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Influence of cooling mediums on mechanical and tribological characteristics of Al/Cu-based composites reinforced with chromium particles

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Abstract

The intensity of radial heat flux during quenching affects the microstructural features of materials. The interface strength is also affected by the radial heat flux in the case of metal matrix composites (MMCs). Thus, the mechanical and tribological behaviour of MMCs may vary with the quenching medium. The present investigation deals with the effect of the quenching medium on the mechanical and tribological behaviour of chromium (Cr) particles reinforced Al/Cu dual matrix composites. Normal load (viz. 20, 40 and 60 N) and weight percentage of Cr reinforcement (viz. 1, 2, 3, 5, 8 and 10 wt. %) were also varied. The powder metallurgy route was followed for the fabrication of composites. The sintered composites were normalised and quenched in oil and water. The results revealed that water-quenched composites exhibited the highest hardness and compressive strength and the lowest wear. The highest compressive strength was approximately 48 MPa for 3 wt. % Cr reinforced water-quenched composites. The coefficient of friction decreased with an increase in Cr content, whereas it was very difficult to generalise the wear behaviour with respect to Cr content. The fractured and worn surfaces were analysed under a scanning electron microscope to know the fracture characteristics and dominant wear mechanisms, respectively.

1. Introduction

Metal matrix composites (MMCs) are replacing several monolithic metals and alloys in various application sectors such as defence, aerospace, transportation and sports due to their outstanding properties like high specific strength, better elevated-temperature characteristics, a low coefficient of thermal expansion and enhanced fatigue and wear resistance [1]. Furthermore, the tailoring strategies of the MMCs concerning their different constituents depend upon their application sectors [2-4]. Therefore, the different constituents of MMCs and the interface/interphase between them should behave exquisitely in a particular application sector.

In the whole plethora of MMCs, aluminium matrix composites (AMCs) are still preferred due to their low cost. The mechanical and tribological properties of AMCs can be enhanced by incorporating a suitable reinforcement in the aluminium (Al) matrix. For example, hard ceramic reinforcements like SiC [5] and Al_2O_3 [6] can be incorporated into the Al matrix, which reduces the chance of adhesion and abrasion, thereby increasing wear resistance. In their research work, David Raja Selvam and Dinaharan [7] incorporated ZrB_2 in the Al matrix and noticed an increase in tensile strength but a decrease in percentage elongation. In another research study, Suresh et al. [8] incorporated TiB_2 in an Al matrix and noticed an increase in wear resistance and ultimate tensile strength. The ceramic particles do not usually deform or pulverise, even at high loads. Thus, during tribological interactions, ceramic particles may act as a third body, increasing the wear rate. Furthermore, the ceramic particles have very low thermal conductivity, which may lead to heat pile-up at the contact surfaces during tribological interactions [9]. This increases the chance of adhesion. To counter these limitations of ceramic reinforcements, some other suitable reinforcements could be incorporated into the Al matrix. Hard metallic reinforcement could be a choice, although it is a much less investigated research area. In their research work, Kumar and Bijwe [10] incorporated metallic reinforcements in non-asbestos organic composites and found that composites with higher metallic contents showed better friction and wear performance. Furthermore, the metal-metal interface is usually stronger as compared to the ceramic-metal interface. However, as per the authors' knowledge, the incorporation of metallic reinforcement in MMCs is not yet consummated.

Copper (Cu) can also be used as a matrix for MMCs in tribology-related applications. It can act as a solid lubricant because it contributes to the formation of a layer of granular material [11]. Furthermore, it possesses higher hardness and thermal conductivity, superior corrosion resistance and a lower coefficient of thermal expansion, compared to Al [11]. These superb properties make Cu favourable in tribology-related applications, compared to Al. However, the higher cost and density of Cu restrict its applications. Thus, the optimum combination of Al and Cu can be used to get the best of both.

