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Lubricated sliding behaviour of h-AMMC/CI contacts under surfactant-assisted MWCNTs mineral oil

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Abstract

The present investigation is focused on the tribological behavior of hybrid aluminium metal matrix composite (h-AMMC) sliding against cast iron (CI), under the surfactant assisted MWCNTs-in-oil lubricant. For this purpose, the MWCNT-in-oil lubricants were prepared in the presence of a non-ionic surfactant. The friction-wear results reveal that the surfactant assisted MWCNT-oil dispersions with an optimized concentration of surfactant significantly improve the friction-wear behavior for composite-cast iron contacts. Inherent properties of MWCNTs, better thermophysical and dispersibility characteristics of nano-dispersions, shear sliding of micellar structures under friction action and formation of protective tribo-layer are the prominent factors that responsible for improvement in lubricity and tribological performance. Characterization of the worn-out surfaces of h-AMMC is carried out using various techniques such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), surface roughness testing and Raman spectroscopy. The study reveals some interesting insights on the performance of surfactant assisted MWCNT-laden lubricants, which might be connoted for the future development of the lubricants to be used in the industrial applications.

Keywords: Nanolubrication, AMMCs, Surfactant, MWCNTs, Lubrication mechanism, Raman spectroscopy, SEM-EDS, Anti-friction, Anti-wear, Lubricant Additive

Introduction

Metal matrix composites (MMCs) have proven their prominence as acceptable alternatives to conventional metal alloys or monolithic materials, in respect to higher values of stiffness and strength with an advantage of low density and applications in various sectors like industries, automobiles, and aerospace [1].

Lubricated tribology of composites is a less explored arena [2]. Recent developments in the particle-based lubricant/lubricated tribology of AMMCs have been explored by various researchers [3-12].

Moreover, the effectiveness of lubricant formulation using the tubular particle additives such as MWCNTs is influenced by particle's dispersion capability and stability in the suspension. This is often improved by functionalizing the nanoparticles or using surfactant and dispersants [13]. However, such studies involving functionalized nano dispersions while improving the tribological behavior of composite surfaces are also not available in the literature [14].

Singh and Bhowmick carried works related to lubrication and wear mechanism mapping of particle based lubricants with and without use of surfactant under hybrid AMMC(h-AMMC)/steel contacts[15,16]. From those studies, it was evident that MWCNTs can be used as potential oil additive under composite contacts. Also, role of surfactant and its concentration on the tribological characteristics of MWCNT-in-oil lubricant for a hybrid AMMC-steel sliding contact was also examined in great detail [14]. Nevertheless, commercially available fully formulated oil was also additized with surfactant-fucntionalized MWCNT and tested under h-AMMC/EN31 contacts. Improved tribological, rheological and thermophysical performance of modified fully formulated oils in comparison to fresh oils and additized mineral oils[13].

No work is carried out on the study of tribological investigation and underlying mechanism of surfactant assisted MWCNT based mineral oil under hybrid aluminium metal matrix composites and cast iron contacts. Hybrid MMC and CI tribopair is an important domain of the industrial research to fulfill the demand of improved engine tribology [13].

Materials and Characterizations

In hybrid composite fabrication, Al6061-T6 alloy is used as matrix material, silicon carbide as hard reinforcement, and graphite as soft reinforcement. A cost-effective stir casting approach was used to prepare the lightweight, high hardness composite. Selection criteria of both the reinforcements, composition and fabrication parameters related to casting were discussed in the previous studies [13, 16]. The BSE and Optical micrographs of fabricated composites are shown in Figure 1. The presence of graphite at the interface of aluminium matrix and ceramic is depicted through the EDS mapping (Figure 2).

A pilot study was carried for dry sliding aluminium and h-AMMC contacts [15]. A significant coefficient of friction (COF) was recorded for aluminium contacts, whereas the reduction in the coefficient of friction for h-AMMC-CI dry contact (average COF is 0.32) [15] is due to the existence of the reinforced carbide particles, which act as load-bearing members and reduces the contact area between the tribo-pairs [17], as well as a smeared layer of graphite releasing from the matrix which acts as a lubricant [18].

