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RESEARCH

Effect of Nano Oil Additive Proportions on Friction and Wear Performance of Automotive Materials

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A B S T R A C T

The effect of nano boric acid and nano copper based engine and transmission oil additives in different volume ratios (1:10, 2:10, and 3:10) on friction and wear performance of cast iron and case carburized gear steel has been investigated. The results show that coefficient of friction increases with increase in volume ratio of engine oil additives and decreases with increasing in volume ratio of transmission oil additives. Cast iron substrate shows higher wear damage than case carburized gear steel. Nano copper additive with crystalline atomic structure shows more severe three body wear compared to boric acid with layered lattice structure.

1. INTRODUCTION

Frictional losses in a typical automobile accounts significantly for the reduction of useful power otherwise available for the motion. Almost 15 % of the total energy loss comes from the friction generated between the sliding parts. Lubricants are supplied to reduce such frictional losses. Frictional losses arise mainly at the piston rings, bearings and transmission parts which undergo boundary lubrication or starved lubrication at certain periods during operation. Additives in lubricants come into effect under such conditions. Nano particulate suspended additives in the base oil are of some interest to address the boundary lubrication issues.

Several authors have studied the effect of boric acid and copper nano particles based additives on friction and wear performance of sliding parts. Pure nano copper particle suspended in raw oil was found to improve the lubricating properties [1]. The operating parameters such as temperature, sliding speeds and concentration were found to influence the frictional performance [2-4]. Sliding movement generates self adhered copper film to effectively reduce friction at the contact [5,6]. The generated film is found to have increased the load bearing capacity of the tribo-pairs [7].

Boric acid nano suspension was also found to be effective in reduction frictional losses. It was more effective as oil suspensions than pure solid films [8]. Boric acid is known to convert into boric oxide layer which adherers to the substrate and regenerate into a fine cluster of boric acid platelets film in the presence of moisture to lubricate the interface [9–12]. The low adhesion between the platelets acts to reduce friction at the interface.

The supplier of oil additives suggested 1:10 ratio of additive and oil mixture to achieve good fuel economy in a commercial vehicle. So in this work, the authors are trying to understand the effect of 3 different volume fractions (1:10, 2:10, and 3:10) of commercially available nano boric acid and copper based additives in the engine and transmission oil used for a heavy duty commercial vehicle on its frictional performance. The tribological performance was assessed under heavy contact load, high frequency and at suitable temperature which are the typical operating conditions of the engine and transmission in heavy commercial vehicles.

2. EXPERIMENTAL DETAILS

High temperature ball-on-flat reciprocating test rig (TR-283M-M7 developed by DUCOM Instruments Pvt. Ltd, Bangalore, India) was used to conduct all the experiments. The coefficient of friction was recorded continuously with time. The test conditions are as provided in Table 1. The parameters selected closely simulate the original conditions in a commercial vehicle.

SAE 15W40 and SAE 90 grade oils are generally used as engine and transmission oils in all heavy duty commercial vehicles (11 tons to 49 tons) in India. Commercially available additives of boric acid (< 50nm size, Motor Silk brand engine and gear oil supplied by Advanced Lubricant Technology Inc., USA) and nano copper (15 % concentration, < 20nm particle size by DONG YANG INT'L GROUP LTD, China) was procured for the study. Motor Silk branded engine and gear oil comes in different containers while the same nano copper was used for both engine and gear oil. The additives were mixed in the base oil in different volume proportions (1:10, 2:10, and 3:10).

Hardened plain carbon steel balls of 10 mm diameter were coupled with flat samples of 20 x 20 x 5 mm dimensions. Cast iron (300 MPa UTS) flat samples were used for experiments with engine oil additives and case carburized BS 970 or EN 36 steel samples were used for experiments with transmission oil additives. EN 36 steel containing 0.15 % C, 1 % Cr, 3 % Ni is normally used for automotive gears. The flat samples were pack carburized at 925 °C for 4 hours and later heat treated at 780 °C before quenching in oil. The case depth is around 0.9 to 1.0 mm. Later on the samples were ground to the required flatness. These materials are typical representatives of several components used for automotive engine and transmission such as cylinder liner, piston rings and case hardened gear. The Vickers hardness under 2 kg load for cast iron and carburized layer of EN36 sample were 260 VHN and 840 VHN respectively. Both the samples were polished to initial roughness level of 0.2 μm (*R*a).

