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Tribological Study at the in-situ Situation for Aluminum 6061 and Steel EN31 During the Dry and Starved Lubricating Condition

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ABSTRACT

Scientists are working on the development of materials and lubricants to reduce friction as well as wear at metal-to-metal interfaces having relative motion. Aluminum is a widely used metal due to its high strength to weight ratio and availability in nature as compared to other metals that are manufactured by the rolling process. The output of the product quality and quantity from the rolling process requires less energy as compared to other manufacturing processes. A tribological study has been carried at the in-situ condition for the interface of Al6061 and steel EN31 on the pin on disc setup. To analyze the effectiveness of lubricant with mating surfaces, the effect of rolling lubricant was analyzed for tribological behavior and compared with the dry condition. The coefficient of friction was reduced up to 80% and the specific wear rate was reduced up to 96% by using rolling lubricant compared to dry conditions at the interface of metals that had relative motion.

Keywords: Friction; Specific wear rate; Pin-on-disc; Lubrication; Dry friction.

INTRODUCTION

The rolling process is a widely used metal forming process. Small hand-driven rolling mills were used even as early as the fifteenth century (Swank, James M., 1965). 70% of the products by mass were made by rolling process. The cold rolling process is economical and efficient which is used for producing sheets and strips which may be used directly as well as a by-product for further cold forming processes. Cold-rolled sheets have uniform mechanical properties, uniform surface texture and microstructure, close tolerance sheet thickness, and good surface quality. Generally, cold-rolled sheets may be used directly as a product, no other surface treatment is required (E. Degarmo et al., 1988).

The interacting surfaces along with their surrounding of roll and strip affect the power consumption to generate the required surface finish of the product during the rolling process. The study of tribological properties like lubrication, wear, friction is important for economic and to maintain dimensional stability of the mating parts.

Various researchers had studied the friction phenomenon between the Aluminum strips and roll (S. Jianlin and Z. Xinming, 1997, J. G. Lenard 1991, L. Lai-Seng and J. G. Lenard, 1984, B. Hum et al. ,1996 & Z. Wang et al., 2003). The coefficient of friction was more affected by rolling speed than the rolling load in cold rolling of Aluminum. As rolling speed increased coefficient of friction decreased (S. Jianlin and Z. Xinming, 1997). A cold rolling model for dry friction was developed (Baltov and Nedav, 1995) For the rolling process, friction is essential but its optimization is required as more friction will consume more power (S. Kondo, 1975). The roughness of the strip surface also affects the lubrication conditions in the rolling (S. S. Lu and Y. H. Chuang, 1995). The surface roughness in the rolling direction had an adverse effect on lubrication while roughness in transverse direction had favorable lubrication conditions for rolling due to the formation of oil pockets (Y. J. Liu et al., 2001). Roughness transfer from steel roll to Al strip was observed during rolling (F. Plouraboué and M. Boehm, 1999). Roll load was varied with roll roughness.

Smooth roll provided the lowest load as starved contact was observed at high surface roughness of rolls (J. Jeswiet, 1998). Ecofriendly easter synthesized by alcohol and acids were prepared and compared with existing aluminum lubricant. These ecofriendly lubricants shown good physical and chemical and tribological properties (P. Nagendramma et al., 2016). Water-based nano lubricants reduced the rolling forces in micro flexible rolling of Aluminum up to 18% and the surface roughness of the sheet was also improved (M. Huo et al., 2020).

So, the effect of lubricants on tribological properties of the tribo-pair of roll and strip material is to be studied. To meet the major challenges of future needs of rolling, the researchers are continuously putting their effort to optimize the power consumption and reduce the wear of the advanced materials used in daily life. On the other hand, some researchers are carrying out the fine art of formulating the working lubricants for maintaining the suitable tribological environment for the lubricating contacts within the rolling regime (J. G. Lenard ,2004; L. B. Sargent and C. J. Stawson, 1974; A. Shirizly and J. G. Lenard, 2000; C. McConnell and J. G. Lenard & A. I. Baltov and A. G. Nedev, 1995).

Hence, improvement of the lubricating condition of rolling has become a subject of an investigation by many designers and researchers. In this study, an attempt has been done for analyzing the effect of rolling lubricant at the mating surface of Al6061 and steel EN31against dry conditions on the Pin on Disc test rig.