The hardness of materials is greatly affected by the quenching medium/rate [12], which in turn affects their wear resistance. Although there are several studies available on the effect of quenching medium on the mechanical and tribological characteristics of metals and alloys [13-15], the investigations on the effect of quenching medium on the mechanical and sliding characteristics of MMCs are very limited. Furthermore, the available literature is primarily focused on ceramic particles reinforced metal matrix composites. The literature considering the effect of metal particles reinforced MMCs is scarce. Thus, in light of the above, the present article focuses on investigating the effect of the quenching medium on the mechanical and sliding behaviour of chromium (Cr) reinforced Al/Cu dual matrix composites. Cr was selected as reinforcement due to its excellent properties, such as high hardness, high melting point, and ability to form a protective coating that prevents the substrate from oxidation [16-19]. Thus, the Cr-reinforced composites were prepared via the powder metallurgy route. Three quenching mediums (viz. normalised, oil and water) were considered.

2. Materials and methods

The powder metallurgy route was adopted to fabricate chromium-reinforced Al/Cu dual matrix composites (Cr-Al/Cu). The Al and Cu powders used for fabrication had a purity higher than 99.5 % and a size of less than or equal to 100 µm. Al powder was supplied by Qualikems Fine Chem, India, and Cu powder was supplied by Otto Chemie, India. To fabricate composites, the Al and Cu powders were mixed in the ratio 1:4 (Cu:Al) by weight using a mechanical stirrer (Heidolph RZR 2020) at 160 rpm for 20 minutes. The optimum ratio was determined in terms of tribological behaviour as discussed in our previous paper [20,21]. The Cr powder (purity higher than 99.9 % and size less than or equal to 150 µm) was then added into the Al/Cu mixture, with weight percentages corresponding to 1, 2, 3, 5, 8 and 10 wt. %. The Cr powder was supplied by Qualikems Fine Chem, India. The obtained mixture was again stirred using the same stirrer at the same parameters. After stirring, the resulting mixture was compaction moulded at a pressure of approximately 60 MPa at room temperature, and disc-shaped compacts were obtained with a diameter of 25 mm.

The sintering of the compacts was performed in a muffle furnace at a temperature of 450 °C for approx. 1.5 hours. Some of the sintered compacts were then normalised, whereas others were quenched in water and oil (kinematic viscosity of approx. 300 mm^2/s at room temperature). The quenching was performed at atmospheric conditions, i.e. at room temperature and atmospheric pressure. The green (without any heat treatment), normalised and quenched composite compacts were then prepared for mechanical and tribological tests. The composite samples were designated as listed in Table 1.

Table 1. Sample designation

Quenching medium	Chromium content in Al/Cu matrix, wt. %					
	1	2	3	5	8	10
Green	C1G	C2G	C3G	C5G	C8G	C10G
Normalised	C1N	C2N	C3N	C5N	C8N	C10N
Oil-quenched	C1O	C2O	C3O	C5O	C8O	C10O
Water-quenched	C1W	C2W	C3W	C5W	C8W	C10W

The mechanical behaviour of Cr-Al/Cu composites was assessed through the compression and Vickers hardness tests. Firstly, the composite samples were ground using emery papers of grades P800, P1200 and P2000, followed by polishing using diamond paste. Compression tests were performed on a material testing system using the Brazilian disc configuration [22] with a moving head rate of 2 mm/min. Three tests were conducted for each composition. The diameter of the composites was 25 mm and the thickness was 4 mm. The Vickers hardness of composites was also evaluated at a load of 5 kg with a dwell time of 30 s (model Mech CS VM30, Mechatronic Control System). The hardness was evaluated at a minimum of three locations (approx. 6 mm apart) on the surface to eliminate the possible segregation effects.

