APPLICABILITY OF SURFACE PLASTIC FLOW PROCESS FOR MODIFICATION OF TRIBOLOGICAL PROPERTIES OF TITANIUM

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The present study proposes a novel surface modification process based on surface deformation, surface plastic flow process, to improve tribological properties of pure titanium (Ti) surfaces. The developed process consists of micro shot peening and roller burnishing: The former and the latter processes are applied to fabricate micro dimples and to penetrate molybdenum disulfide (MoS2) fine powders into the dimples. During the burnishing process, the surface was truncated and the penetrated MoS2 into the dimple was densified simultaneously. As a result, the treated surface was relatively flat and consisted of micro dimples filled with dense MoS2. Tribological properties of the treated surface were evaluated with a ring on disc type testing apparatus using a hardened steel ring as a mated specimen in lubricated condition. Results indicate that the tribological properties of the MoS2 penetrated surface have significantly improved including restriction of occurrence of seizure.

Keywords:
surface design, surface texture, solid lubricant penetration, surface plastic flow, shot peening, roller burnishing, tribology, titanium

1. Introduction

Titanium and titanium alloys are the candidate materials for mechanical components such as aerospace components requiring superior specific stiffness and strength [Boyer 1996]. In addition, the anti-oxidation properties are excellent; and titanium has been used in conventional mechanical components, such as bolts, nuts, and valves subject to sliding motion [Croccolo 2012]. On the other hand, lower thermal conductivity and higher reactivity have occasionally resulted in inferior tribological properties including seizure occurrence [Abdel-Aal 2009].

Coating is frequently used as the surface modification for reduction and stabilization of frictional resistance of titanium [Boving 1990]. Nitride and carbide coating having sufficient adhesion strength at the interface is an effective means to improve the tribological properties of titanium. However, the coating process required controlled environment and the specimen geometry was restricted. Although, the coating process of solid lubricant such as graphite [Miyoshi 2008] and molybdenum disulfide (MoS2) [Martins 2006] were also attempted, the adhesion strength was insufficient and the wear loss of the coating layer has frequently resulted in seizure occurrence of titanium. Therefore, development of a novel coating process for the solid lubricants is expected.

The present study proposes a surface modification technique to fabricate the solid lubricant film, based on surface plastic flow processes for improvement of tribological properties of titanium surfaces. The modified surface structure consisted of truncated titanium region and molybdenum disulfide (MoS2) layer densely filled into the micro sized dimples. The tribological properties were evaluated with a ring on disc type testing apparatus using a hardened steel as a mated material. Mechanism of the low and stable frictional resistance of the modified surface is discussed.

2. Experimental

2.1. Surface modification

A commercial grade pure titanium was used for the specimen. A disc shape, Ø 42 × Ø 20 × t9 mm was fabricated with turning. The following surface modification was carried out on the edge surface of the disc. The proposed technique of the surface modification consisted of micro shot peening and roller burnishing: The former and the latter processes are applied to fabricate micro dimples and to penetrate molybdenum disulfide powder (MoS2, 2 μm in size). During roller burnishing, truncation of the surface and densification of the MoS2 layer have occurred simultaneously.

An overview and a schematic of the micro shot peening apparatus and the impact media are shown in Fig. 1. Glass beads of 50 μm in size used as impact media were stored in the storage tank. Pulsed pressurized air was introduced into the tank through the inner tube of the double walled nozzle. Further acceleration of the glass beads was obtained by mixing higher pressure air from the outer tube at the tip of the nozzle. As a result, the flow rate and the impact velocity were possible to control individually by adjusting air pressure. The micro shot peening condition is listed in Table 1.