Table 1. Test conditions

Normal force	50 N
Oil temperature	90 °C
Frequency	20 Hz
Stroke length	2 mm
Time	180 m

3. RESULTS

The following section explains only the observations of the results obtained. A detailed discussion on the observations is separately given in Section 4.

3.1 Effect of additive proportions in engine oil

The effect of nano additive on friction profiles are as shown in Fig. 1a and 1b. The friction profiles are found to stabilize after initial bedding-in period. The additives seem to gradually influence after certain period and the COF stabilizes within a specific range. It is observed that 1:10 ratio has shown very small reduction in coefficient of friction (COF) compared to other two ratios although it almost merges with the base oil without any additives. The other two ratios have shown 25 to 30 % increase in COF compared to 1:10 ratio mixture clearly indicating the inferior effect of excessive additions. The two ratios of nano copper (2:10 and 3:10) also have shown slightly higher COF compared to boric acid additives.

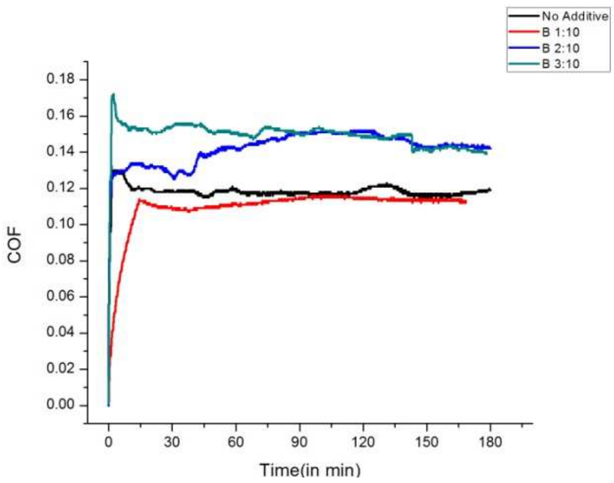

Fig. 1a. Coefficient of friction profiles for boric acid (B) additive in various proportions in engine oil.

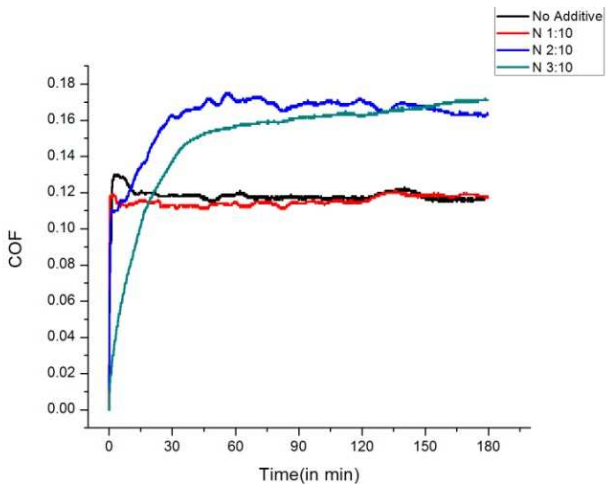

Fig. 1b. Coefficient of friction profiles for nano copper (N) additive in various proportions in engine oil.

The COF comparison between boric acid and nano copper based additives for various ratios are as shown in Fig. 2.

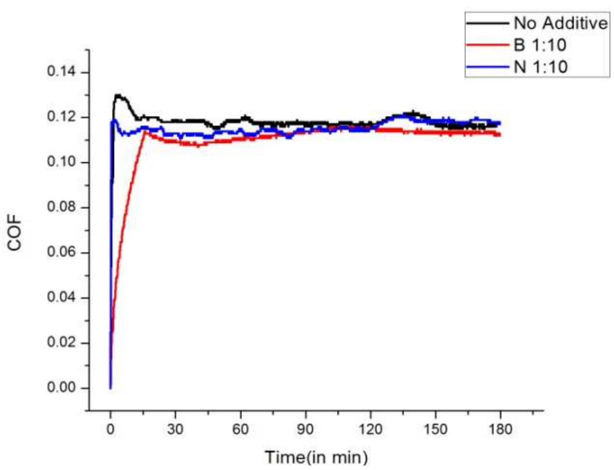

Fig. 2a. Comparison of coefficient of friction profiles of boric acid (B) and nano copper (N) additives in various proportions in engine oil for 1:10 ratio.

