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Wear of metal/PTFE coatings in rolling line contact

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The paper presents results of an investigation to assess the performance of aluminium bronze coatings and molybdenum coatings both filled with PTFE and deposited on steel substrate in rolling line contact. The experimental results show that both types of coating studied have an outstanding wear and surface fatigue resistance. Under pure rolling conditions, the aluminium bronze coating was found to be more wear resistance than molybdenum coating. However, after 1.2×10^6 load cycles under the normal load of 36 N and 98 N, both coatings did not suffer any serious surface damage. Optical and scanning electron microscopy studies indicated that surface asperity peaks present in the coating supported the load. PTFE initially present in the coating was mainly lost due to a mild adhesive wear resulting in transfer film formation on the steel couter-surface. This, in turn, provided efective solid lubrication for the contact zone.

1. Introduction

Poly(tetrafluoroethylene) (PTFE) has been widely used as an engineering polymer mainly due to its chemical inertness, very low friction, and outstanding thermal stability. In contrast, PTFE shows high sliding wear when in contact with smooth surfaces and a pronounced cold-flow phenomenon under load. For these reasons, PTFE based composites containing reinforcing additives (metals and metal oxides) have emerged as a promising group of materials for applications where low friction and low wear are simultnaneously required. Sliding contact performance of these composites has been thoroughly investigated and a number of hypotheses explaining the role and action of fillers have been put forward. It is now widely accepted that fillers provide support for the external load acting on the contact and PTFE acts as a solid lubricant [1]. In this way a significant increase in wear resistance, comparing to pure PTFE, can be achieved. Also, it is believed that in sliding contact, adhesion of PTFE transfer film to the counter surface plays an important role in reducing wear rate of PTFE. Briscoe *et al.* [2] argued that inorganic fillers might reduce the wear of the polymer by increasing the adhesion of the first transfer layer to the counterface. Tanaka [3] showed that fillers significantly decrease the polymer wear by disruption of the banded structure of PTFE. The same effect can be achieved by rotating the contact area independently of main sliding motion, as reported by Briscoe and Stolarski [4]. Bowers *et al.* [5] and Steijn [6] demonstrated in their electron diffraction and TEM studies that the PTFE transfer films were produced due to slippage between crystalline slices of banded structure of PTFE and were oriented in the sliding direction [7]. Gong *et al.* [8] established that there is a chemical reaction between the transfer film of PTFE and steel substrate but they found no apparent link between the effect of chemical binding and the wear rate of PTFE. Similar findings were reported by Senior *et al* [9]. The tribo-chemical reactions between zinc filled PTFE, produced by moulding and sintering technique, and steel or aluminium counter surfaces were also studied using a pin-on-block reciprocating sliding contact [10]. However, no clear correlation between an increase in adhesion of the PTFE based composite to a substrate and the wear reduction was established. It was also suggested that under friction conditions, instead of carbon, fluorine atoms in PTFE chain are responsible for the chemical reaction with metal substrate as suggested by Buckley [11, 12]. Pratt [13] and later Gong *et al.* [8] observed that the wear rate

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of PTFE is beneficially affected by inorganic fillers such as Mo, Zn, SE, Ni, Y_2O_3, and SiO_2 by a factor of nearly 1000 with no increase in friction coefficient. The PTFE composites used in space applications contain additives such as Mo, Ag, bronze, and MoS_2. Minami *et al.* [14] reported that PTFE-Mo composites show outstanding performance in preventing surface damage despite coefficient of friction around 0.6 to 1.0. This behaviour is attributed to an in-situ formation of metal fluoride during which Mo acts as a catalyst in the transfer film formation process [15].

The PTFE based composites find increasing application in hybrid rolling contact bearings with silicon nitride ball for space shuttle turbo-pumps, high-speed vacuum pumps and jet engines [15]. However, the systematic information on the performance of PTFE based composites in rolling contact is not readily available in the open literature. Therefore, the main objective of the studies presented in this paper was to ascertain the performance of PTFE incorporated into aluminium bronze and PTFE incorporated into molybdenum coatings in rolling dry contact.

2. Experimental methods

The surface fatigue induced wear was investigated using two-disc test apparatus shown, schematically, in Fig. 1. The driving disc had diameter of 150 mm and thickness of 10 mm. The disc was made of a hardened steel its periphery surface was finished to required roughness. The driven disc, with 50 mm diameter and 4 mm thickness, was made of a mild steel and its circumference was coated by PTFE based composite.