Outer tube gas pressure	Inner tube gas pressure	Nozzle distance
0.6 MPa	0.3 MPa	100 mm

Table 1. *Micro shot peening condition*

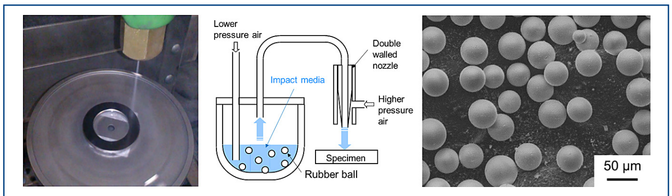

Figure 1. *Overview of micro shot peening process(left), schematic of apparatus (middle) and SEM image of impact media(right)*

Roller burnishing was carried out after the shot peening. An overview of the roller burnishing process is shown in Fig. 2. The roller material was fine-grained cemented carbide (WC-Co) with a diameter of 37mm and a tip radius of 4.5 mm. The roller was mounted to the tool post of a conventional lathe through the holder installed loading system and the contact load was applied with a pre-loaded coil spring. The roller burnishing condition is listed in Table 2.

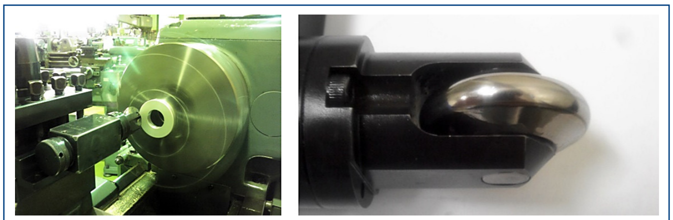

Figure 2. *Overview of burnishing process*

Contact load	Disc rotation speed	Feed rate of roller
25 N	550 rpm	0.44 mm/rev.

Table 2. *Roller burnishing condition*

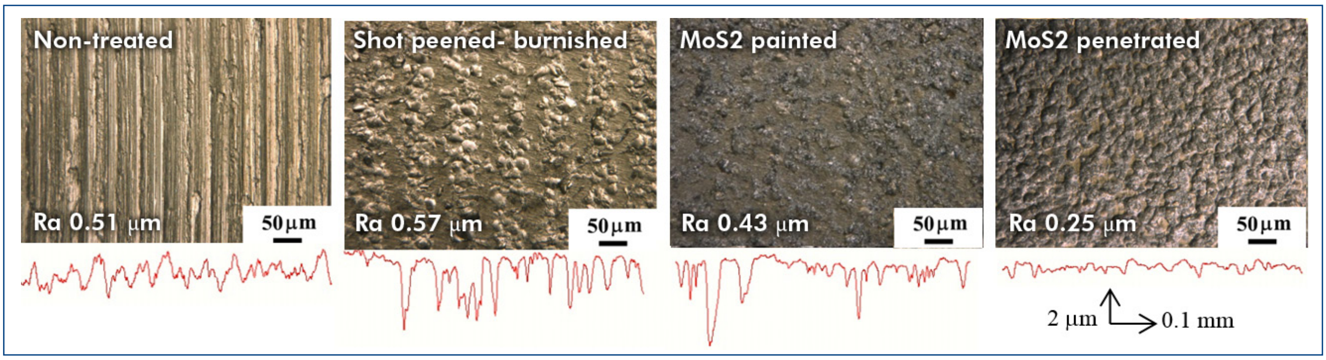

Fig. 3. *Optical micro image and surface profile of titanium disc surface treated with various conditions*

An optical micro-image and a surface profile of discs treated with various conditions are shown in Fig. 3. Periodical grooves having 2 μm of depth and 44 μm in pitch, corresponding to the feed rate of the turning condition were found on the non-treated surface. The grooves had disappeared by shot peening, and micro dimples of 15-25 μm in diameter covered the surface. After the roller burnishing process, the pile-up region at the edge of the dimple was truncated. As a result, a surface texture consisting of truncated dimples of 10-20 μm in diameter and 2-4 μm in depth was found on the shot peened-burnished surface.

MoS2was applied onto the surface after shot peening with different methods, painting and penetrating. In the former process, MoS2 powder suspended in ethanol was painted on the shot peened-burnished surface. When ethanol evaporated, MoS2 film was left on the surface. Although coated with MoS2 film, the surface profile showed that the micro dimples without MoS2still remained. In the penetration process, the ethanol with MoS2 was painted on the shot peened surface then the burnishing was applied. The surface profile of the MoS2 penetrated surface was relatively flat. To evaluate the densification of the MoS2 phase, a micro Vickers indentation was applied on the MoS2 phase at an indention load of 0.1 N. Expanded images of the impression are shown in Fig. 4. The painted MoS2 phase had disappeared and no impression was found. On the other hand, the impression was found on the penetrated phase. As a result, the densification of the penetrated phase was high enough to evaluate the hardness.

