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Tribological performance of Zinc soft metal coatings in solid lubrication

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Abstract. Solid lubrication by soft coatings is an important technique for superior tribological performance in machine contacts involving high pressures. Coating with soft materials ensures that the subsurface machine component wear decreases, ensuring longer life. Several soft metal coatings have been studied but zinc coatings have not been studied much. This paper essentially deals with the soft coating by zinc through electroplating on hard surfaces, which are subsequently tested in sliding experiments for tribological performance. The hardness and film thickness values have been found out, the coefficient of friction of the zinc coating has been tested using a pin on disc wear testing machine and the results of the same have been presented.

1. Introduction

Certain solid materials when used as lubricants reduce coefficient of friction and wear of rubbing parts by preventing direct metal-to-metal contact between their surfaces even under high loads. Solid lubricants are applied in different ways including coating as a thin layer applied on one of the surface (normally tool in case of metalworking). Alternative methods are application in powder form to the contact area or as additive in a base oil. Metals chosen as solid lubricants normally have very low shear strength coupled with high compressive strength (so that it can take high loads) and good adhesion properties. Solid lubricants combine many advantages in comparison to liquid lubricants and these advantages include the ability to work under high loads, high thermal stability and offering multiple ways of application. Solid lubricants are available in a variety of forms, prominent among which are the lamellar solids, soft metals, organic lubricants and soaps. Among them, soft metals have not been explored sufficiently in literature for their lubricating properties. The metals so far most tried as soft coatings are lead, tin, bismuth, indium, cadmium and silver, which were used in the form of coatings obtained by one of the methods of electroplating, vapour deposition and thermal spraying. Electroplating route is the most inexpensive of all and hence this is the method used in the present work while zinc was chosen as the soft metal for solid lubrication. Earliest works on soft metal coatings identified that the relative shear strengths of soft metal coating to substrate, coating thickness, surface roughness and environmental influence on oxidation coating were identified as important parameters and that there is an optimum thickness of coating at which the friction coefficient is minimum [1-3]. Soft coating metals that were investigated so far for tribological applications are lead [1,3-9], silver [10-13], gold [1, 14-16], indium [1,3], nickel [2, 17-20], chromium [17], copper [13, 22] and cadmium [1].

Zinc is one of the most widely available and inexpensive metal available on earth whose solid lubrication properties have not been sufficiently studied in literature. Zinc coatings also impart excellent corrosion resistance to bulk metals in storage and if it can offer also superior tribological performance in solid

coated form, it can be of immense attraction. Hence, the tribological performance of zinc-coated surfaces has been investigated in this paper.
Solid lubricant coatings offer several advantages over liquid lubricants including potential for usage in vacuum, in low as well as high temperature environments, at low speeds of sliding, in radiation environment with little flammability and resulting in less environmental risks and lesser contamination [1].

2. Shear mechanics of soft metal coatings

Soft metallic coatings on relatively harder substrate lubricate by undergoing shear deformation and thus prevent the need for higher strength substrate to shear in order for sliding to occur against the harder tool (Fig-1).

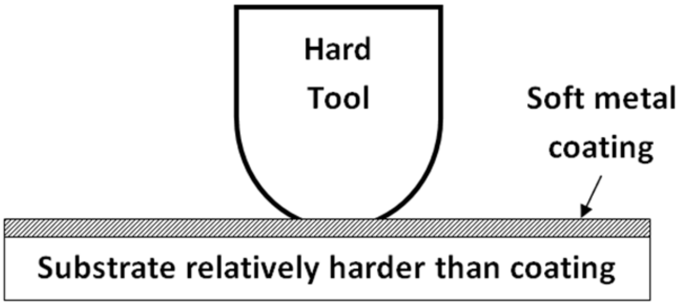


Figure 1. Mechanics of soft metal coating in tribological performance.

Mathematically, the coefficient of friction can be expressed as in equation (1) assuming that shearing of the soft metal coating exclusively contributes to friction and that the other mechanisms namely, ploughing and presence of third body including oxide layers or any aqueous (liquid) depositions can be neglected [1].

$$\mu = \frac{F_s}{N} = \frac{(\tau_s)(A_r)}{(H)(A_r)} = \frac{\tau_s}{H} \tag{1}$$

Generally, graphite and molybdenum disulphide (MoS_2) are predominantly used as solid lubricant. In the form of dry powder, these materials are effective lubricant additives due to their lamellar structure. The lamellas orient parallel to the surface in the direction of motion. Even between highly loaded stationary surfaces the lamellar structure is able to prevent contact. In the direction of motion the lamellas easily shear over each other resulting in a low friction. Large particles best perform on relative rough surfaces at low speed, finer particle on relative smooth surface and higher speeds. Other components that are useful solid lubricants include boron nitride, titanium nitride, polytetrafluoroethylene (PTFE), talc, calcium fluoride, cerium fluoride and tungsten disulphide. Sufficient study has been made on the tribological performance of these coatings and the results can be found in some standard texts [1].

3. Coating of zinc on specimen

In the present work, sliding experiments on zinc-coated aluminium and mild steel surfaces were carried out using the standard pin-on-disc experimental test rig. The coatings were produced using the standard electroplating process. The experimental procedure involved was as follows. The surface preparation of the mild steel samples involved filing of the samples to remove the initial rust followed by grinding on the surface using the tool and cutter grinder to ensure good surface finish. The final finish was obtained by use of emery paper. In all experiments the pin was coated with zinc using the electroplating process.