Firstly, a dense layer of metallic undercoat of thickness approximately 200 μm was deposited onto the sand blasted circumference surface of the low carbon steel disc using an atmospheric plasma process. The size of Mo particles was in the range from 45 to 90 μm while the size of aluminium bronze particles was between 45 and 125 μm. The chemical composition of aluminium bronze powder used for coating was as follows: 89 wt% Cu, 10 wt% Al and 1 wt% Fe. A relatively porous second metallic interlayer of about 100 μm in thickness was deposited onto the dense undercoat. Finally, PTFE was sprayed onto the interlayer and filling in all the surface pores.

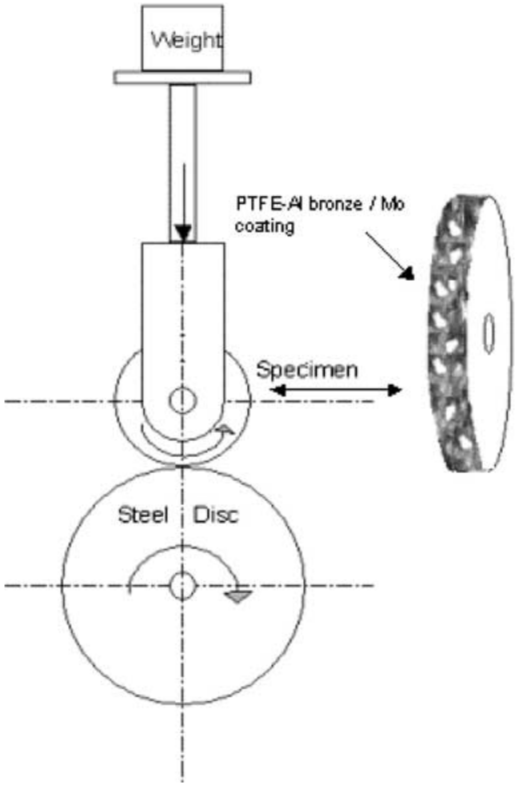


Figure 1 Schematic representation of the apparatus and the coated test disc.

The coated discs were tested at a constant rotational speed of 180 rpm for 1.2×10^6 load cycles in ambient condition, i.e., temperature of 20°C and relative humidity of 50%. One full revolution of the coated disc corresponded to one load cycle applied to a point on the periphery surface. The load on contact, applied as a dead weight, was constant throughout the testing programme at 36 N or 98 N. Prior to testing, the surface roughness measurements and optical microscopy observations of coatings were carried out. Before each test the surface of the steel driving disc was polished to a roughness of approximately 0.03 μm using a set of diamond polishing compounds. Tests were interrupted at regular intervals to examine the coated surface for cracks and signs of damage. Surface profilometry was used to measure the changes in topography after every 0.5×10^6 load cycles at eight different locations along the periphery of the disc. Post-test microscopy examinations of coated surfaces were conducted to determine the nature of the damage. The wear rate was measured by weighing the coated disc and debris, if formed. For both loads on the contact, testing was repeated and the recorded weight changes averaged. A variation of not more than about 10% in wear magnitude was observed under nominally the same contact conditions.

3. Results and discussion

Figs 2 and 3 show the effects of the number of load cycles on the wear rate of the PTFE-aluminium bronze and PTFE-Mo coatings during pure rolling. It can be seen that the wear of the PTFE-aluminium bronze coating is quite low at the load of 36 N. After an initial wear of about 2 mg during the first 2×10^5 load cycles, which could be attributed to a running-in process, the wear rate remained very low until 1.2×10^6 load cycles were reached. At that stage the total wear was about 3 mg for the PTFE-aluminium bronze coating. However, the total amount of wear for the PTFE-Mo coating was about three times higher than that of the PTFE-aluminium bronze coating. In the case of the PTFE-aluminium bronze coating, the maximum amount of wear was attained after about 2×10^5 load cycles. Afterwards, the wear decreased steadily. In contrast, the maximum wear for the PTFE-Mo coating was reached after approximately 3×10^5 load cycles and the minimum wear occurred at 4×10^5 load cycles. Afterwards, the wear rate remained almost constant until a marked decrease occurred at about 1.1×10^6 load cycles. Under the load of 36 N, both coatings attained a minimum wear at 1.1×10^6 load cycles.