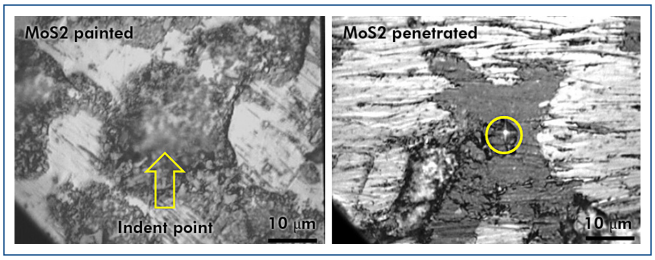

Figure 4. *Optical micro image of Vickers impression*

2.2. Apparatus for tribological properties

Evaluation of tribological properties with a ring on disc type testing apparatus is shown in Fig. 5. The disc specimen was mounted to a stationary shaft with a measurement device for friction torque. The ring specimen was fixed to a drive shaft located on the upper part of the apparatus. The mating specimen was a hardened steel containing 0.45 wt. % carbon (S45C, JIS), having a ring geometry of Ø 40 × Ø 30 × h15 mm and a Vickers hardness of 700 Hv. The testing surface was polished with diamond slurry less than 0.01 μm of arithmetical mean deviation of profile Ra.

The testing conditionsare listed in Table 3. The lubricant oil was supplied just before the experiment and was not replenished. After the oil supply, contact load with a dead weight was applied, and then the disc specimen was driven with a DC motor. The friction torque was measured with a device installed below the disc specimen. The experiment was carried out in laboratory air. The settled sliding distance was 2000 m and the experiment was interrupted when the rapid increase of the friction torque was detected. The experiment was carried out 3 times for each treated surface.

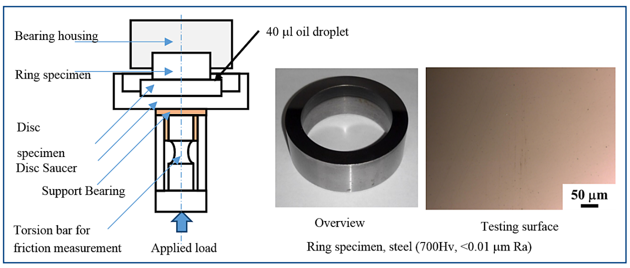

Figure 5. *Schematic of testing apparatus and mating ring specimen*

Applied load	Sliding speed	Sliding distance	Lubricant oil, PAO
10 N	1.0 m/s	2000 m	5cst@40°C

Table 3. *Testing condition for tribological properties*

3. Results and Discussion

3.1. Friction coefficient

The friction coefficient calculated from the measured friction torque as a function of sliding distance is shown in Fig. 6 for the nominal and the shot peened-burnished and in Fig. 7 for the MoS2 applied discs, respectively. The friction coefficient of the non-treated surface ranged from 0.3 to 0.5 and increased with