EXPERIMENTATION

Frictional and wear properties have a vital role in the daily lives of human beings. It consumes power and decides the life of the product. A Pin-on-disc tribometer was employed to analyze the coefficient of friction and the specific wear rate of the in-situ material having relative motion. The material of the disc was steel EN31and the material of the pin was Al 6061. Negligible wear of steel EN31was assumed as compared to the pin of Al 6061. The composition of the material was as per Table1 &2.

Table 1. Composition of Aluminum Pin.

Component	**Al**	**Mg**	**Si**	**Fe**	**Mn**	**Ti**	**Zn**	**Ni**	**Cr**	**V**
% value	98.402	0.6184	0.5787	0.2879	0.0077	0.0072	0.0526	0.0255	0.0103	0.0006

Table 2. Composition of steel EN 31 Disc.

Component	**Fe**	**Cr**	**Mn**	**C**	**Si**	**Mo**	**Ni**	**Cu**	**Al**
% value	96.8898	1.0942	0.6514	0.4207	0.2828	0.2449	0.1193	0.0681	0.0513
Component	**V**	**P**	**S**	**As**	**Co**	**Pb**	**B**	**W**	
% value	0.0469	0.0339	0.0286	0.0259	0.0226	0.0141	0.0127	0.0018	

The Vickers microhardness of the specimens was measured on a Vickers microhardness tester. The specimen was polished and kept on the platform of the tester. Then a specific load of 0.30 N or 0.03 kg was applied for 120 seconds. An impression was marked by the Vickers hardness indenter on the specimen surface. The hardness values were taken at a different position on the specimen surface. Then arithmetic mean was calculated of all the values. The testing was done for the Aluminum pin and EN31 steel disc specimen. The average microhardness for the Aluminum pin was 33.0 HV and for the EN31steel disc was 2004.9HV.

SPECIFICATIONS OF EN31 STEEL DISC AND ALUMINUM PIN SAMPLES

Figure 1(a). Bottom Specimen, EN31 Disc 100 mm diameter.

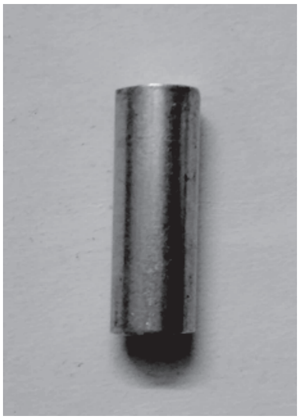

Figure 1(b). Top Specimen, Aluminum 6061 cylindrical pin 8mm diameter and 30mm length.

An EN 31 steel disc was taken for experimentation as in Figure1 (a). Disc surface was prepared by the first surface grinding and then lapping (R.C. Singh et al.,2016). Surface roughness was checked by a stylus surface roughness tester at a radius of 20,30,40,50,60 and 70 mm in the circumferential direction and 60 degrees in radial directions from a reference line. The reading was repeated on 5 surfaces of the disc and 5 samples of the Aluminum pin. The average surface roughness Ra value was 0.51 and 0.44 μm respectively. A cylindrical Al 6061 pin of diameter 8 mm and 30mm in length was taken for testing on EN31 steel circular disc as shown in Figure 1(b). The cylindrical pin face was prepared by rubbing pins on fine grade emery paper and debris was removed by rubbing it on soft tissue. Flatness was checked by ink impression. To minimize the bending effect Aluminum cylindrical pin was rigidly clamped so that only 4mm length remained out of the clamp for the test on the EN31 steel disc. An aluminum rolling lubricant was used for starved lubrication between mating pairs. The properties of the lubricant used was as given in Table 3.

Table 3. Properties of Rolling Lubricant.

Property	**Value**
Kinematic Viscosity at 40°C, (c St)	2.4
Flash Point, °C, (COC), (Min)	80
TAN, mg KOH /gm	0.002
Distillation Range, a) IBP b) FBP	 205 242

DESCRIPTION OF PIN ON DISC TEST RIG

A high-temperature rotary tribometer performs as per ASTM G-99 was used for the testing rig. The bottom specimen is fixed on a circular disc which is rotated by a motor with varying speeds. The speed ranges between 300 to 3000 rpm. The specimen is fixed by four bolts on the circular disc. The upper specimen of Pin has been clamped in the specimen holder vertically. Dead weights on pans that have a horizontal platform supporting the direction of gravity were used for loading. The forces were transmitted through a lever mechanism. The specifications of the wear test rig are shown in Table 4.