The electroplating process was carried out with a solution of $ZnCl_2$, Boric Acid and Distilled water, which acts as the electrolyte using electric power of 0.75V and 3A for 10 minutes, which was given through the AC-DC converter. Nitric acid solution was used for cleaning of samples before and after coating to ensure there are no impurities in the coatings. Measuring of the coating thickness was carried out using micrometer and vernier calipers. The difference of the coated thickness of the sample (4.4mm) and uncoated initial thickness of the coated sample (4.35mm) enabled the determination of the coating thickness, being equal to half of the difference between them, as 25 microns. The estimation of the bulk hardness of the samples was done in the Brinell hardness testing machine. Two readings were taken at the applied load and the average of the two was considered (Table 1).

Table 1. Readings from the Brinell hardness testing machine.

Test No.	Normal Sample	Electroplated Sample
1	161HBW 10/3000	184HBW 10/3000
2	158HBW 10/3000	179HBW 10/3000
Average BHN	159.5	181.5

Estimation of the micro-hardness of the samples was done using the Bower's micro-vickers' hardness tester. Four readings were taken at each load applied i.e., at 50gf and at 500gf without coating (Table 2) and with coating (Table 3).

Table 2. Micro-hardness values of the surfaces of mild steel specimens without coating

Non-coated normal sample					
50gf			500gf		
d1	d2	VHN	d1	d2	VHN
15.25	15.72	386.47	54.72	55.03	307.84
17.58	16.33	322.66	57.1	60.37	268.69
17.15	16.17	333.89	54.38	59.53	285.82
16.9	17.42	314.72	55.9	56.45	293.76
Average VHN = 339.435			Average VHN = 289.0275		

Table 3. Micro-hardness values of the surfaces of mild steel specimens with coating

Coated sample					
50gf			500gf		
d1	d2	VHN	d1	d2	VHN
25.75	25.17	142.98	74.77	69.75	177.52
25.5	23.25	156.02	69.12	68.8	194.92
24.9	23.35	159.27	72.9	72.6	175.15
25.08	23	160.44	72.07	71.25	180.51
Average VHN = 154.68			Average VHN = 182.03		

As can be seen from Table 2 and 3, the surface hardness values of coated samples is considerably lower than those of uncoated samples for both the loads of hardness testing. The discs and pins were prepared as per the specification of the standard pin-on-disc experimental procedure and corresponding AUTOCAD drawings are shown in Figures 2 to 4. The material for the pin was chosen to be oil hardening non-shrinking (OHNS) die steel and two different materials for the discs, namely, mild steel and aluminium.