The friction profile merges with base oil at 1:10 ratio while it shows higher COF than base oil for other ratios. COF of boric acid is 10 to 12 % lesser than nano copper for 2:10 and 3:10 ratios.

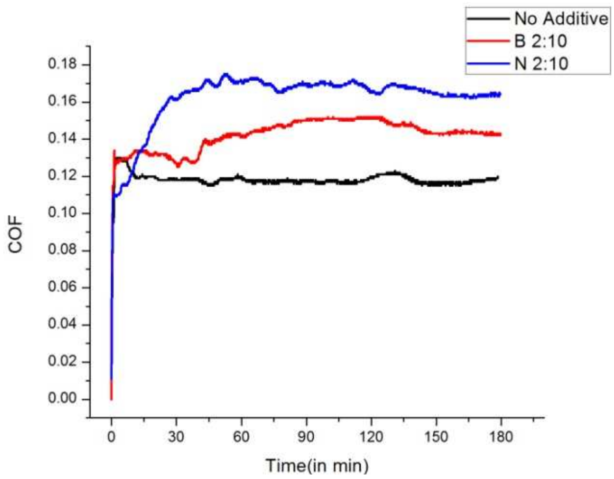

Fig. 2b. Comparison of coefficient of friction profiles of boric acid (B) and nano copper (N) additives in various proportions in engine oil for 2:10 ratio

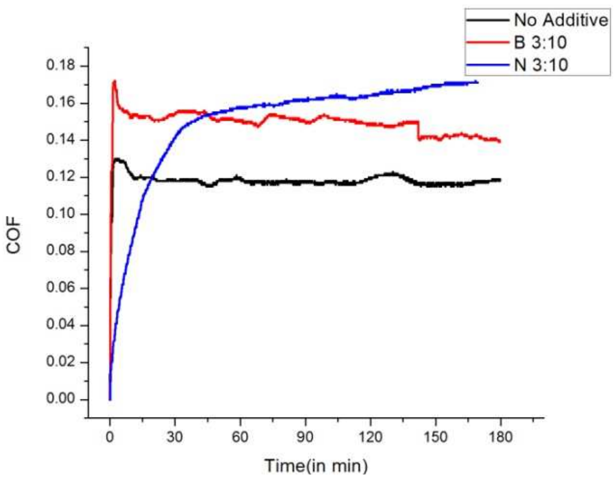

Fig. 2c. Comparison of coefficient of friction profiles of boric acid (B) and nano copper (N) additives in various proportions in engine oil for 3:10 ratio.

3.2 Effect of additive proportions in transmission oil

The COF profiles of additives in various ratios in transmission oil are as shown in Fig. 3. The reverse trend is observed here compared to the performance of additives in engine oil. The sliding counterpart here is carburized gear steel unlike plain cast iron in former case. It is observed that COF slightly reduces with all the ratios of additives for both boric acid and nano copper. Nano copper additive shows higher reduction of COF (~ 12 – 15 %) compared to boric acid (~ 5%).

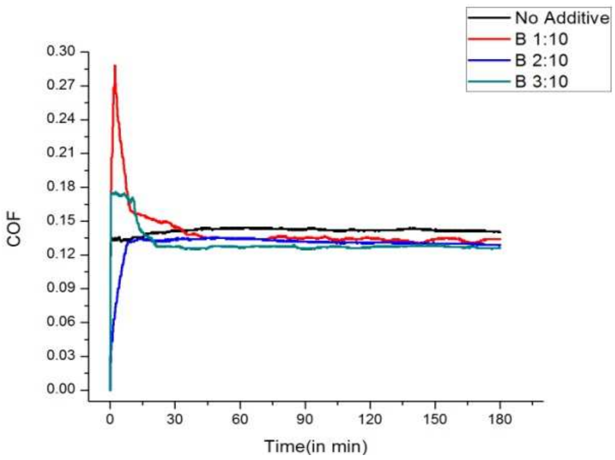

Fig. 3a. Coefficient of friction profiles for Boric acid (B) additive in various proportions in transmission oil.