Table 4. Specification of the pin on the disc Tribometer.

Parameter	**Value**
Pin size (mm)	Diameter of 8,10,12
Disc size (mm)	Diameter 100 x thickness 8
Wear track diameter (mm)	Min 20 and max 80 in the step of 2
Disc speed (rpm)	Min 300, max 3000
Normal load (N)	Min 0.1; max 200; least count 0.1
Wear (µm)	0-2000 in the step of 1, LVDT
Disc speed sensor (rpm)	300-3000, proximity type
Normal load range (N) and sensor	20-200 N, Deadweight
Frictional force (N)	0-200, Load Cell

EXPERIMENTAL PROCESS

Wear tests as per ASTM G99 were carried on the high-temperature rotary tribometer as shown in Figure 2.Five set of EN31discs and 50 samples of pins were used in the tests. First, the test was done in dry conditions than in starving lubrication conditions. In the first set at 20 N load, tests were done on sliding speed of 1.25, 1.5, 1.75, 2, and 2.5 m/s, and sliding distance was taken constant 1500m.Same process were repeated for load 25,30, 35,40 N with sliding speed of 1.25, 1.5,1.75, 2.0, 2.5 m/s respectively. Initial weight and weight after the test of the Aluminum pin were recorded on the electronic balance having the least count of 0. 001gm.The same sets of tests were done with starving lubrication conditions.

Friction and wear values were recorded on a computer by the sensors. The weighing balance method was used to calculate the specific wear rate of the cylindrical pin.

$$Specific\ wear\ rate = \frac{Change\ in\ volume\ (m^3)}{Load\ (N) x\ Sliding\ Distance (m)} m^3/Nm$$

$$Change\ in\ volume = \frac{Weight\ loss\ (kg)}{Density\ of\ material\ (\frac{kg}{m^3})}\ m^3$$

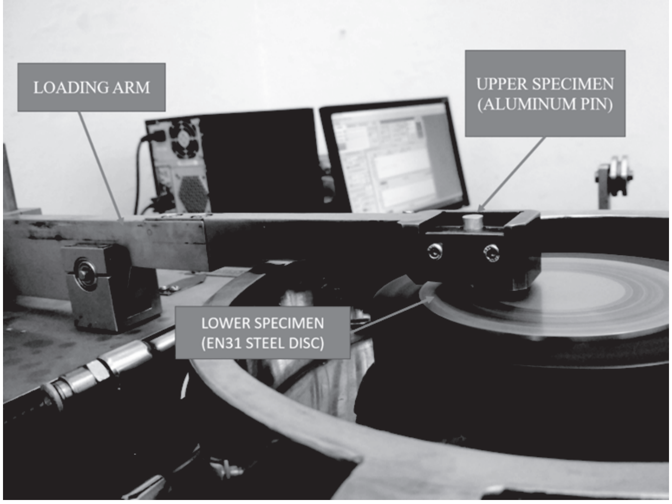

Figure 2. Tribometer in working condition.

RESULTS AND DISCUSSION

Results showed that at all loads and all sliding speeds coefficient of friction had been reduced in starved lubricating conditions. At 25N and 2.5m/s sliding speed, it had been reduced up to 86.75% and had been reduced up to 86.63 % at 35 N load at 2.0 m/s sliding speed (Table5).

Table 5 .Comparison of coefficient of friction (COF) in dry and starved lubricating condition.