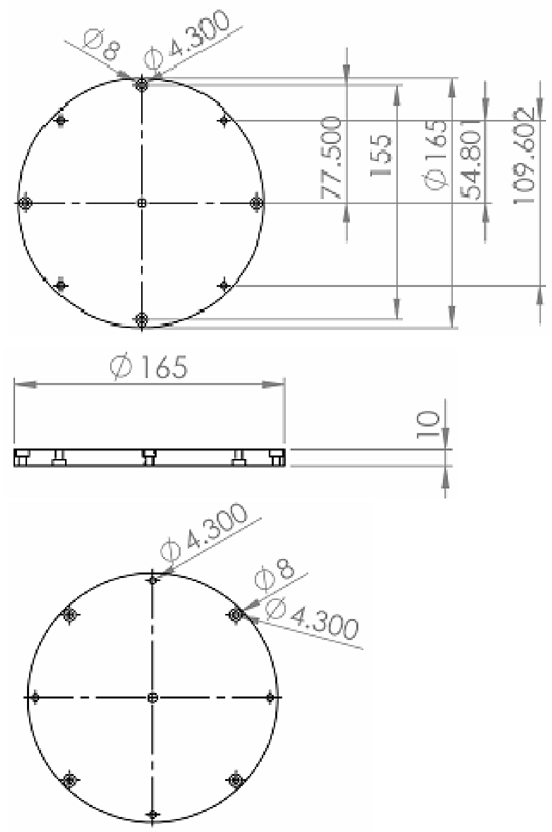


Figure 2. Top, front and bottom views of the disc

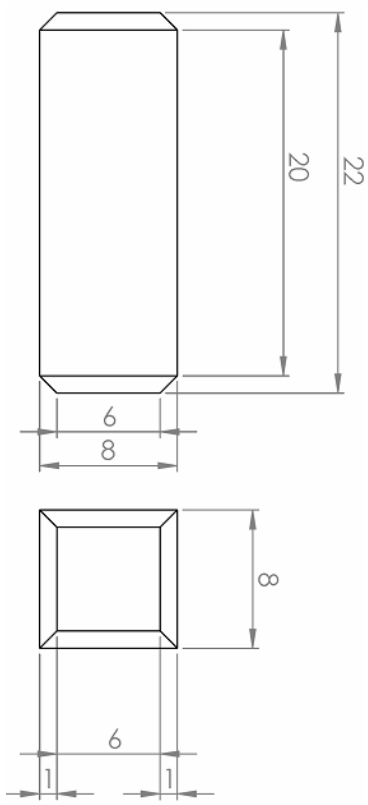


Figure 3. Front and bottom views of square pin

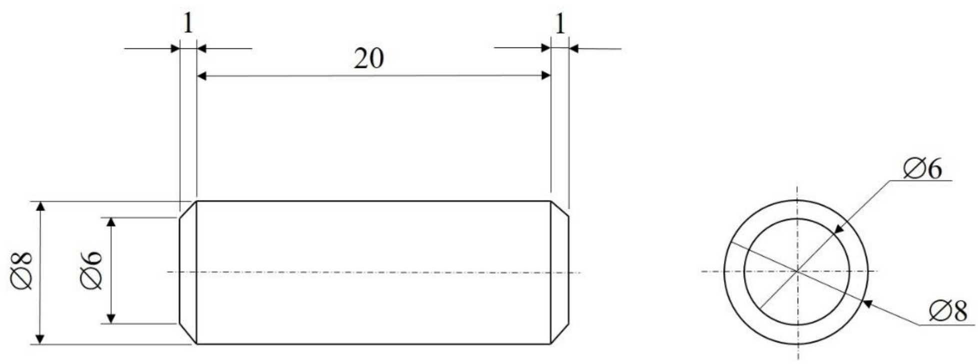


Figure 4. Front and right side view of the cylindrical pin

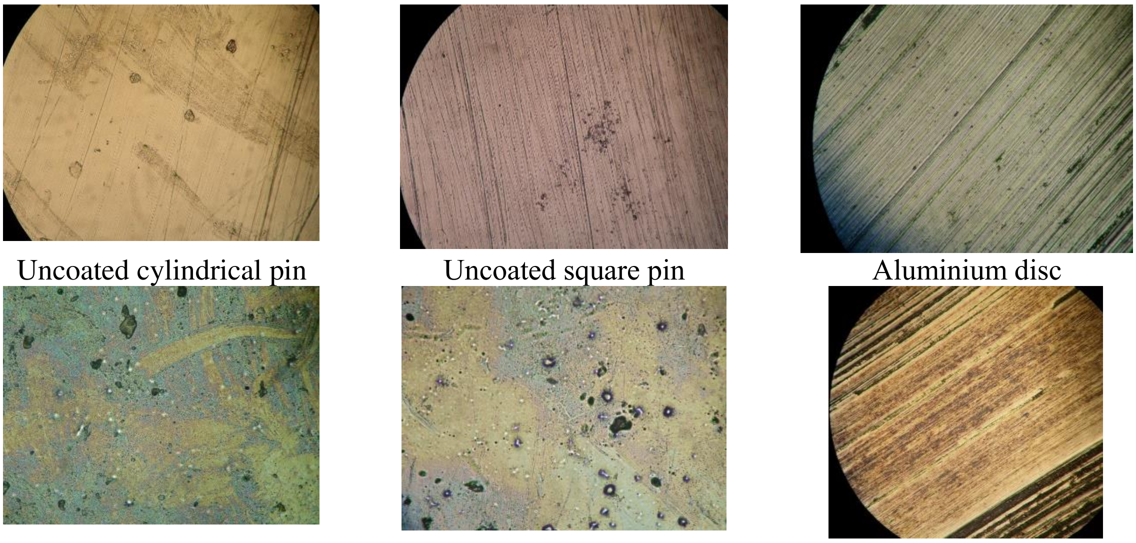
The circular discs were prepared from square plate raw material by first trimming the edges of it to a near octagon inscribed in a 170 mm diameter circle. The plate was then turned on a four jaw chuck lathe in order to remove the uneven surfaces and to get the final circular specimen of diameter of 165 mm. Kerosene was used as coolant and facing operation was carried out to impart smoothness and to avoid the formation of the tool lay paths. The centre hole was drilled with 6mm diameter using the drill tool on the lathe followed by other holes on the radial drilling machine. Emery paper of grades 600, 1/0, 2/0 and 4/0 were used to impart the necessary surface finish.

Figure 5. The square and cylindrical pins before coating

Figure 6. Coated pins are shown to the left and the uncoated pins are shown to the right

Figure 7. The uncoated contact surfaces are shown at the top and the coated surfaces are below the uncoated surfaces.

The square pin was made by first reducing the dimensions of the work piece to 8.5mm*8.5mm square base using the shaper.
It was then reduced in a tool and cutter grinder to 8mm*8mm by giving small increments in the depth of cut. This gave a uniform surface finish. It was further finished using emery paper of grades 600, 1/0, 2/0, 3/0 and 4/0 on the polishing machine in the materials testing lab. A chamfer of 1mm at 45o was given to the contact surfaces.
For cylindrical workpieces, the diameter of the raw solid bar was first reduced to 8.5mm diameter on lathe followed by grinding to 8 mm diameter on a cylindrical grinding machine using two centre drills. The remaining processing steps are similar to square pins.



Uncoated cylindrical pin — Uncoated square pin — Aluminium disc
Coated cylindrical pin — Coated square pin — Mild steel disc

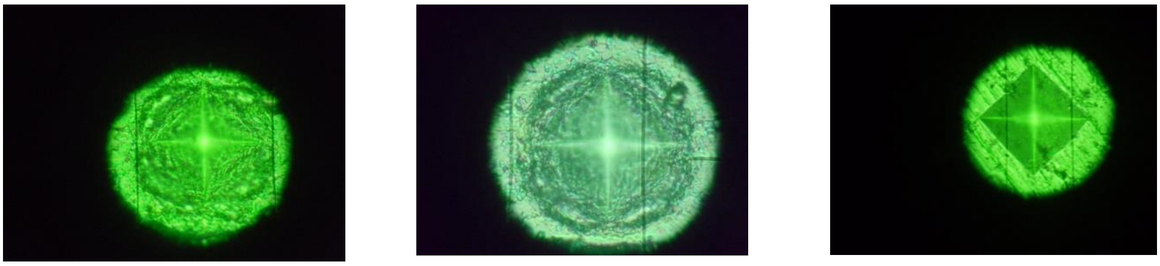
Figure 8. Contact surfaces in metallurgical microscope (Meiji, Japan)