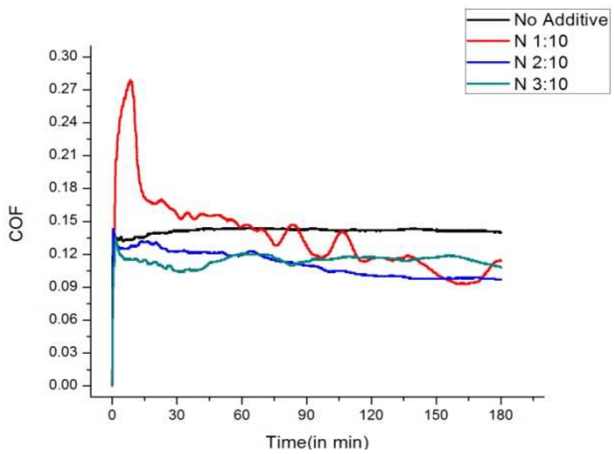

Fig. 3b. Coefficient of friction profiles for Nano copper (N) additives in various proportions in transmission oil.

The COF comparison between boric acid and nano copper based additives for various ratios are as shown in Fig. 4. Both the additives have shown 10 to 30% reduction in COF. Nano copper has shown slightly better COF reduction compared to boric acid.

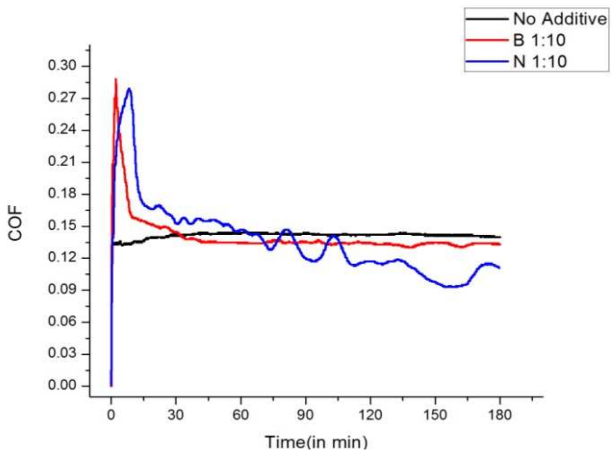

Fig. 4a. Comparison of coefficient of friction profiles of boric acid (B) and nano copper (N) additives in various proportions in transmission oil for 1:10 ratio.

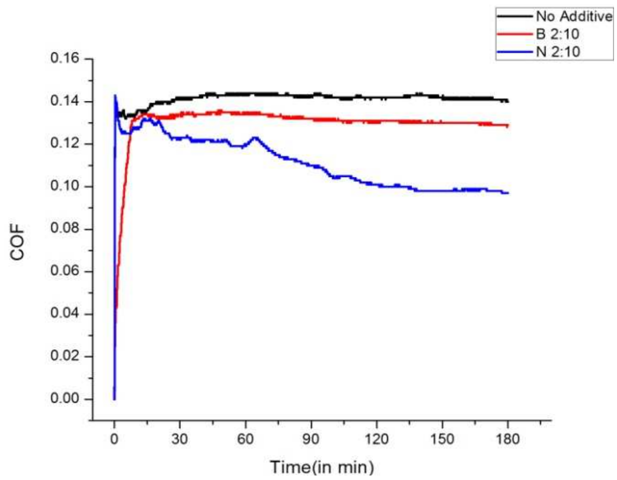

Fig. 4b. Comparison of coefficient of friction profiles of boric acid (B) and nano copper (N) additives in various proportions in transmission oil for 2:10 ratio.