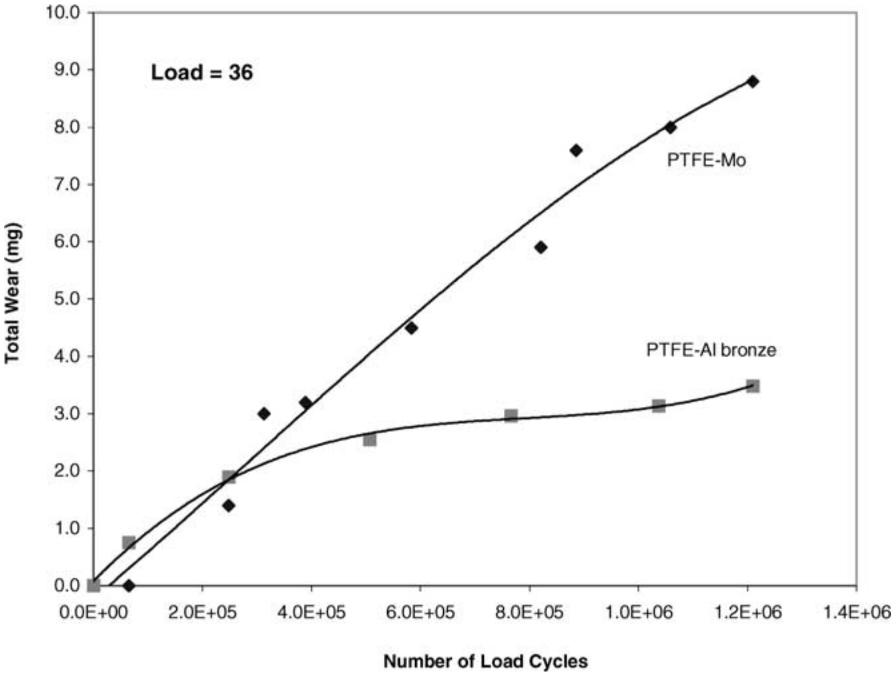


Figure 2 Variation of total wear as a function of number of load cycles at 36 N.

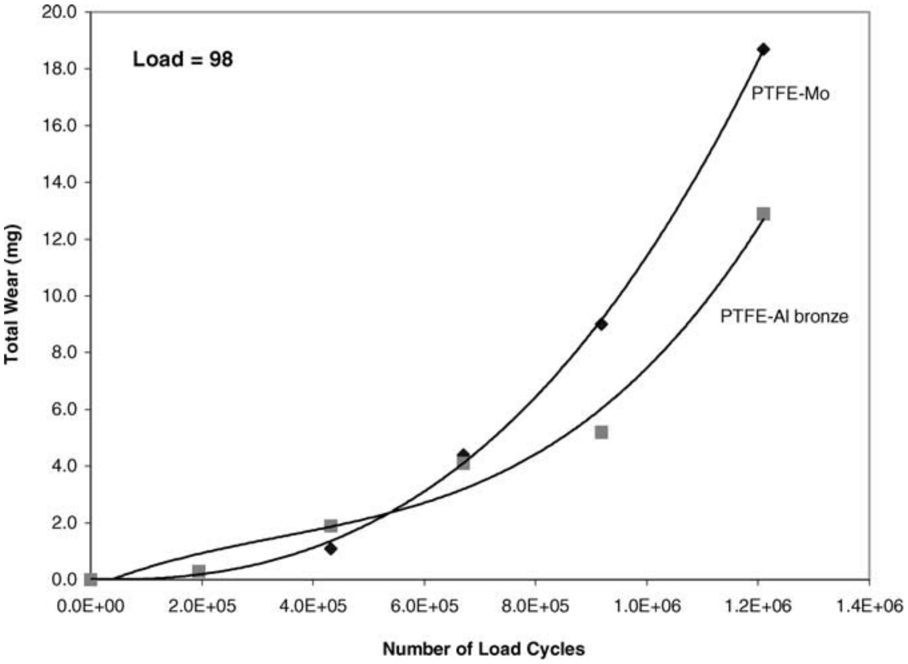
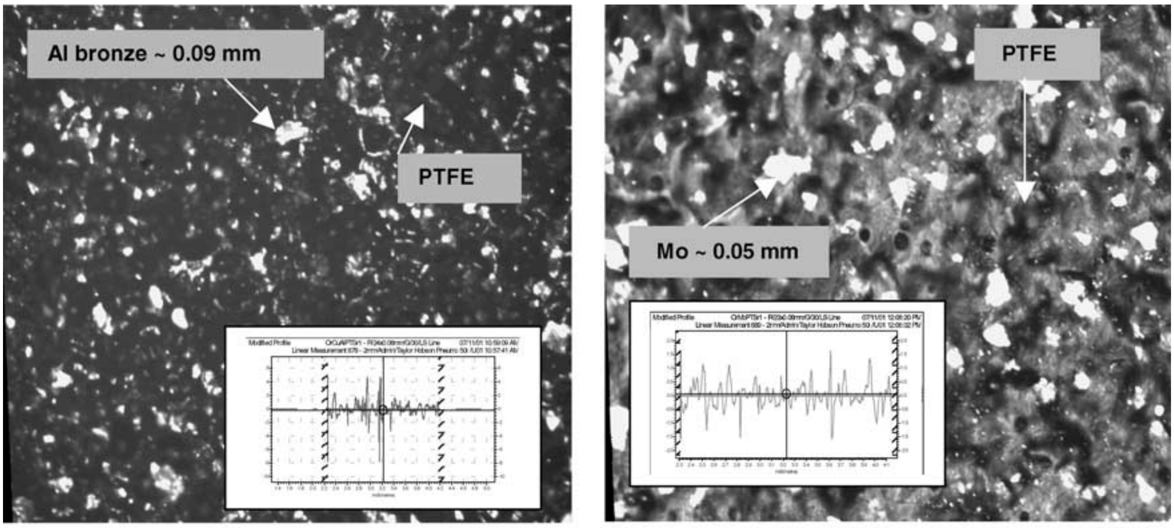