Zinc electroplated and uncoated specimens were readied from the total of 12 contact surfaces were obtained from the square (8surfaces) and cylindrical (4surfaces) pins. Out of these, 6 surfaces were

coated using electroplating technique in the workshop. Two square pins and one cylindrical pin were electroplated at an electrical power of 2V and 3Amp for 8mins.
The thickness of the coating was measured using a micrometer with a least count of 10microns. The thicknesses of the samples were measured before and after coating. Figures-5 to 7 show the manufactured specimens. Figure 8 shows the surface scans of unslid surfaces in the Meiji metallurgical microscope. Figure 9 shows the various instruments used in the investigations.

Metallurgical microscope Micro-Vickers hardness tester Pin-on-disc tribometer
Figure 9. Testing instruments

In the micro-Vickers hardness testing, the zinc coated surfaces underwent extensive plastic flow at the surfaces layers resulting in imprecise indentations whereas the uncoated surfaces showed clear diamond shaped indentations (Figure 10).



(a) (b) (c)
Figure 10. Micro-Vickers hardness indentations, (a) Indentation on coated steel, (b) Indentation on coated Aluminium, and (c) Indentation on uncoated steel.

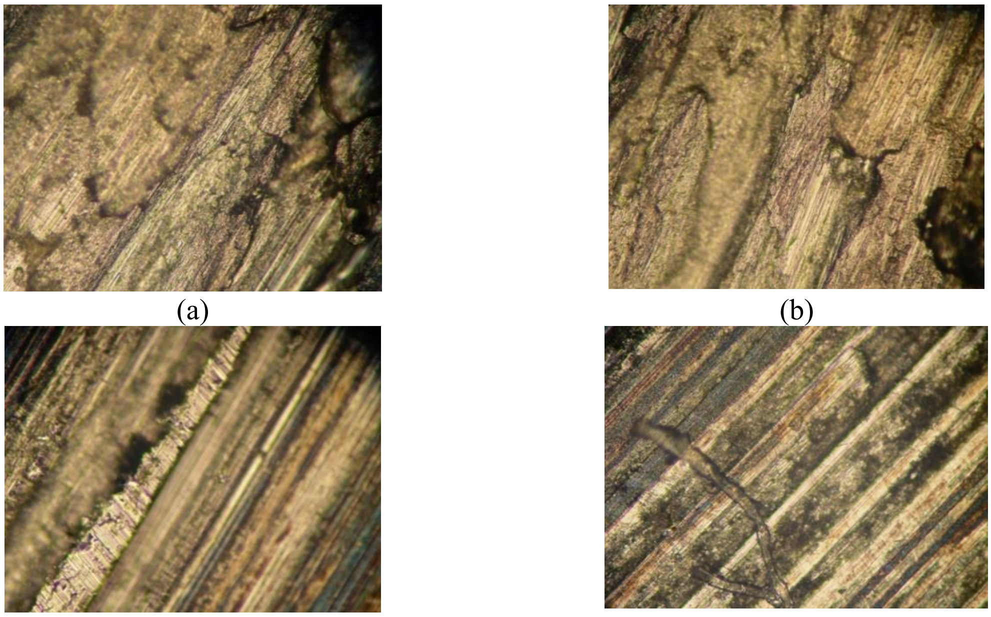
4. Results and Discussion

Table 4 shows the coefficient friction values obtained on the pin-on-disc testing machine for the two cases of with coating and without coating at a rotation speed of 300 rpm.

Table 4. Values of coefficient of friction with and without coating at 300 rpm

Load	Pin	Disc	Average Coefficient of friction	
			Uncoated	Coated
30N	OHNS die steel coated with zinc	Aluminium	0.6128	0.1212
50N		Aluminium	0.6638	0.1438
30N		Mild Steel	0.1724	0.0881
50N		Mild Steel	0.2277	0.1288

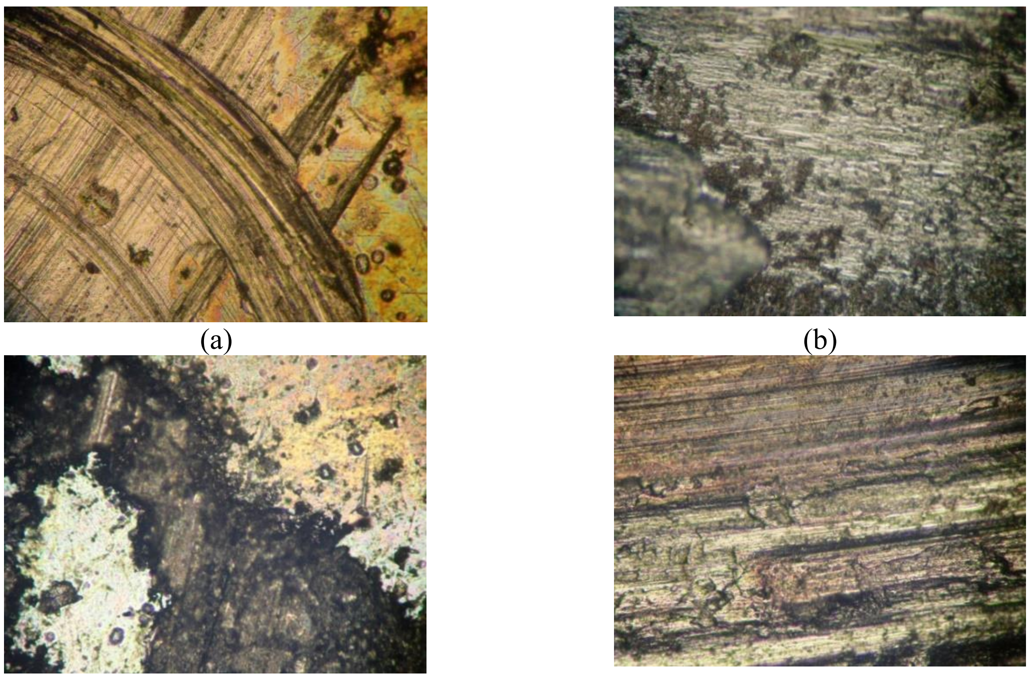
It is clear from Table 4 that significant reductions in coefficient of friction were achieved with zinc coatings in all the cases. Further it is evident that the coefficient friction has slightly increased with the normal load. The zinc coating more effective in reducing the friction in case of Aluminium than in case of mild steel.