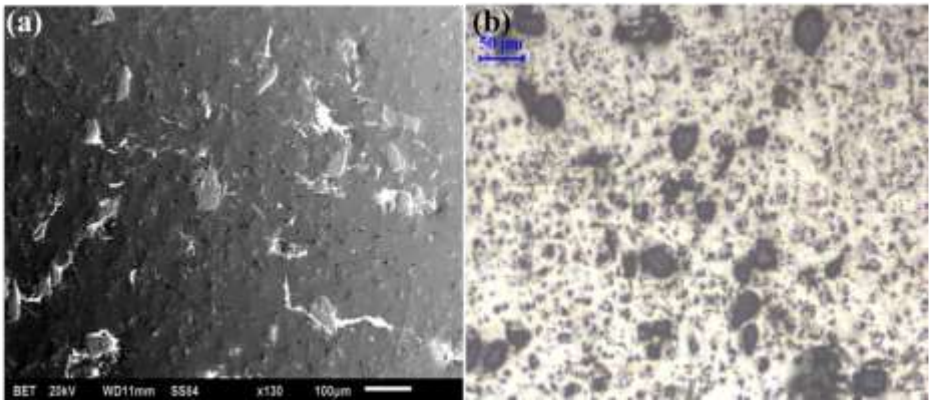

Figure 1: (a) BSE micrograph (b) Leica micrograph, of h-AMMC.

In the present study, a pin-on-disc tribometer (TR-201 LE) is used to conduct friction and wear examinations. For the sake of comparison, tests were conducted under constant tribological parameters (Load: 9.81N, Velocity: 0.5 m/s, and Time: 1800 sec). The preparation process of surfactant-assisted MWCNTs oil dispersions is described in the previous articles [13-16].

Graphite flakes can be visible in the disc material (see Figure 3). This feature will provide vulnerability to results of friction/wear and lubrication mechanisms.

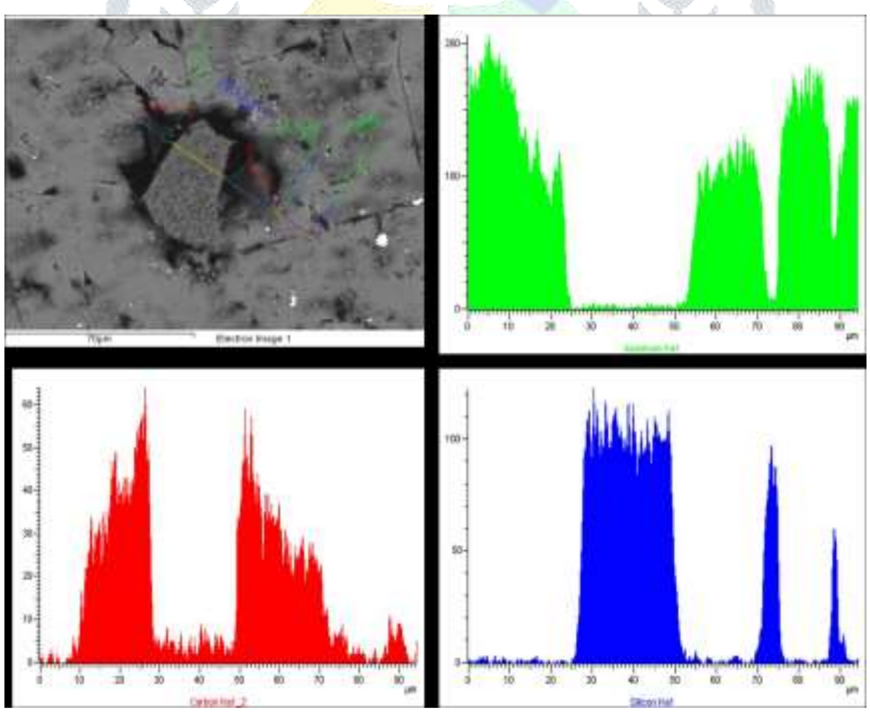

Figure 2: EDS micrograph showing the presence of graphite at the interface of aluminium matrix and ceramic.