Figure 3 Variation of total wear as a function of number of load cycles at 98 N.

At the load of 98 N, the wear of both coatings was, in general, low at the beginning of testing. After 5×10^5 load cycles the wear rate was about 2 mg. After that the wear was increasing steadily with almost a constant rate. When 1.2×10^6 load cycles was reached, the total wear amount of the PTFE-aluminium bronze and the PTFE-Mo coatings were approximately 13 and 19 mg respectively. However, the wear increase caused by the increase in the load on contact from 36 N to 98 N was higher for the PTFE-aluminium bronze coating. This might be attributed to the difference in hardness between aluminium bronze and molybdenum, a factor of significance especially under higher load on the contact.

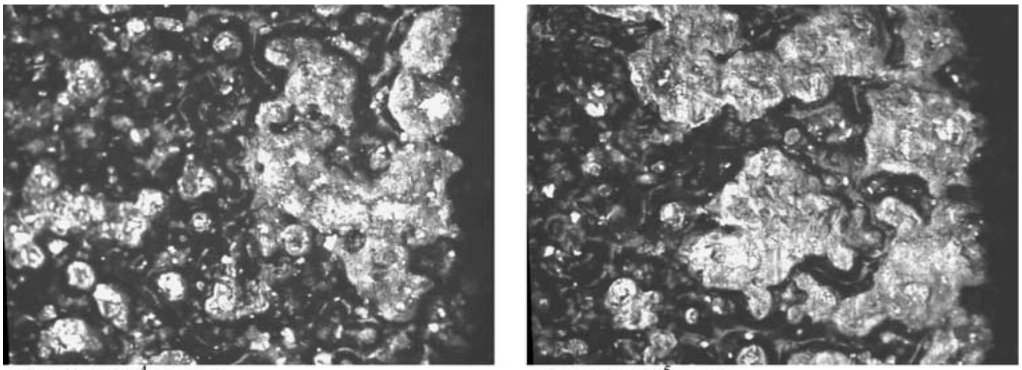
These results highlight the fact that aluminium bronze particles in the porous coating had a more beneficial effect in decreasing the removal of PTFE from the matrix than molybdenum particles. Micrographs showed in Fig. 4 depict the surfaces of original PTFE-aluminium bronze and PTFE-Mo coatings. The surface roughness values for aluminium bronze and molybdenum undercoats were 2.07 μm and 1.6 μm respectively. These values ultimately affected the final surface roughness after application of PTFE. The surface roughness of the PTFE-aluminium bronze coating was $\mathrm{Ra} = 0.86$ μm and that of PTFE-Mo coating was equal to $\mathrm{Ra} = 0.36$ μm. It is apparanet that the rolling resulted in eliminating the highest surface asperities and