SNO.	LOAD (N)	SLIDING SPEED (m/s)	COF (Dry) µm	COF (with starved lubrication) µm	% reduction of COF in lubricating condition
1	20	1.25	0.2231	0.0917	58.92
		1.5	0.2030	0.0395	80.54
		1.75	0.2214	0.0743	66.47
		2	0.2551	0.1028	59.72
		2.5	0.2609	0.0532	79.62
2	25	1.25	0.2659	0.0459	82.72
		1.5	0.2817	0.0488	82.66
		1.75	0.2889	0.0646	77.62
		2	0.2994	0.0406	86.43
		2.5	0.4335	0.0574	86.75
3	30	1.25	0.2916	0.0880	69.82
		1.5	0.2847	0.1133	60.20
		1.75	0.2926	0.0949	67.55
		2	0.2861	0.1297	54.66
		2.5	0.3018	0.1501	50.25
4	35	1.25	0.3056	0.0609	80.07
		1.5	0.2942	0.0732	75.11
		1.75	0.3040	0.0769	74.72
		2	0.4224	0.0565	86.63
		2.5	0.5616	0.0859	84.71
5	40	1.25	0.3189	0.0723	77.34
		1.5	0.3246	0.0707	78.23
		1.75	0.3333	0.0811	75.68
		2	0.4390	0.0697	84.12
		2.5	0.3188	0.0844	73.53

Results showed that at all loads and all sliding speeds specific wear rate (SWR) had been reduced in starved lubricating conditions. At 25 and 35 N load and sliding speed of 2.5m/s, it had been reduced up to 98.38 % (Table 6).

Table 6. Comparison of specific wear rate (SWR) in dry and starved lubricating condition.

SNO	**LOAD**	**SLIDING SPEED (m/s)**	**SWR in DRY condition (m^3/Nm) x10^{-16}**	**SWR with starved lubrication (m^3/Nm) x10^{-16}**	**% Reduction in SWR**
1	20	1.25	0.1222	0.0123	89.90
		1.5	0.3247	0.0630	80.61
		1.75	0.1111	0.0827	25.56
		2	0.0889	0.0370	58.33
		2.5	0.0827	0.0259	68.66
2	25	1.25	0.1077	0.0395	63.30
		1.5	0.0928	0.0395	57.45
		1.75	0.0839	0.0375	55.29
		2	0.0672	0.0267	60.29
		2.5	1.4815	0.0158	98.93
3	30	1.25	0.1531	0.0379	75.27
		1.5	0.0831	0.0798	3.96
		1.75	0.0996	0.0543	45.45
		2	0.0617	0.0305	50.67
		2.5	0.0412	0.0222	46.00
4	35	1.25	0.1390	0.0332	76.14
		1.5	0.0642	0.0332	48.35
		1.75	0.0691	0.0254	63.27
		2	1.0469	0.0169	98.38
		2.5	1.2981	0.0219	98.32

5	40	1.25	0.1167	0.0259	77.78
		1.5	0.0846	0.0173	79.56
		1.75	0.0914	0.0296	67.57
		2	0.2173	0.0185	91.48
		2.5	0.0586	0.0247	57.89

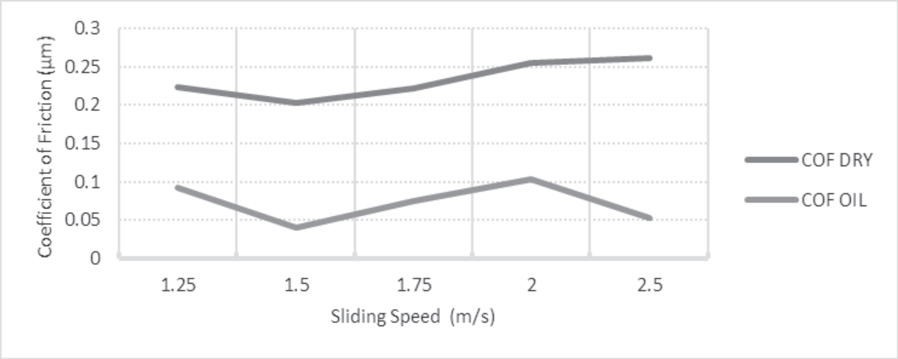

Figure 3. Variation of the COF at contact load of 20N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

The coefficient of friction (COF) was reduced at all the sliding speed in starving lubrication condition art 20N load (Figure 3).