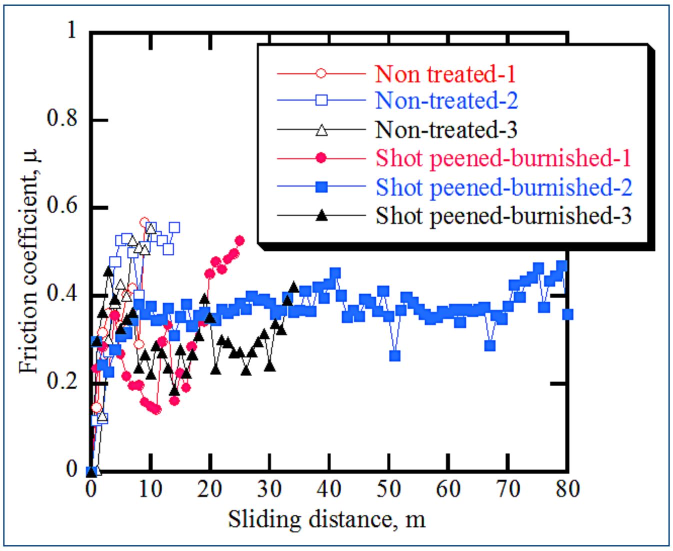

Figure 6. *Friction coefficient of disc surface without MoS2 as a function of sliding distance*

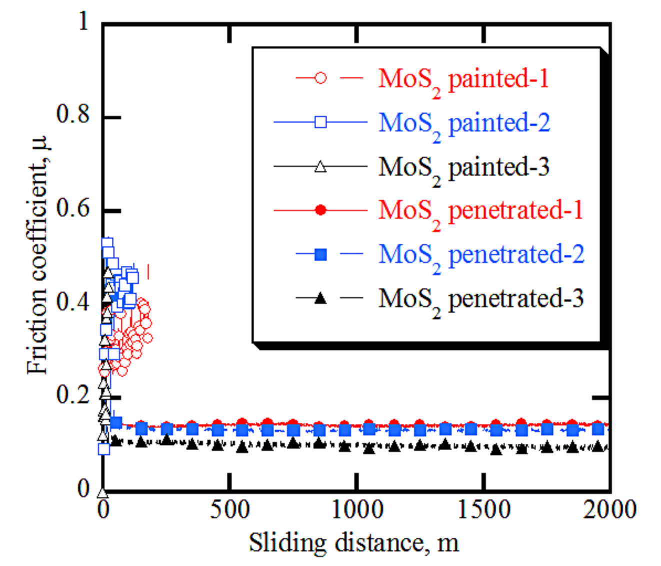

Figure 7. *Friction coefficient of disc surface with MoS2 as a function of sliding distance (Note that the range of the sliding distance was different to that of Fig. 6.)*

the increase in the sliding distance. The seizure accompanying with large noise occurred at less than 15 m of the sliding distance and the experiment was interrupted. The sliding distance up to the seizure of the shot peened-burnished surface was longer than that of the nominal surface. However, the friction coefficient ranged from 0.15 to 0.5 and the effect of the surface texture on the decrease of the friction coefficient was small.

The friction coefficient of the MoS2 painted specimen ranged from 0.2 to 0.5 and similar to those of the nominal and the shot peened-burnished discs and the sliding distance up to the seizure increased. On the other hand, the friction coefficient of the MoS2 penetrated surface was approximately 0.12 to 0.15 and stable during the experiment without seizure. Therefore, it was found that the friction properties varied according to the MoS2application process, and a significant improvement of the friction properties including seizure occurrence was obtained with the MoS2 penetrated disc.

3.2. Worn Surface Image and Profile

An optical micro-image and a surface profile of discs after the experiment are shown in Fig. 8. Comparing with Fig. 3, the surface morphology was different except in the result of MoS2 penetrated disc: Deep grooves were formed and micro dimples were eliminated. In addition, the painted MoS2phase had disappeared. In the MoS2 penetrated surface, grooves were shallow and the MoS2 phasehad still survived.

An optical micro-image and a surface profile of the ring after the experiment are shown in Fig. 9. Similar to the disc surface, the ring surface morphology was similar and the transferred region was formed except in the result mated with MoS2 penetrated surface. SEM/EDX analysis showed that the transfer region on the ring has resulted in the adhesion of the titanium. Because of the higher density, it is concluded that the penetrating MoS2 has sufficient adhesion strength against the stress acted at the interface between the ring and the disc during the experiment. Therefore, it is estimated that the survived MoS2 resulted in restrictingtransfer of titanium to the steel ring surface and that the friction properties became low and stable without seizure occurrence.