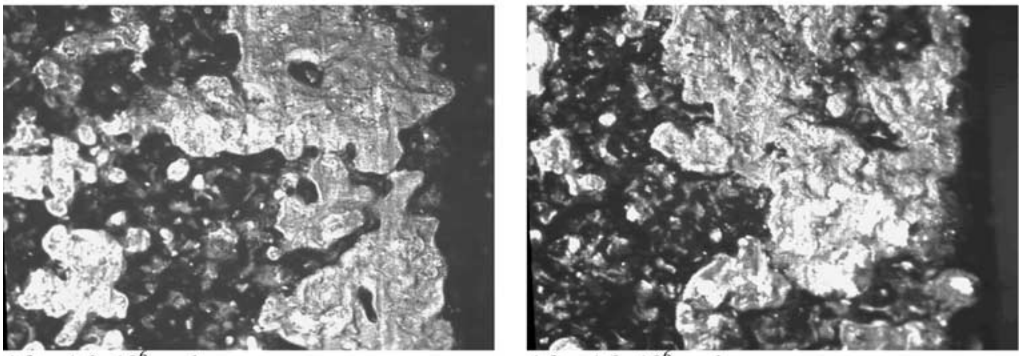
(B)
(Ra=0.86)

(A)
(Ra=0.36)

Figure 4 Photomicrographs and surface profiles of original PTFE-All bronze and PTFE-Mo coating.


After 6.5×10^4 cycles

After 7.7×10^5 cycles

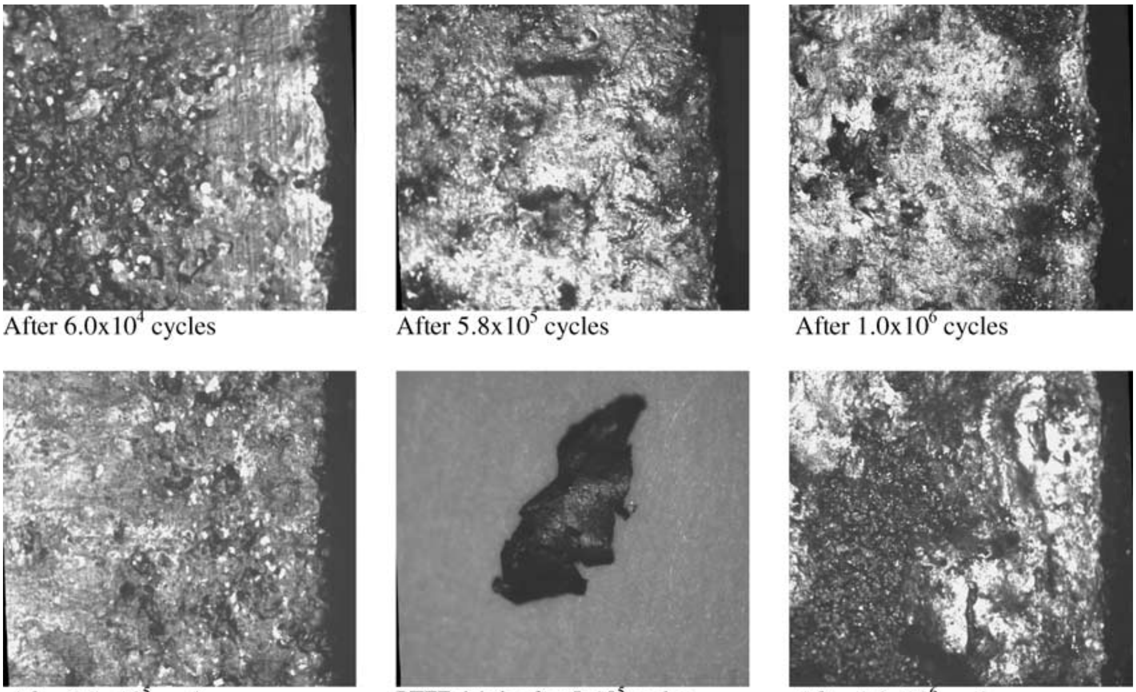

After 1.0×10^6 cycles

After 1.2×10^6 cycles

Figure 5 Photomicrographs of PTFE-Al bronze coatings in rolling line contact under 36 N for various load cycles.