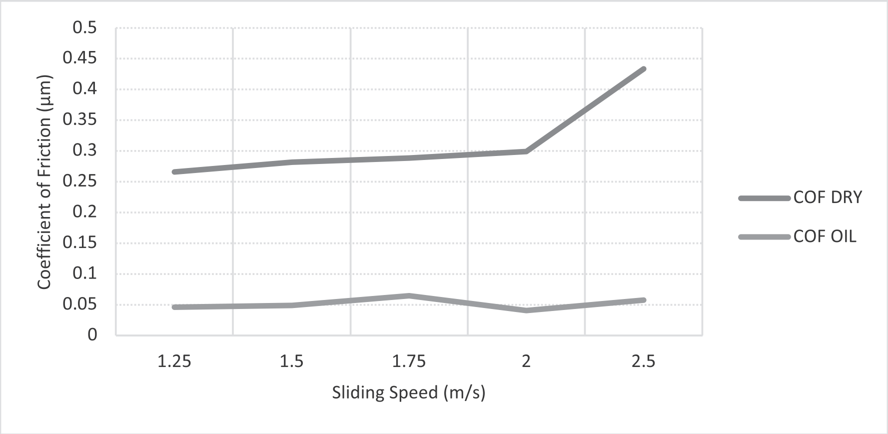

Figure 4. Variation of the COF at contact load of 25N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

COF in starving lubrication was reduced at 25N load also than the dry condition. It was also observed that at 25N load COF increased in dry condition than the COF at 20N load while it reduced in starving lubrication condition (Figure 3 &4).

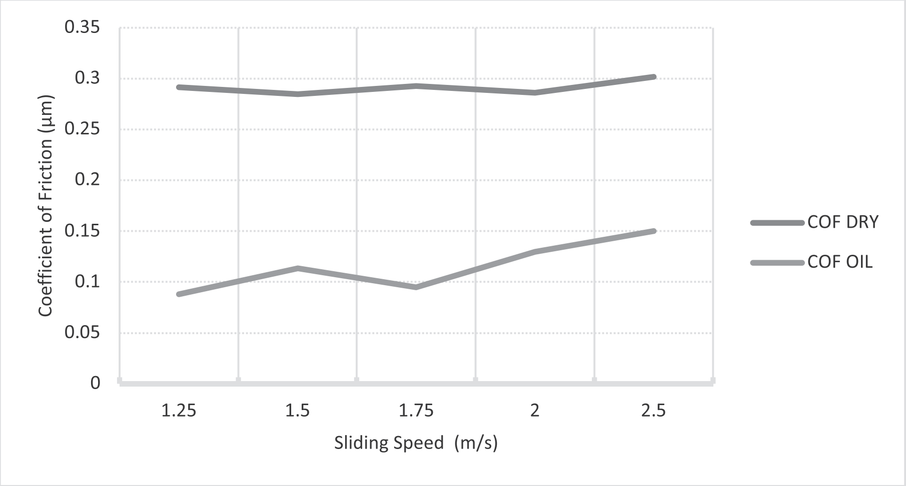

Figure 5. Variation of COF at contact load of 30N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

COF in starving lubrication was reduced at 30N load also than the dry condition. It was also observed that at 30N load COF increased in dry conditions than the COF at 20N and 25N load (Figure 3,4 &5).

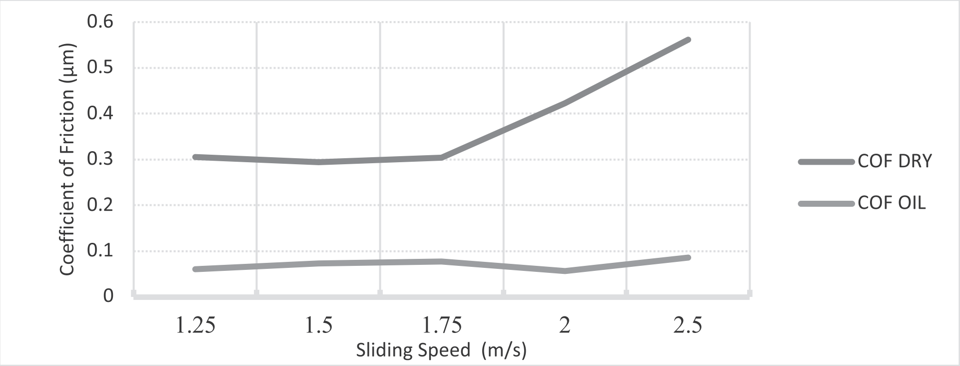

Figure 6. Variation of the COF with contact load of 35N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

COF in starving lubrication was reduced at 35N load also than the dry condition (Figure 6).