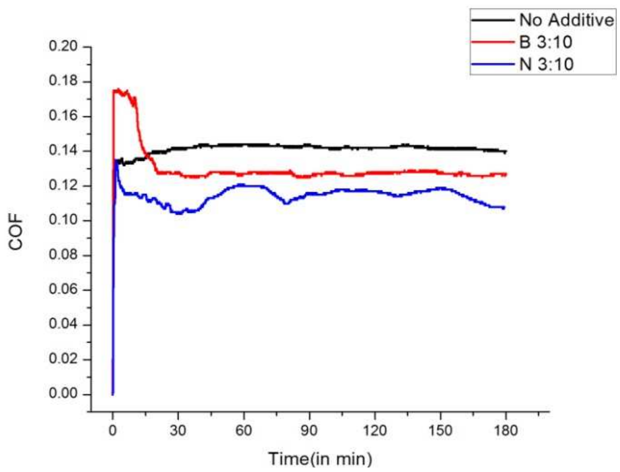

Fig. 4c. Comparison of coefficient of friction profiles of boric acid (B) and nano copper (N) additives in various proportions in transmission oil for 3:10 ratio.

3.3 Wear track features

The comparison of wear tracks for both the additives under different experimental conditions are shown in Fig. 5. Figure 5a shows the wear tracks for engine oil with additives in various ratios. General observations show that the damage is more on softer cast iron sample than case carburized steel sample. Figure 5a indicates that engine oil without additive shows reduced wear than nano copper while the boric acid additive shows decreasing damage with increase in additive ratio even with high COF values (Fig. 1a). The damage is extremely high with nano copper additive for all the ratios.

In case of transmission oil additives, the wear damage increases with increasing ratios (Fig. 5b) in spite of reduction in COF (Fig. 4). Wear damage on sample without additive is comparable with 1:10 ratio. Both the additives shows almost similar wear damage when suspended in transmission oil on hard surface. But the damage is far less compared to additives in engine oil with cast iron as counter sample.

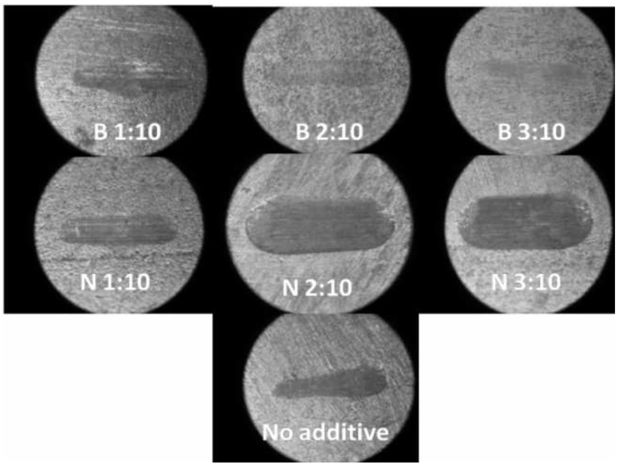

Fig. 5a. Wear tracks of boric acid and nano copper in engine oil.

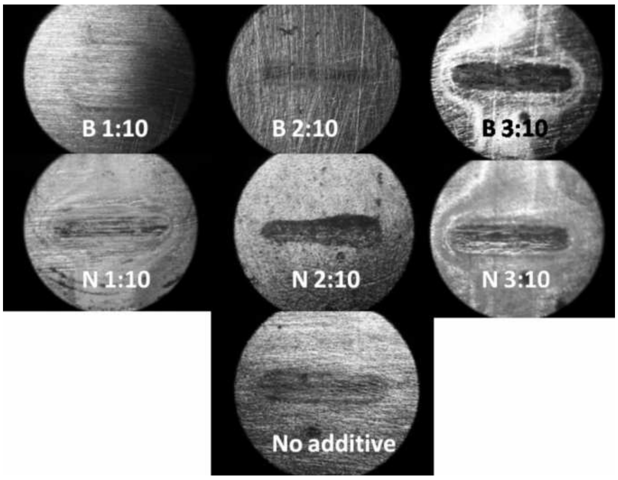

Fig. 5b. Wear tracks of boric acid and nano copper in transmission oil.

3.4 Wear track depth analysis

The comparison of wear depths is shown in Fig. 6 and 7 for various proportions of boric acid and nano copper in engine and transmission oil. The wear depth for various additive proportions shows decreasing trend for boric acid while it shows increasing trend for nano copper in engine oil (Fig. 6) as also confirmed in Fig. 5a with decreasing wear track damage. The wear track width also decreases accordingly. The depth of damage is very high for 2:10 proportion of nano copper and decreases for 3:10 ratio. The wear damage of nano copper is much larger than sample without additives.