4. Summary

The surface modification technique based on the surface plastic deformation process consisting of micro shot peening and roller burnishing are proposed and applied to titanium disc surface. The treated surface consists of dispersed micro dimples filled with dense molybdenum disulfide phase and has relatively flat surface profile. The evaluation of tribological properties with a ring on disc type testing apparatus shows that the friction coefficient is lower and stable and that the sliding distance up to

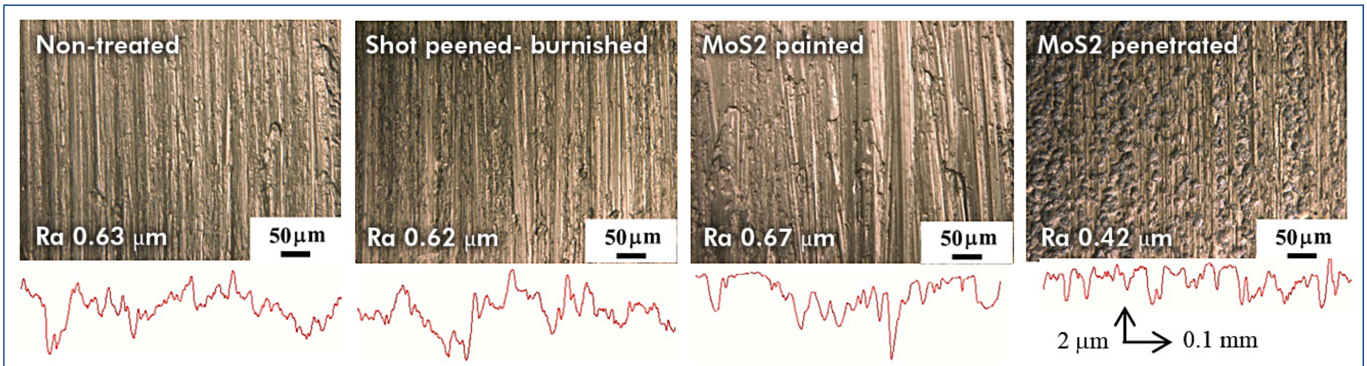

Figure 8. *Optical micro image and surface profile of discs after the experiment (The sliding direction corresponded from top to bottom of the image)*

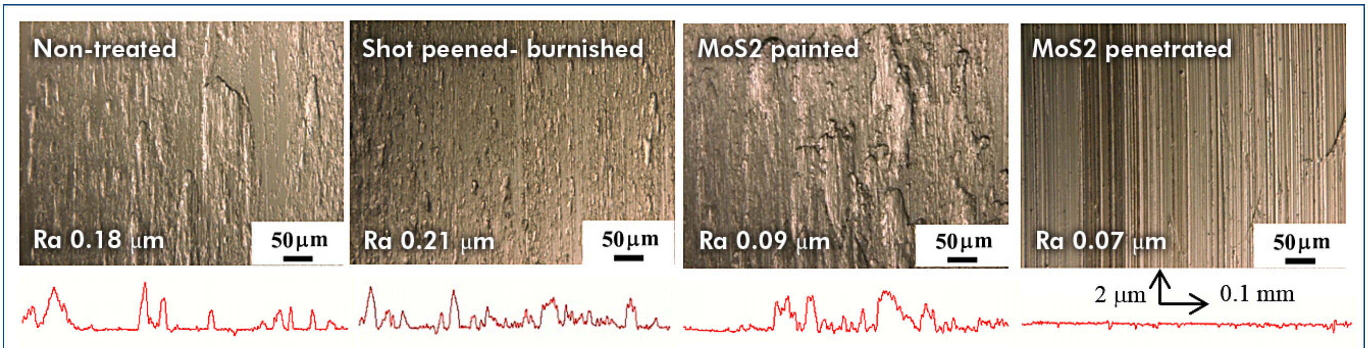

Figure 9. *Optical micro image and surface profile of rings after the experiment*

the seizure significantly increases. The penetrated molybdenum disulfide phase has survived after the experiment and the transfer of titanium on to the steel surface is small. Consequently, it is concluded that the surface plastic deformation process is an effective means for improvement of friction properties of titanium.

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