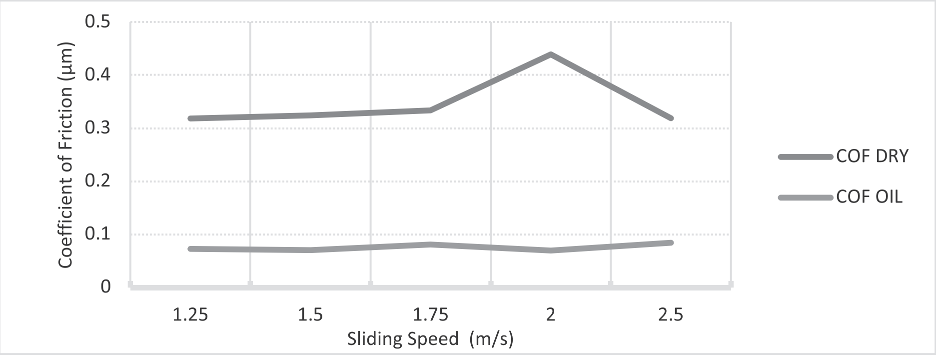

Figure 7. Variation of the COF with contact load of 40N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

COF in starving lubrication was reduced at 40N load also than the dry condition. (Figure 7).

From the plots between sliding speed and the coefficient of friction (Figure 3-7), it is clear that the COF was higher in dry conditions than the coefficient of friction in starving lubricating conditions.

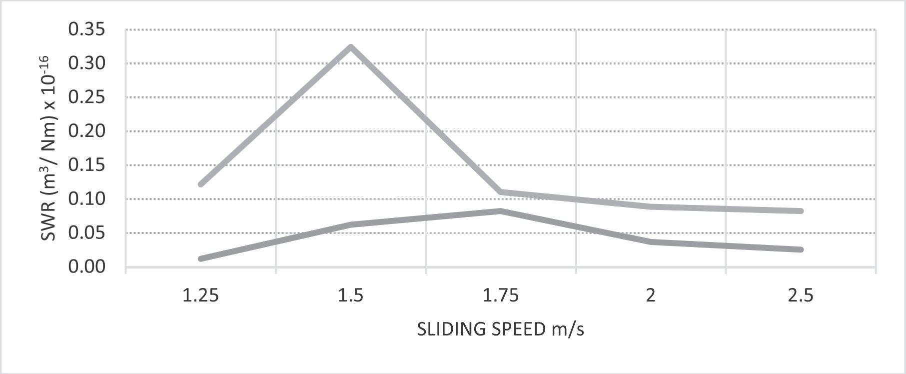

Figure 8. Variation of the SWR at contact load of 20N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

Specific wear rate also reduced in starving lubrication condition than the dry condition at 20N load (Figure 8).

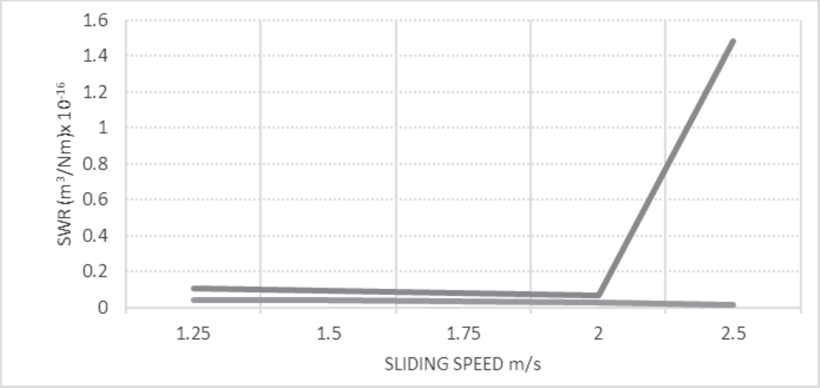

Figure 9. Variation of the SWR at contact load of 25N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

At 25N load also specific wear rate reduced in starving lubrication conditions than the dry condition (Figure 9).