(a) (b) (c) (d)

Figure 11. Wear results of discs, (a) Aluminium disc surface when slid with coated pin, (b) Aluminium disc surface when slid with coated pin, (c) Mild steel disc surface when slid with coated pin, and (d) Mild steel disc surface when slid with coated pin. The magnification in all the cases is 50×.

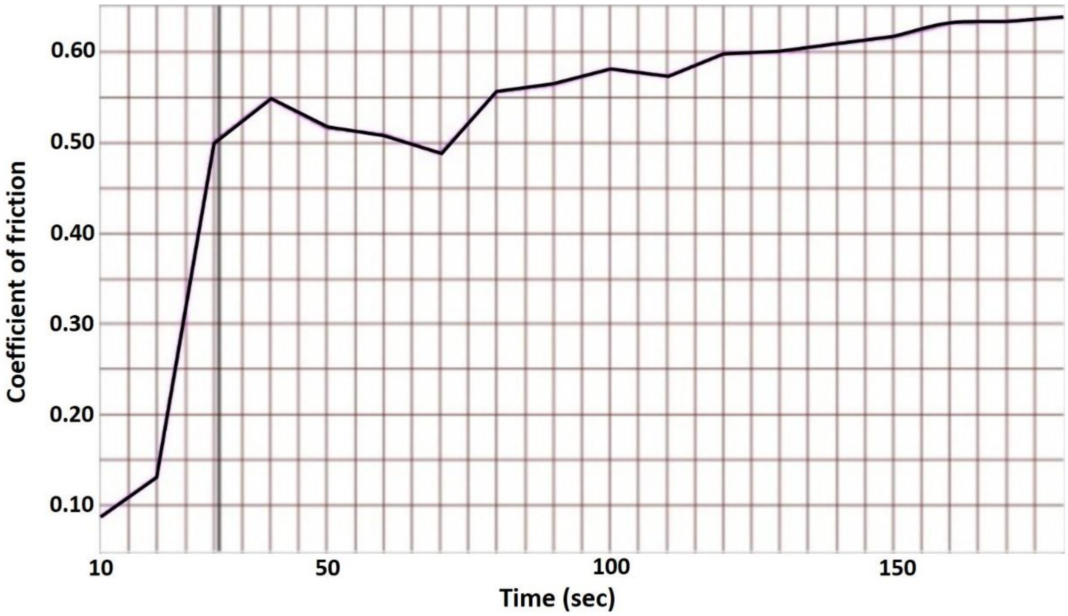
Figure 11 shows the surfaces of the discs after the wear tests. It is clear from these figures that hardly any zinc was transferred from the pin to the disc surface in any of the four cases. Further, smooth wear tracks can be observed to have been formed on the disc without much ploughing.



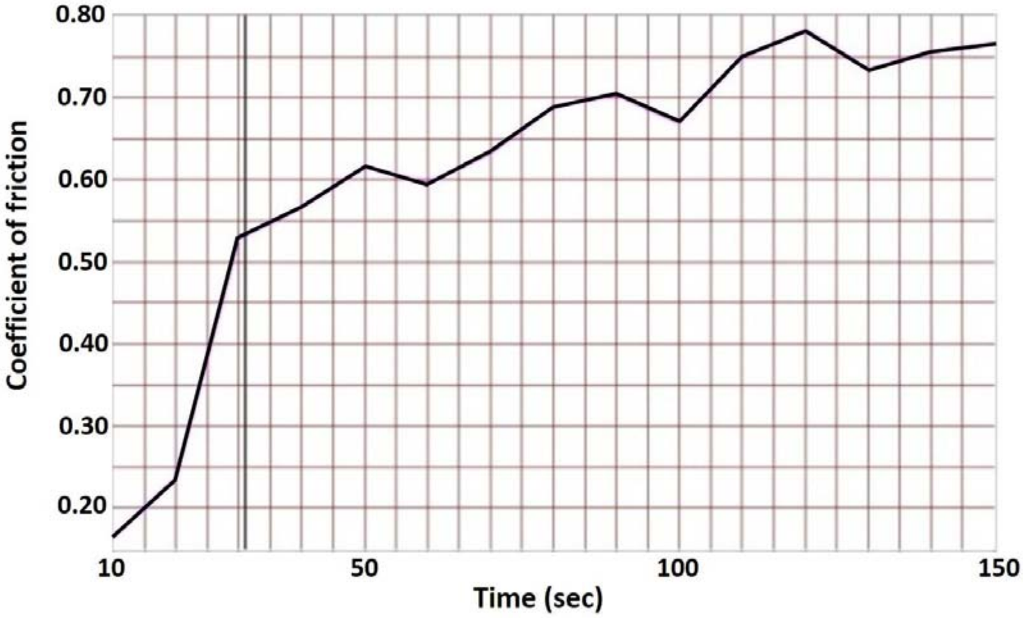
(a) (b) (c) (d)

Figure 12. Wear results of pins, (a) Wear of coated pin slid against Aluminium disc, (b) Wear of uncoated pin slid against Aluminium disc, (c) Wear of coated pin slid against mild steel disc, and (d) Wear of uncoated pin slid against mild steel disc. The magnification in all the cases is 50×.