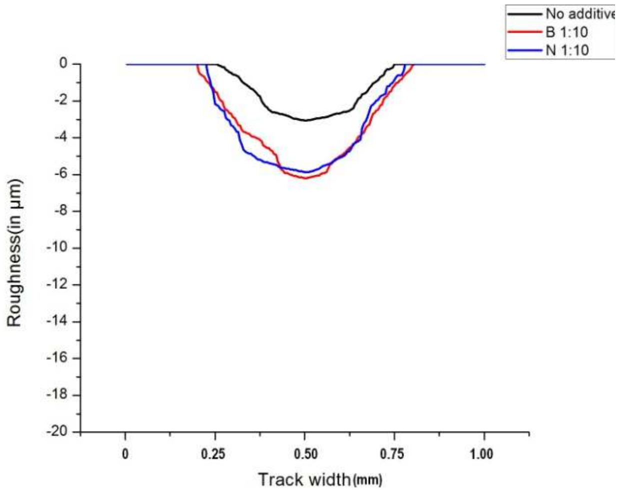

Fig. 6a. Comparison of wear depths for boric acid (B) and nano copper (N) for 1:10 ratio in engine oil.

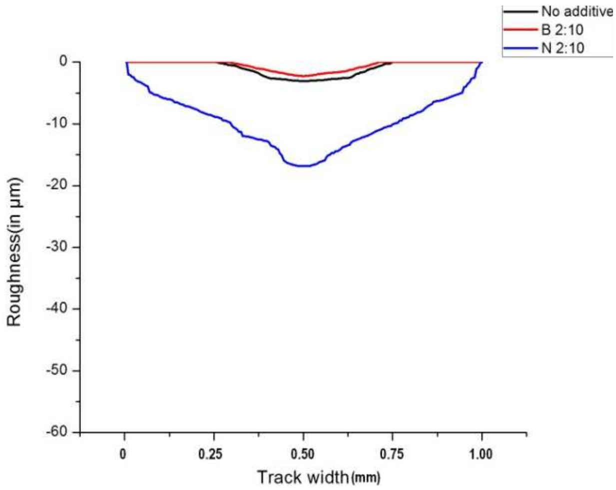

Fig. 6b. Comparison of wear depths for boric acid (B) and nano copper (N) for 2:10 ratio in engine oil.

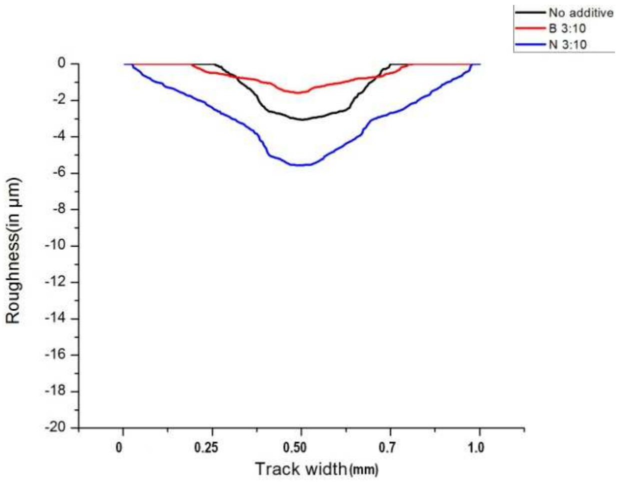

Fig. 6c. Comparison of wear depths for boric acid (B) and nano copper (N) for 3:10 ratio in engine oil.

In contrast, the wear damage depths for various additive proportions in transmission oil (Fig. 7) are much less compared to engine oil (Fig. 6).

The reverse trend is also seen here. Both the boric acid and nano copper additives have shown an improvement in wear protection compared to engine oil on cast iron substrate. Even here, the highest proportion of nano copper (3:10) has done a wear damage similar to sample without additives.

