14 Velocity effect on galling for the STS410A plate

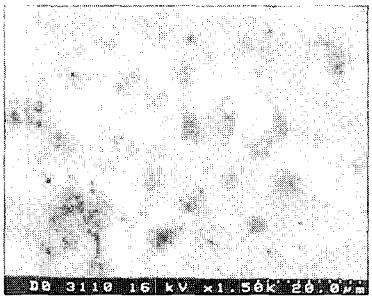
Table 4(a) EDS analysis of the STS410A surface before the test

Element	Si	P	Cr	Mn	Mo	Total
Weight percent	1.66	4.91	91.71	1.25	0.47	100

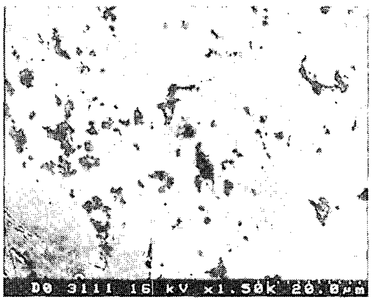
Table 4(b) EDS analysis of the STS410A surface after the test at a velocity of 960 mm/min

Element	Si	P	Cr	Mn	Mo	Total
Weight percent	1.77	1.85	83.82	0.94	11.62	100

SEM images of the STS410A (Cr coated) plate and STS444 pin combination are shown in Fig. 15 before and after the test. Before the test, the surface contained no other material, whereas a transition material was observed afterward. An EDS analysis, shown in Table 4, indicates that galling can be predicted from the sharp increase in the Mo that transitioned from the pin.



(a) before the test



(b) after the test

Fig. 15 SEM images of the STA410A surface for a test velocity of 1960 mm/min

4.4.3 Other combinations

The same tests were performed for other combinations to determine the range of critical velocities, shown in Fig. 16. This figure indicates the effect of velocity on galling and suggests a safe zone for practical applications.

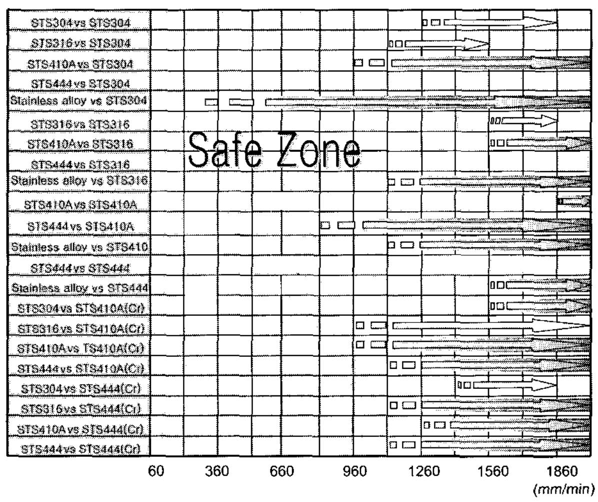


Fig. 16 Range of critical velocities

4.5 Discussions

After considering various galling factors, the combinations of ST316 and STS444, stainless steel alloy and STS444, and STS444 and STS444 have a high resistance to galling. The combination of STS444 and STS444, however, was judged inappropriate in terms of its mechanical contact area. In addition, the manufacturing productivity of STS444 is poor. Therefore, a combination of stainless alloy and STS304, which satisfied the load test, was selected as the best valve seat material. Although galling may occur for this combination under extremely high velocities, the load condition is more important than the velocity condition in water valves. Valve seats with this combination of materials are being produced, and they perform better compared to the existing product.

5. Conclusions

A suitable material for metal valve seats in water works systems was determined by analyzing the incipient galling tendencies of the mating parts. The load tests showed that the tendency of galling usually increased with the applied load. For some metal combinations, however, it decreased suddenly when partial melting occurred. Initially, the galling tendency was thought to increase sharply with the load when the same metal was used for both parts because of the influence of chemical attraction. However, the influence of hardness was more important than chemical attraction, and the magnitude of the load did not influence the amount of galling.

As the sliding speed increased, the galling increased and then decreased for some combinations, while in others it continuously increased. The former had a low or slowly reduced tendency to generate galling. These combinations had similar phases as those having a low tendency to generate galling in the load tests. Therefore, if the surface roughness was constant, the critical galling stress was a fixed quantity. The later combinations had a larger tendency to generate galling. If the speed exceeded a critical value, fatal damage could occur due to a perfect seizure. Although the presence of a transition material is not a measure of galling, transition deposits that depended on the sliding speed were observed on the plate surface.

The influence of the load was slight for the coated materials, but the influence of the sliding speed was severe. The damage characteristics and the tendency to generate galling depended on the properties of the metal and external conditions (*e.g.*, load and speed).

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