smoothing the undercoat. At the same time, the highest surface asperities provided support for the load applied to the contact (see Figs 5 and 6). Consequently, PTFE regions around asperity peaks were shielded and did not come into direct contact with the counter surface. This seems to be especially true for the PTFE-aluminium bronze coating (Fig. 5). Fig. 6 shows the changes in coating surrface appearance as a function of the number of load cycles. As can be seen the surface of the PTFE-Mo coating, which was initially smoother, underwent a mild adhesive wear just after 5×10^5 load cycles at the load of 36 N due to increased expose of PTFE to the contact with the counter curface.Fig. 6 also illustrates the debris forms due to detachment of PTFE transfer film from the counter surface. A typical size of wear particle is 0.8 mm in length and 2–3 μm in thickness. A fresh transfer film was continuously formed and the old one removed from the counter surface as debris. In case of the PTFE-aluminium bronze, the transfer film remained on the counter surface and, perhaps, a reverse transfer from the counter surface to the coating surface took place as no debris were formed.

It was also noticed that, under the load of 36 N, there were no metallic particles in wear debris for both



After 6.0x10^4 cycles

After 5.8x10^5 cycles

After 1.0x10^6 cycles

After 3.1x10^5 cycles

PTFE debris after 5x10^5 cycles
Size range ~ 0.30-0.8 mm
Aspect ratio ~ 0.35

After 1.2x10^6 cycles

Figure 6 Photomicrographs of PTFE-Mo coatings in rolling line contact under 36 N for various load cycles.

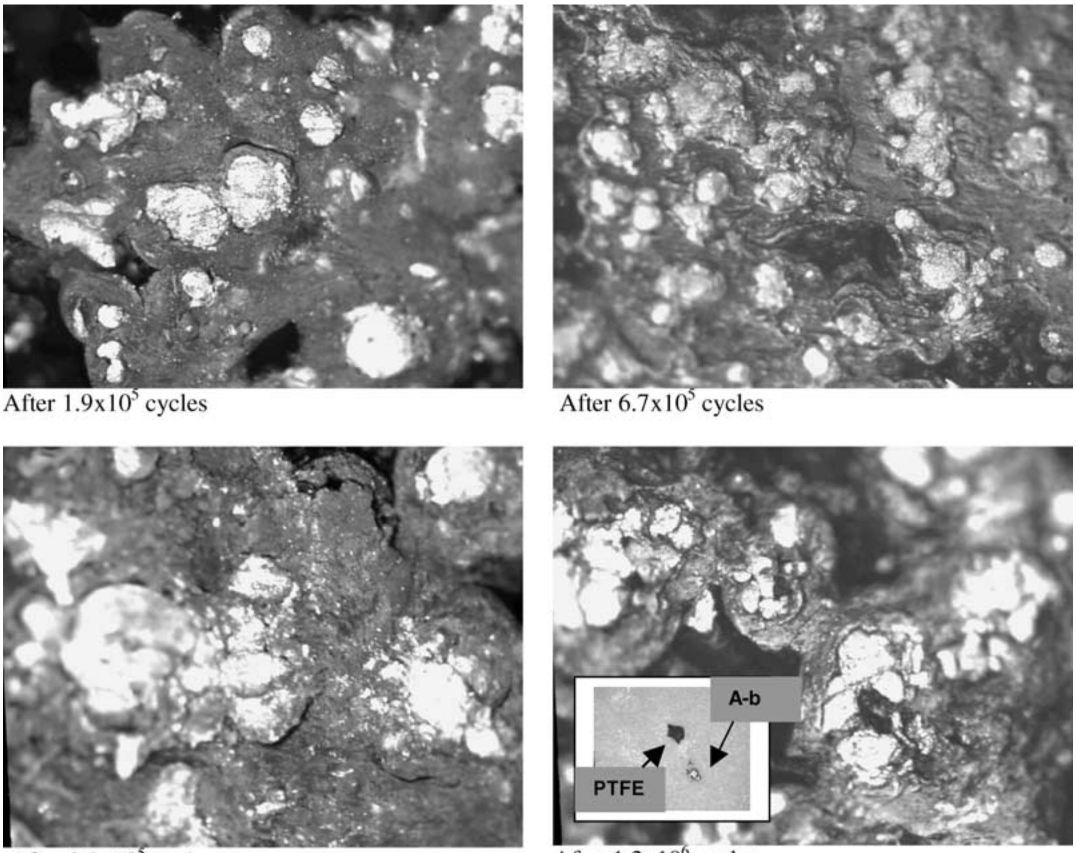
PTFE-aluminium bronze and PTFE-Mo coatings through the whole test duration of 1.2×10^6 load cycles. It is believed that the transfer film of PTFE played a major role in providing required solid lubrication. Gong *et al.* [8] reported that in their study concerning wear of PTFE sliding against steel, iron fluoride was formed at the interface between transfer film formed by PTFE-Cu composite and steel counter surface. They argue that the formation of iron fluoride was an evidence of a strong adhesion of the transfer film to the counter surface with Cu atoms acting as a catalyst. This might be used to explain why, in the present study, there was a strong film formation for the PTFE-aluminium bronze coating. After reaching a steady state, the transfer of PTFE was occurring in both directions, that is from the coating to the counter surface and back. It is quite possible that iron fluoride was formed within the contact due to copper rich aluminium bronze particles resulting in the formation of a stable film on the counter surface.