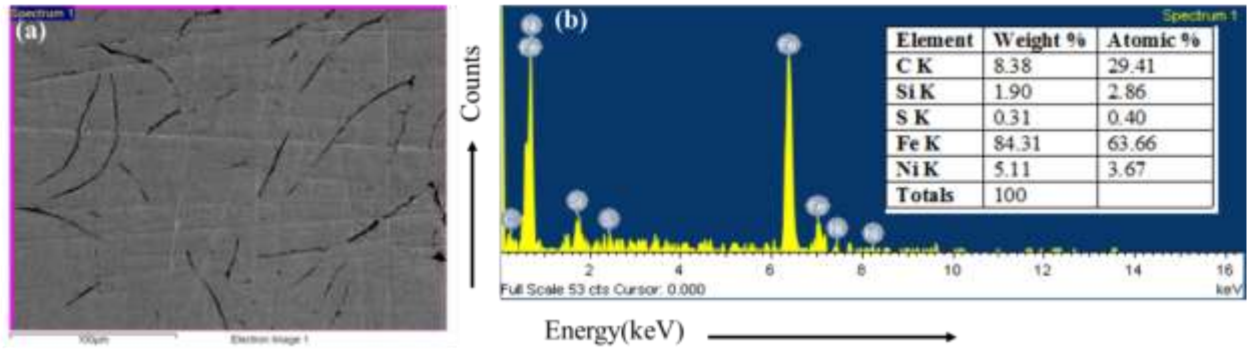

Figure 3: EDS micrograph of CI specimen

Results & Discussion

In the previous study, unlubricated, lubricated, and MWCNT particle-based lubricated tests were conducted [15]. From the friction curve (see figure 4), it is cleared (from table 1) that with the application of surfactant-assisted MWCNT oil dispersions, cof is now decreased further to~0.042±0.013, which is lowest among other sliding conditions.

Table 1: Important studies relevant to tribological investigations of h-AMMC/CI sliding contacts.

Sliding condition	**COF,μ**	**Wear rate, $mm^3/m\times10^{-4}$**	**Surface roughness parameters, Ra,Rq &Rz**
Unlubricated [15]	0.32±0.026	18.79±0.048	-
Fresh oil(SN500) [15]	0.08±0.024	6.32±0.014	Ra=0.83 μm, Rz=4.9 μm & Rq=1.05 μm
Fresh oil (SN500)+MWCNTs [15]	0.05±0.003	1.09±0.008	Ra=0.46 μm, Rz=2.5 μm & Rq=0.57 μm
Fresh oil (SN500)+MWCNTs +SPAN80 [Present study]	0.042±0.012	0.123±0.004	Ra=0.40 μm, Rz=1.7 μm & Rq=0.47μm

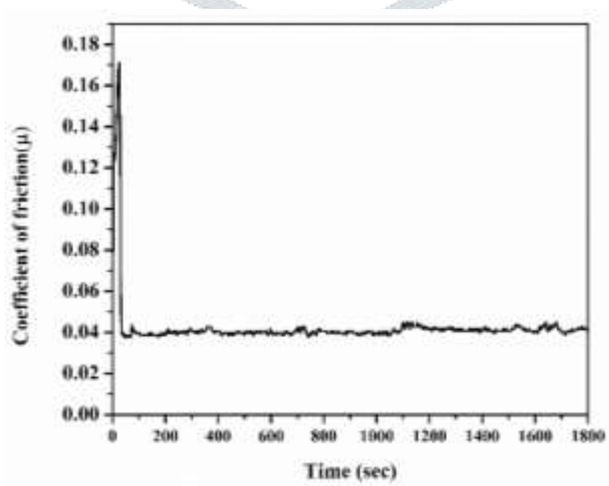

Figure 4: COF versus time variation of h-AMMC/CI contact under surfactant-assisted MWCNT sliding (Load: 9.81 N, Velocity: 0.5 m/s & Time: 1800 sec).

This decrease was due to protective tribolayer formation. Raman spectroscopy of worn-out composite pin surface sliding against CI after surfactant-assisted MWCNT oil is represented in Figure 5. These spectrums depict the observed peaks corresponding to carbon nanostructures. The obtained results are in line with the previous literature results [19-21]. The various bands such as G, D, and 2D of graphitic structures in the spectrum were obtained on usual Raman shifts at 1568, 1335, and 2671 cm^{-1}.