Figure 12 shows the surfaces of the pins after the wear tests. It is clear from these micro-photographs that the zinc coating effectively prevented any scuffing and metal pickup of disc material, either Aluminium or mild steel, suggesting prevention of gross adhesion, even though the zinc coating has been largely depleted roughly about 30 seconds of sliding. This observation suggests that while zinc coatings are serving as effective solid lubricants, their retention on the tool surface is a problem and a solution is required for it. Wear test plots were recorded on the computerized pin-on-disc machine for coated pins slid against Aluminium and Steel discs at different speeds and loads. Some of these results are shown in Figure 13 to Figure 16 below.



(a)



(b)

Figure 13. Wear tests showing the coefficient of friction for Alumnium disc rotating at 300 rpm, under a load of 30 N and slid against (a) coated pin and (b) uncoated pin.

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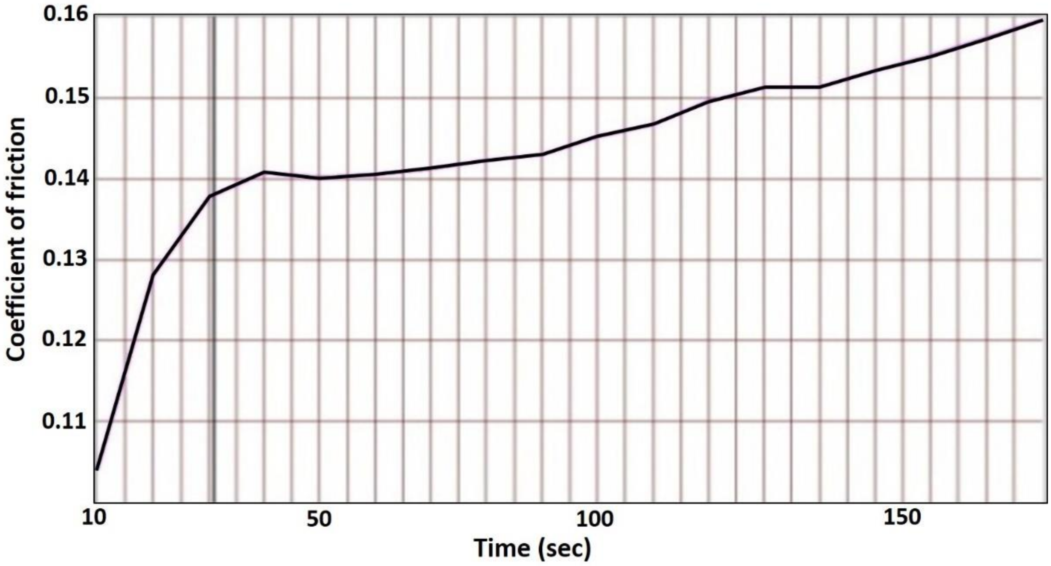
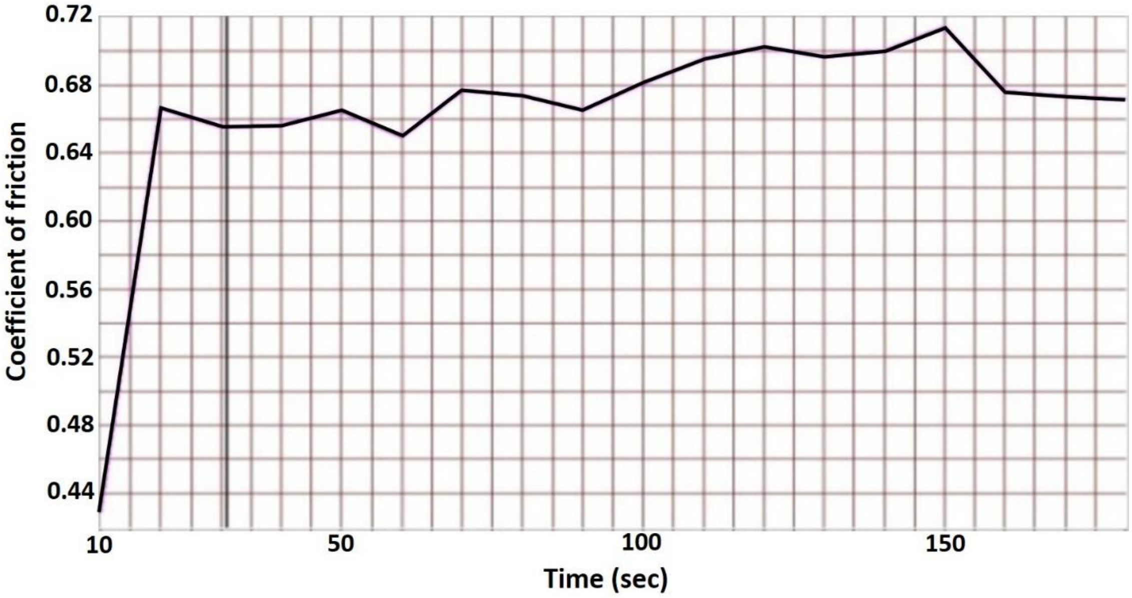
From the figure 13 it is evident that the coefficient of friction increases with sliding distance in the both the uncoated and coated cases but it increases more drastically and maintains at high value in the case of the specimen without zinc coating. The net increase in coefficient of friction is also less in coated case than that in the uncoated case.