Visula observations also revealed that the transfer film was formed after 3.2×10^4 load cycles for PTFE-aluminium bronze and PTFE-Mo coatings at the load of 36 N. However, first PTFE debris were observed for the PTFE-Mo coating after 3.8×10^5 load cycles. No debris formation was observed for the PTFE aluminium bronze coating until 1.2×10^6 load cycles were attained. At the load of 98 N, first visible transfer film was formed after 1×10^4 to 2.2×10^4 load cycles and first wear debris were noted after 5×10^5 and 2.5×10^5 load cycles respectively for the PTFE-aluminium bronze and PTFE-Mo coatings.

The above findings suggest that the presence of harder molybdenum particles in rolling contact resulted in the peeling off of the transfer film of PTFE. This could be due to a weak adhesion of the transfer film formed by the PTFE-Mo coating to the counter surface even though some researchers [13, 14] found that a metal fluoride was formed during sliding/rolling process and molybdenum acted as a catalyst. Gong *et al.* [8] on the other hand suggested that poor adhesion of the transfer film formed by the PTFE-Mo composite was probably due to the presence of molybdenum oxide.

Figs 7 and 8 contain photomicrographs of the PTFE-aluminium bronze and PTFE-Mo coatings taken after achieving various numbers of load cycles under the load of 98 N. These photomicrographs clearly indicate that the transfer of PTFE from the coating to the steel counter surface was intensified as the load increased to 98 N. The wear due to the transfer of PTFE started at the very early stage. This took the form of peeling off of very thin layers of PTFE from around the metallic asperities within the contact area, which were exposed after a relatively short time. As a result of that, a blistered surface was formed and the transfer film was created on the counter surface. As shown in the photomicrographs, wrinkles appeared in PTFE at the early stage of the test followed by surface cracks in PTFE regions around the metallic grains. Subsequently, these cracks resulted in pit-like formations in PTFE and in some cases metallic grains were occasionally pulled out from the coating (see Fig. 7). There were no metallic particle losses from the PTFE-Mo coating although there was a continuous production of PTFE debris leaving some metallic grains as isolated islets (see Fig. 8). Overall, the PTFE-aluminium bronze coating was found to be more wear resistant than the PTFE-Mo coating under the load of 98 N. This is most probably due to the similar mechanism suggested for the wear process under the load of 36 N.

Fig. 9 shows the wear rates, expressed as weight loss per load cycle, for the PTFE-aluminium bronze and PTFE-Mo coatings as a function of load. It is quite