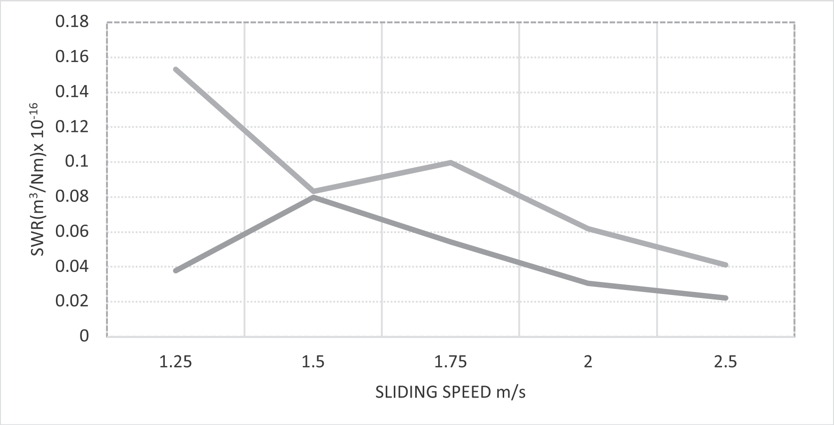

Figure 10. Variation of the SWR at contact load of 30N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

At 30N load also SWR reduced in starving lubrication conditions. It was varying with sliding speeds (Figure10).

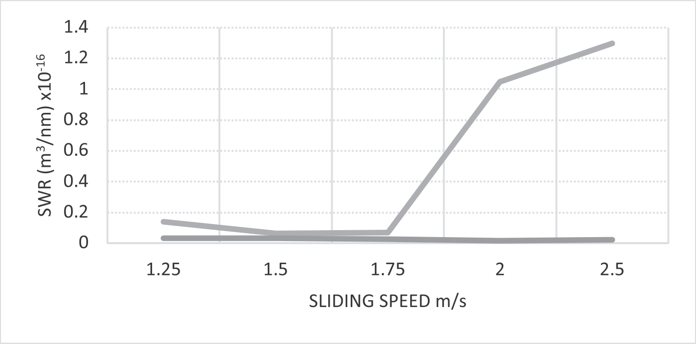

Figure 11. Variation of the SWR at contact load of 35N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

At 35N load, the SWR rate was reduced in starving lubrication conditions. SWR for the dry condition was increased with sliding speed (Figure11).

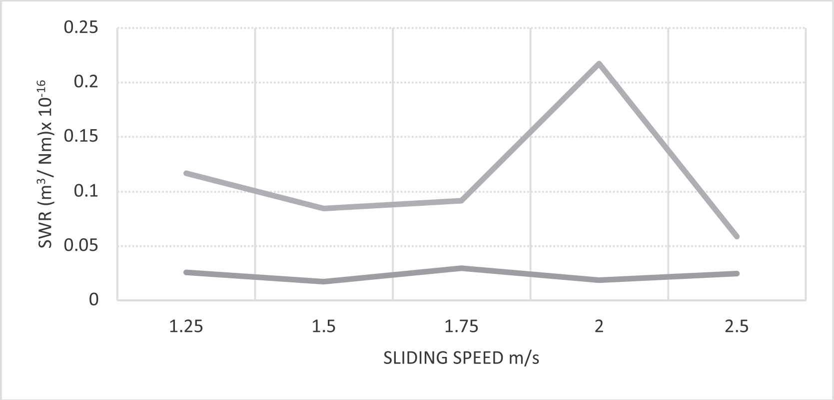

Figure 12. Variation of the SWR at contact load of 40N (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

At 40N load also SWR rate was reduced in starving lubrication conditions. SWR for the dry condition was varying with sliding speed (Figure12).

From the plots between SWR and sliding speed at various loads (Figure 8-12), it is clear that SWR at all the sliding speeds in dry conditions was less than the SWR at starving lubricating conditions.