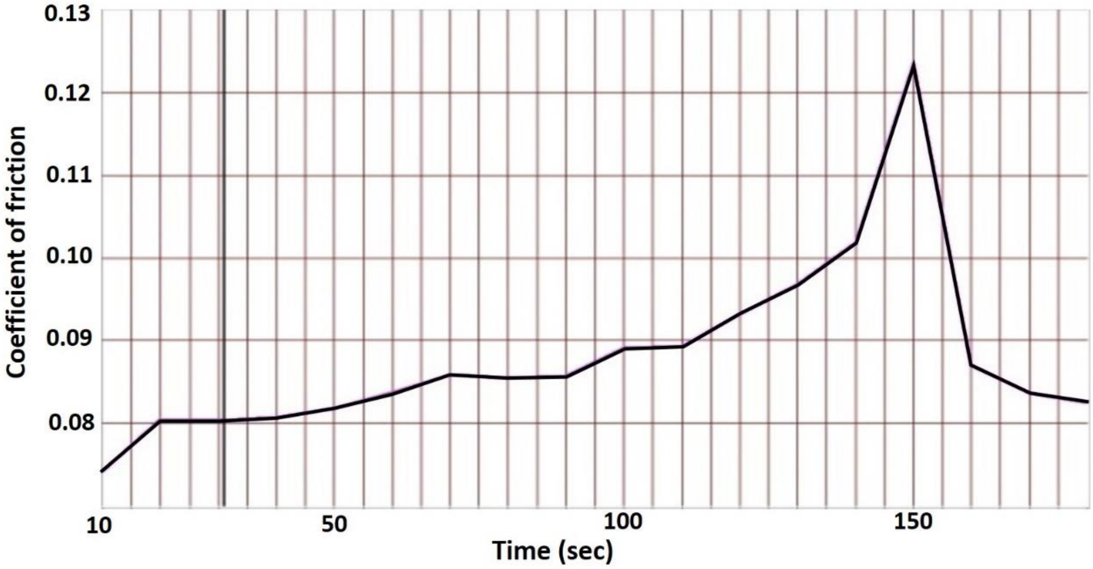


(a)

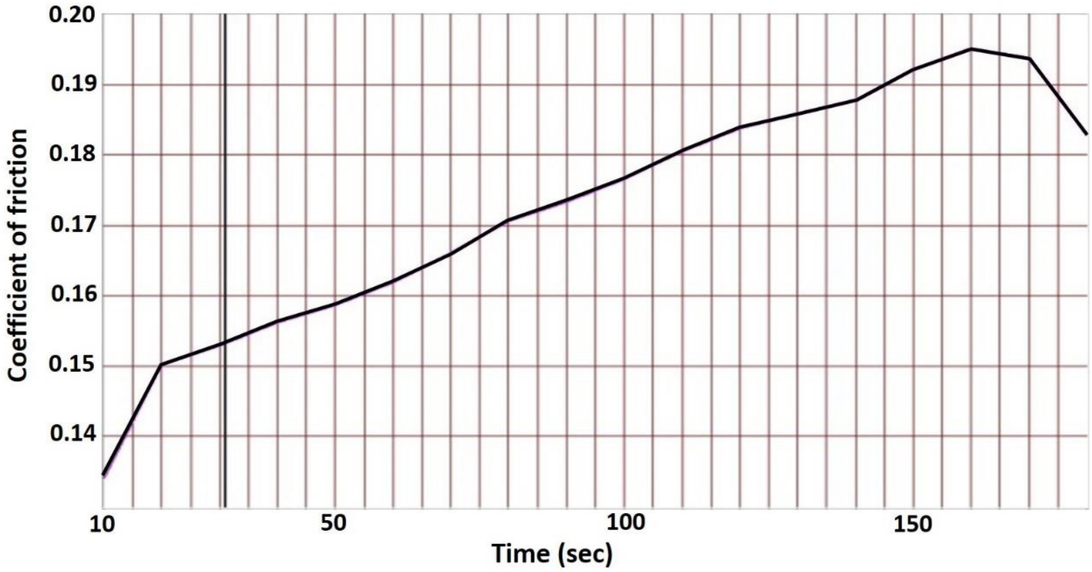


(b)

Figure 14. Wear tests showing the coefficient of friction for Alumnium disc rotating at 300 rpm, under a load of 50 N and slid against (a) coated pin and (b) uncoated pin.