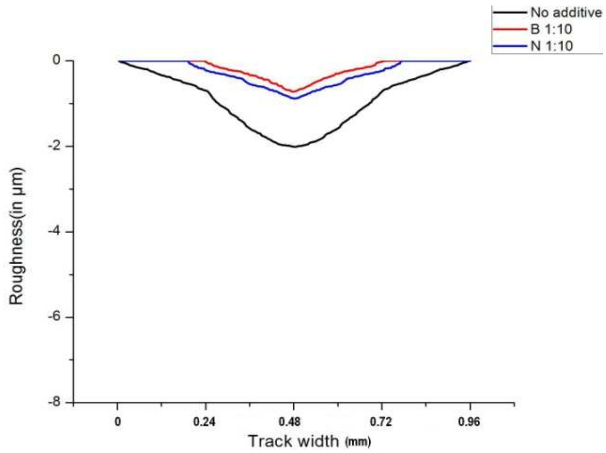

Fig. 7a. Comparison of wear depths for boric acid (B) and nano copper (N) for 1:10 ratio in transmission oil.

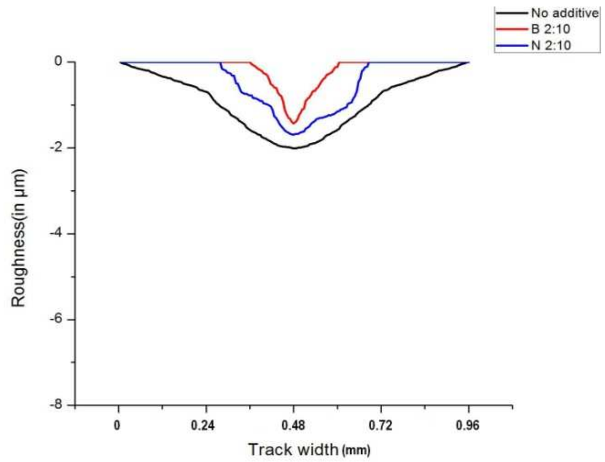

Fig. 7b. Comparison of wear depths for boric acid (B) and nano copper (N) for 2:10 ratio in transmission oil.

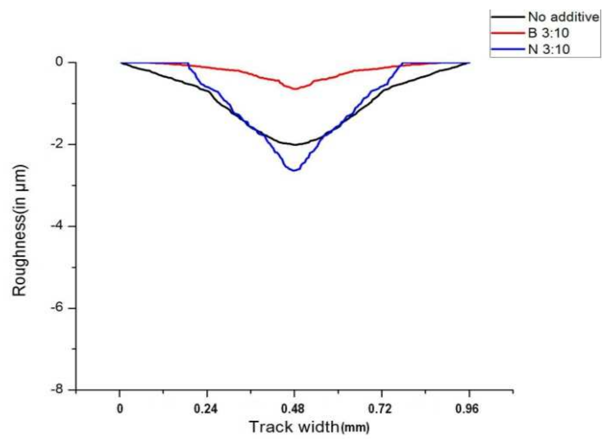

Fig. 7c. Comparison of wear depths for boric acid (B) and nano copper (N) for 3:10 ratio in transmission oil.

4. DISCUSSIONS

The results show some interesting trends with various additives and their ratios in the base oil on the COF profiles. It is observed that, COF increases with increasing additive ratios in case of engine oil and reduces for transmission oil.

In case of experiments with engine oil, the tribo-pairs comprise of a hardened steel ball on a soft cast iron material. With the application of normal load, the point contact is known to generate humongous contact pressure. Hence the softer material elastically complies more than the hard material. So the suspended nano particle that gets inside the contact point also has to undergo the pressure variations as that of the contact. Moreover the cast iron contains embedded soft flaky graphite within the contact which is known to initiate cracks and subsequent wear of material generating metallic debris. So the increase in COF is possibly the hindrance to the sliding motion from the nano particles as well as the embedded graphite flakes / metallic debris. Higher concentration of nano particles might actually induce more hindrance by lumping and blockading and make the contacts more difficult to slide over each other. Even the friction profiles with slight ups and downs indicate the possibility of such phenomena.

On the other hand, the additives in transmission or gear oil have shown a reverse trend. The tribo-pair comprises of hardened steel ball on case carburized gear steel. The contact stress distribution pattern and magnitude is quite different from that of former case. Both the tribo-pairs are hard enough to resist higher level of compliance. The contact diameter and depth for the same normal load on the hardened surface is much lesser than softer substrate thereby increasing the contact pressure. The increased pressure is probably more effective in shearing the boric acid latticed structure or flattening the nano copper particles that get inside the contact to reduce friction as well as wear.