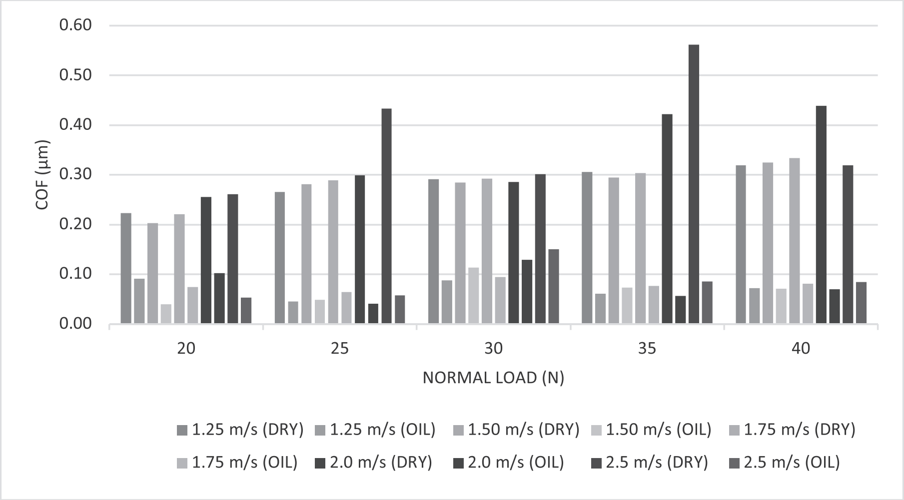

Figure 13. Variation of COF with sliding speed (m/s) at different loads (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

From the bar chart also, it is clear that at all the sliding speeds COF was reduced. COF has been increased with load in dry condition. (Figure13).

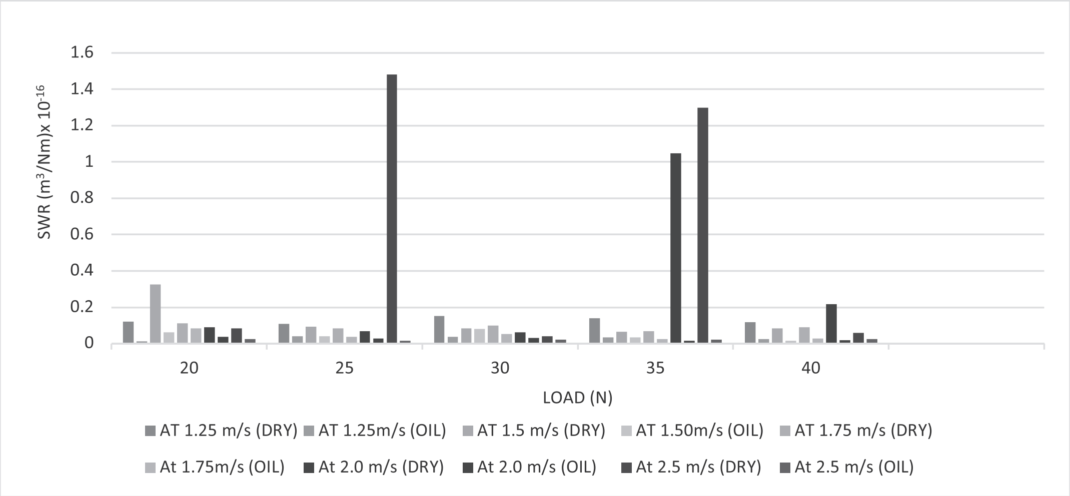

Figure 14. Variation of SWR with sliding speed (m/s) at different loads (Sliding distance=1500m, ambient temperature 30°C, dry and starved lubrication).

From the bar chart also, it is clear that at all the sliding speeds SWR was reduced in starving lubrication conditions. (Figure14)

From the plots, it is also clear that variation in SWR with sliding speed is more at all the loads in dry conditions. While SWR does not vary so much with varying sliding speeds that indicates that wear particle which is between mating surface during process affected the wear in dry condition while in the lubricating condition these may remove by lubricant and not enhanced the wear.

CONCLUSION

Rolling lubricant was found effective in reducing friction and wear rate of material in tribo test of mating pair of EN31 and Aluminum 6061 material. Results showed that at all the sliding speeds and for all the loads coefficient of friction in starving lubricating conditions reduced up to 83% than the dry condition. Specific wear rate also reduced up to 98% when rolling lubricant was used between mating surfaces in starved conditions. In dry conditions, the specific wear rate was fluctuating and non-predictable while in the lubricating condition it had a smooth rate. These results may be used in the cold rolling process of Al 6061 for selecting lubricants between the roll and the strip.

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