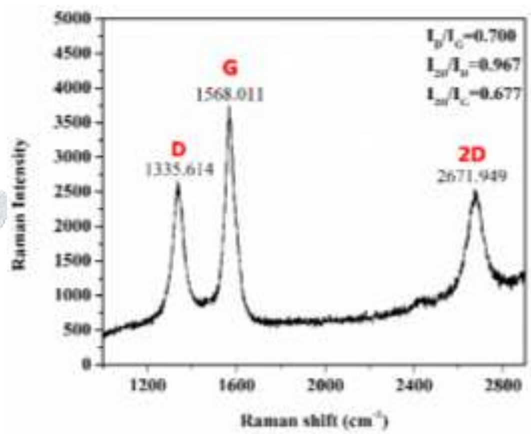

Figure 5: Raman spectrum of worn-out composite pin surface sliding against CI after surfactant-assisted MWCNT oil dispersions.

Also, surfactant-assisted dispersions are more stable and dispersible, improving lubrication performance by monitoring viscosity and film thickness [13]. The authors have used a non-ionic surfactant, SPAN 80, to modify MWCNT particles in the present study. A little consideration shows that the formation of micelle and shear sliding of micelle phenomenon also improves the lubricity and friction.

Also, there is a reduction in the surface roughness parameter values from 0.83 μm (for fresh oil sliding [15]) and 0.46 μm (for MWCNT-oil dispersions [15]) to 0.40 μm (in the present study-surfactant assisted MWCNT oil dispersions(see, Figure 6). This lowering of roughness values must be due to entrapment of functionalized solid additive and formation of mixed layers, and the polishing phenomenon under the given loading conditions. The friction behaviors could exemplify these decreases in the roughness. In grafted SPAN80-MWCNT particles, the occurrence of penetrated nanosized particles with their length in micron size helps shield the asperity contacts to a significant level [15].

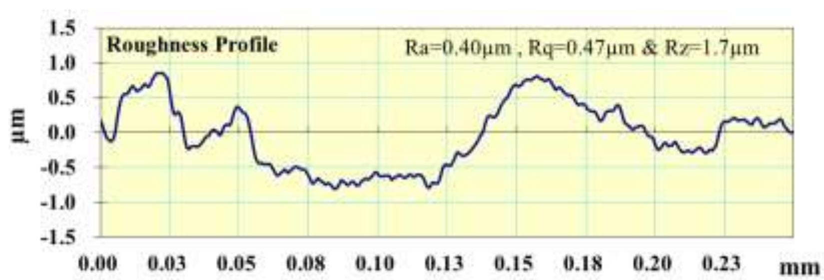

Figure 6: Surface roughness of worn-out h-AMMC pin after the tribological test at a sliding velocity of 0.5 m/s, applied a load of 9.81N and time of 1800sec, sliding under

surfactant-assisted MWCNTs oil dispersions, sliding against CI.

A less worn-out surface was captured in the electronic microscopy (see, Figure 7). Oxidation, abrasive, and adhesive wear modes were the dominating mechanism in this lubricated sliding. However, oxidation cracks and pits can be easily seen in the micrographs. Material transfer phenomenon is also occurred during sliding, as a significant amount of Fe is traced in all the EDS spectrums (see Table 2). Minute presence of Cr ensures the possibility of the transfer. EDS also detects oxygen in all the selected EDS maps. This demonstrates the oxidation of aluminium into amorphous natured aluminium hydroxides under high localized temperature conditions [15]. An outstanding amount of carbon percentage was detected in the EDS maps, which confirms the formation of continuous patches of a carbonaceous layer. Also, this carbon may contribute towards the formation of iron carbides which provides a better antiwear effect for the lubricated contacts [15]. Deep insight characterization of tribo-layer will be discussed in future works.