Another interesting observation is that boric acid slightly reduced COF compared to nano copper (Fig. 2b and 2c) in case of experiments with engine oil experiments possibly due to easy shearing of layered lattice structure compared to nano copper with a crystalline structure typical of a metal. The load distribution pattern under soft cast iron and hardened steel ball possibly favors shearing action. But in case of experiments with transmission oil, nano copper showed slightly lower friction (Fig. 4). The sliding force required for metallic copper layer under hard carburized steel and hardened steel ball might be lesser than a layered compound like boric acid which may lose favorable alignment towards the sliding direction and gets distorted to increase the frictional force. The contact load distribution profile and magnitude in both these cases might differ significantly to affect such a difference in COF profiles.

From the observations of features in the wear tracks, it can be inferred that both the properties of the substrate material and the concentration of additives in the oil plays a significant role [2–4]. Softer substrates show more wear damage. Higher concentration of additives is actually detrimental to the sliding pairs. Therefore 1:10 dilution recommended by the supplier itself seems to show better results than higher concentrations. The damage is more with nano copper than boric acid based additive possibly from the three body wear mode of interaction. Copper being a metallic particle possibly tends to be more severe in three body interaction at higher concentrations under lower contact pressures than its boric acid counterpart. It possibly tends to erode the softer substrate but interacts favorably only on hardened surfaces. It can also be inferred that even though the nano suspensions are soft and lubricious by nature, they tend to harshly damage the sliding surface at higher concentration possibly through transient agglomeration and pile-up at the leading edge of the contact. Variations in normal load may give different results which are not investigated here. But contact pressure, the nature of additives and the substrate properties play a significant role in wear and friction profile of the contact. The wear depth profiles indicate differences in depth and width according to the wear protection offered by the respective additive. In many cases the nano copper additive has created deeper and wider tracks than boric acid due to three body wear process described earlier.

Closer observations with SEM and EPMA at the wear tracks did not reveal any permanent adherence or pile up of layers indicating that the particles lowers the friction or wears down the surface by three body interaction without any permanent settlement as adhered layers. Higher load and frequency also generates frictional heat at the contact and sometimes causes the conversion of compound based lubricants like boric acid to other forms such as metaboric acid or boric oxide due to heat induced dehydration [13]. Such compounds are not anymore lubricious and may damage the surface. The particle size is also an important parameter in the tribological activity of sliding pairs. It is not a fixed number for all the systems. Optimum size for a particular system can only be identified after extensive experiments. At present, it can be inferred that boric acid based additive at all the three proportions tested has shown better results compared to nano copper for the chosen loading and frequency conditions. The concentration of additives above the recommended proportion (1:10) is detrimental to the sliding members in terms of wear protection although it has shown favorable response for transmission oil compared to engine oil.

5. CONCLUSIONS

Nano boric acid and nano copper based additives in different volume proportions (1:10, 2:10, and 3:10) in engine oil SAE 15W40 and transmission oil SAE 90 were investigated for its friction and wear performance on cast iron and case carburized EN 36 steel. It was observed that COF generally increases with increase in concentration of additives in engine oil with cast iron samples. This is possibly due to higher compliance of soft cast iron substrate leading to transient agglomeration and pile up at the leading edge from the nano particle additives. The COF deceases for both the additives in case of transmission oil on hard case carburized surface due to increased contact pressure and sufficient flattening of nano particles with possibly lesser impediments.

The worn features show decreasing damage in engine oil with cast iron substrate and increasing damage in transmission oil with case hardened steel substrate for boric acid additives in three different proportions. Nano copper shows higher damage for incremental additive proportions in both engine oil and transmission oil due to crystalline nature of metallic particle with three bodies wear mode of interaction compared to boric acid film with layered lattice structure. The layers of boric acid are easy to shear compared to metallic system with regular atomic crystal structure. The depth of wear tracks also confirms the same.

Finally it can be inferred that based on the nature of the substrate material, boric acid shows better results than nano copper with incremental additive proportions in engine and transmission oil. Higher proportions of additives more than the recommended ratio (1:10) is actually detrimental for the sliding pairs.

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