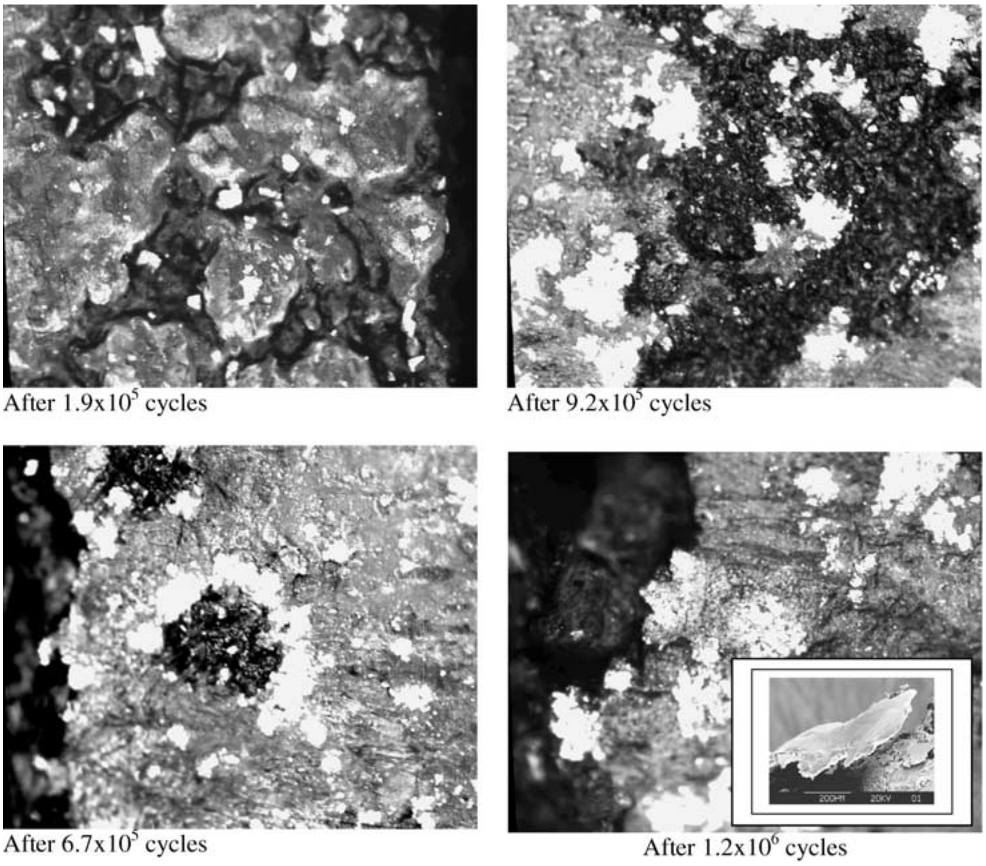
After 1.9×10^5 cycles

After 6.7×10^5 cycles

After 9.2×10^5 cycles

After 1.2×10^6 cycles,
PTFE debris, size range 0.18-0.28 mm
aspect ratio ~ 0.6
(A-b) Al bronze debris, size range 0.09-0.13 mm
aspect ratio ~ 0.7

Figure 7 Photomicrographs of PTFE-Al bronze coatings in rolling line contact under 98 N for various load cycles.



After 1.9×10^5 cycles

After 9.2×10^5 cycles

After 6.7×10^5 cycles

After 1.2×10^6 cycles

Figure 8 Photomicrographs of PTFE-Mo coatings in rolling line contact under 98 N for various load cycles.

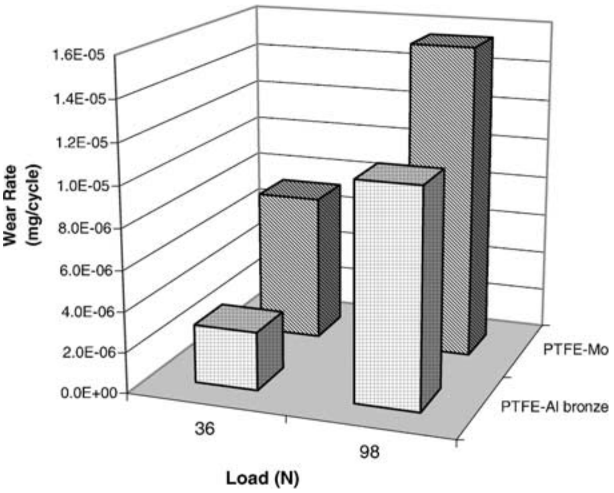


Figure 9 Variation of wear rate with coating type and load.

clear that the PTFE-alumininum bronze coating outperformed the PTFE-Mo coating under both 36 N and 98 N loading.

4. Conclusions

The results of studies presented in this paper allow the formulation of the following conclusions.

(i) PTFE-aluminium bronze and PTFE-Mo coatings were found to be remarkably wear and surface fatigue resistant and able to retain their service life over the period of 1.2×10^6 load cycles.

(ii) Wear rates of the PTFE-aluminium bronze coating were lower than wear rates of the PTFE-Mo coating under test conditions applied.

(iii) Microscope examinations showed that the wear was mainly due to the transfer of PTFE film from the coating to the counter surface.

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