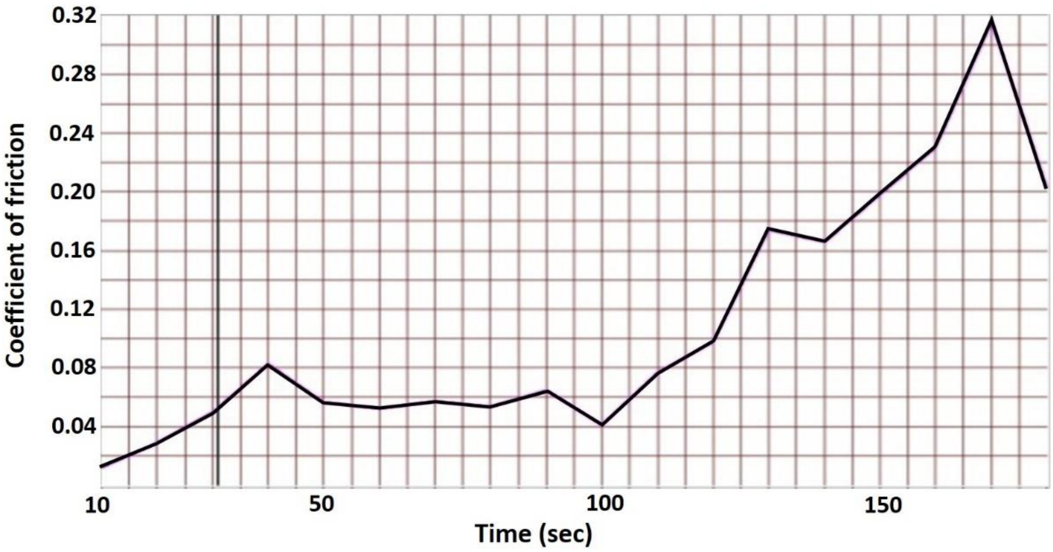
(a)



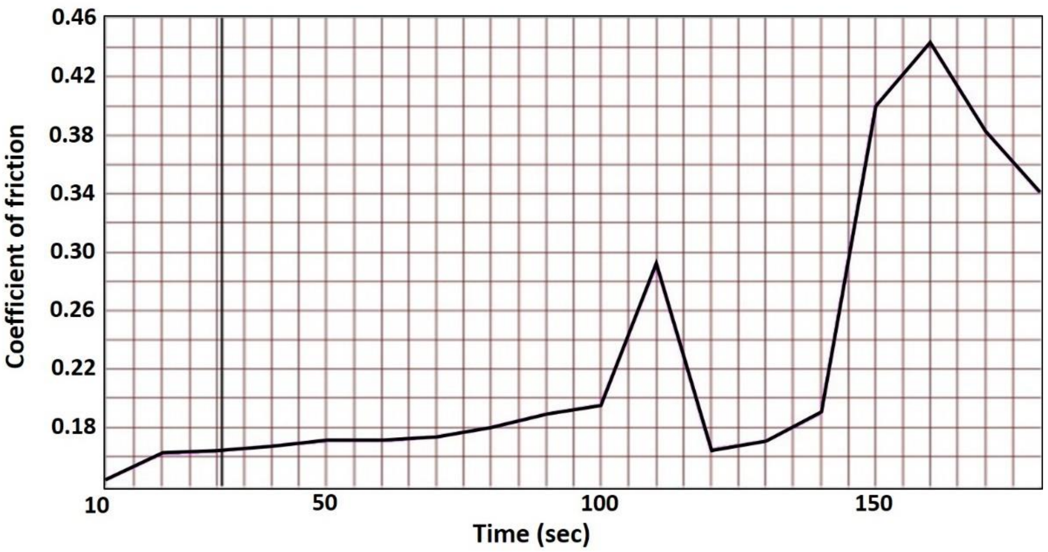
(b)

Figure 15. Wear tests showing the coefficient of friction for mild steel disc rotating at 300 rpm under a load of 30 N and slid against (a) coated pin and (b) uncoated pin

The cases of Figures 14(a) and 14(b) are especially interesting as in these both the coated and uncoated cases as the coefficient of friction increases monotonically and then stabilizes. This is unlike the remaining cases in which the coefficient of friction reaches a peak value after around 150 seconds of sliding and then begins to decrease.



(a)



(b)

Figure 16. Wear tests showing the coefficient of friction for mild steel disc rotating at 300 rpm under a load of 50 N and slid against (a) coated pin and (b) uncoated pin

Figure 15-16 show similar trends where with increase in the load the contrast between coated and uncoated cases further increases with the coefficient of friction being reduced to lower values in coated case for the same load.

5. Conclusions

Based on the results presented, the following conclusions can be drawn on the behaviour and effectiveness of zinc as a solid lubricant coating.

- Electroplating steel samples with zinc decreases the Vickers micro-hardness value as zinc is softer than the base metal.

• Zinc coating contains heavy deformation of surface layers in micro-Vickers hardness testing indentations and thereby results in imprecise indentations.

• Frictional force increases with load applied. This is natural as the normal force increases, it increases the frictional force.

• At 50N load and with the Aluminum Disc, we can clearly see that the coefficient of friction and the wear are less while using coated tools than while using uncoated tools.

• Similarly, at 50N load and with the Mild Steel Disc, we can see that similar conditions are seen as with the Aluminum Disc at 50N load and coated pin.

• Wear on the discs is comparatively lesser while using coated tools. This can be seen from the table showing the wear due to coated and uncoated surfaces.

• The wear on the coated tool is found to be limited to only the coating, no scuffing or metal pickup was found to occur as evident from the micro-photographs of pin and disc surfaces taken after the sliding experiments and hence it can be concluded that the zinc coating has the ability to increase the tool life to a certain extent. Further, it is found that the zinc coating is not stable and goes off after about 30 sec of sliding. Therefore, it is essential to find a bonding agent that will keep the zinc coating for longer duration of sliding on the tool.

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