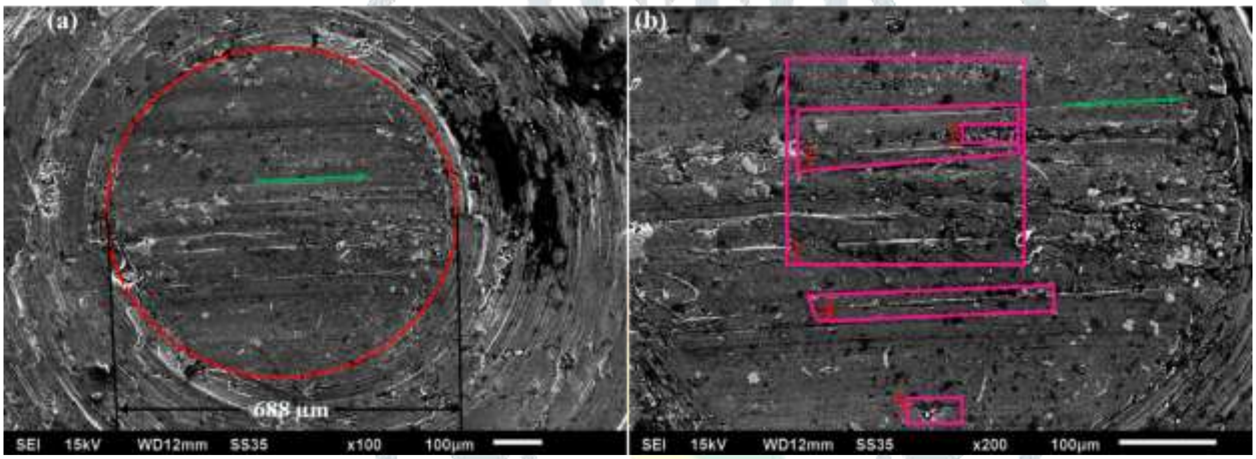

Figure 7: (a) Overview of the worn-out h-AMMC pin after surfactant assisted MWCNT oil sliding (b) Selected EDS maps on SEM micrograph. Inset rectangles marked in figure (b) represent the selected EDS areas. Green arrows depict the sliding direction.

Table 2. Elemental analysis (wt.%) on the worn-out h-AMMC pin sliding against CI surfaces under surfactant-assisted MWCNTs oil dispersions.

EDS spectrum	C K	O K	Na K	Mg K	Al K	Si K	Mn K	Fe K	S K	Cr K
1	25.72	9.86	0.10	0.43	54.67	2.96	0.16	6.11	-	-
2	38.10	21.20	0.22	0.19	26.31	0.85	0.33	12.32	0.11	0.36
3	23.51	11.57	0.08	0.40	54.55	3.47	0.33	6.00	0.09	-
4	23.30	7.98	0.01	0.48	63.26	2.06	0.12	2.41	0.05	0.33
5	26.77	10.37	0.04	0.47	43.95	15.29	0.05	2.80	0.07	0.20

Conclusions

The primary objective of the present investigation is to study the role of non-ionic surfactants in the tribological properties of the selected hybrid AMMC-CI pair. MMC characterization and surface analysis (Microstructural, morphological, and topography) of the worn-out specimen reveals the following interesting facts.

- Surfactant-assisted MWCNTs oil dispersions effectively control friction and wear of h-AMMC/CI contacts.
- Inherent properties of MWCNTs like high thermal conductivity and young's modulus and effortless disintegration into Graphene sheets (confirmed by Raman spectroscopic results) are the primary factors for improving tribological performance.
- High dispersibility characteristics and better rheological properties are important reasons for improved lubricity.
- Penetration of nanosized particles with their length in micron size helps in shielding the asperity contacts to a significant level.
- Protective carbonaceous tribolayer is responsible for better tribological properties.
- Wear performance is monitored by the presence of MMLs (carbide particles and material transfer products and solid lubricant(embedded Gr from the matrix) coupled with CNTs under liquid lubrication and their synergic effects provided adequate antiwear resistance for contacts.
- SEM-EDS and topography investigations disclose the underlying tribolayer compositions and their role in defining the favorable tribological characteristics. The formations of continuous carbonaceous and composite tribolayers and the grafting of the surfactant on the MWCNTs are attributed to the enhanced tribological behavior of h-AMMC-CI tribopair under surfactant modified MWCNTs-oil dispersion.

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