The friction and wear behaviour of Cr-Al/Cu composites were evaluated using a pin-on-disc tribometer (model BRO21HO, Magnum Engineers). The composite samples were prepared to a diameter of 10 mm and polished to a *Ra* value of 0.3 µm prior to wear testing. The counter-body (disc) surface was also polished to obtain maximum conformity of interacting surfaces. The disc was also ground to a surface roughness (*Ra* value) of 0.3 µm. The counter-body was a hardened ground steel disc (EN32), having a hardness of 65 HRC. To ensure maximum conformity, the friction couple was subjected to a running-in process for a sliding distance of 3000 m at a normal load of 20 N and a sliding velocity of 1 m/s. The composite samples were cleaned with acetone after running-in and weighed. Samples were then subjected to tribological tests with a sliding distance of 4000 m. The normal load varied as 20, 40 and 60 N, while the sliding velocity was kept constant at 1 m/s. The tests were conducted for a minimum of three replicas. Samples were weighed after the tests to obtain wear. All tests were conducted at atmospheric pressure and ambient temperature (26 – 31 °C). The humidity was in the range of 50 to 66 %.

3. Results and discussion

3.1 Microstructure

The microstructure of the composites was analysed using scanning electron microscopy (SEM). The SEM images of heat-treated and quenched composites are shown in Figure 1. To differentiate Al, Cu and Cr particles in SEM images, EDX analysis of composite C3W was performed, as shown in Figure 2.

It can be seen from Figure 1 that even after normalising, there were a few interparticle pores (porosity of 3 – 3.8 %, measured by Archimedes principle), which mainly occur due to linear and rotational motion of the particles in the presence of pressure during the compaction stage. However, if the sintering temperature is raised to approach the eutectic temperature or melting temperature of the low melting point powder, i.e. Al in the present case, transient liquid-phase sintering may lead to the development of particle-like pores. Thus, the sintering temperature was kept at 450 °C. The intraparticle bond networks of Al and Cu were also noticed. The porosity of sintered composites was the highest for oil-quenched composites (porosity of 6.1 – 7.3 %), followed by water-quenched (porosity of 4.7 – 5.4 %) and normalised composites, as can be depicted from Figure 1.

The high porosity of quenched composites may be attributed to the contrasting thermal expansion coefficients of Al, Cu and Cr. Furthermore, in the case of oil-quenched composites, the oil infiltrated into the pores and polluted the reinforcement/ matrix interfaces. Moreover, the quenching coefficient of water is higher than that of oil [23],

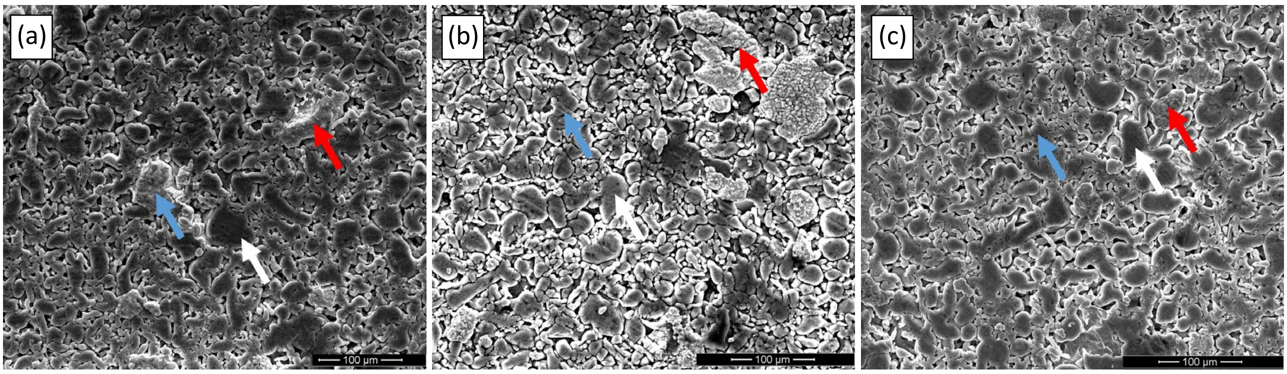

Figure 1. Microstructure (SEM image) of composite: (a) C5N, (b) C5O and (c) C5W; white, blue and red arrows indicate Al, Cu and Cr particles, respectively

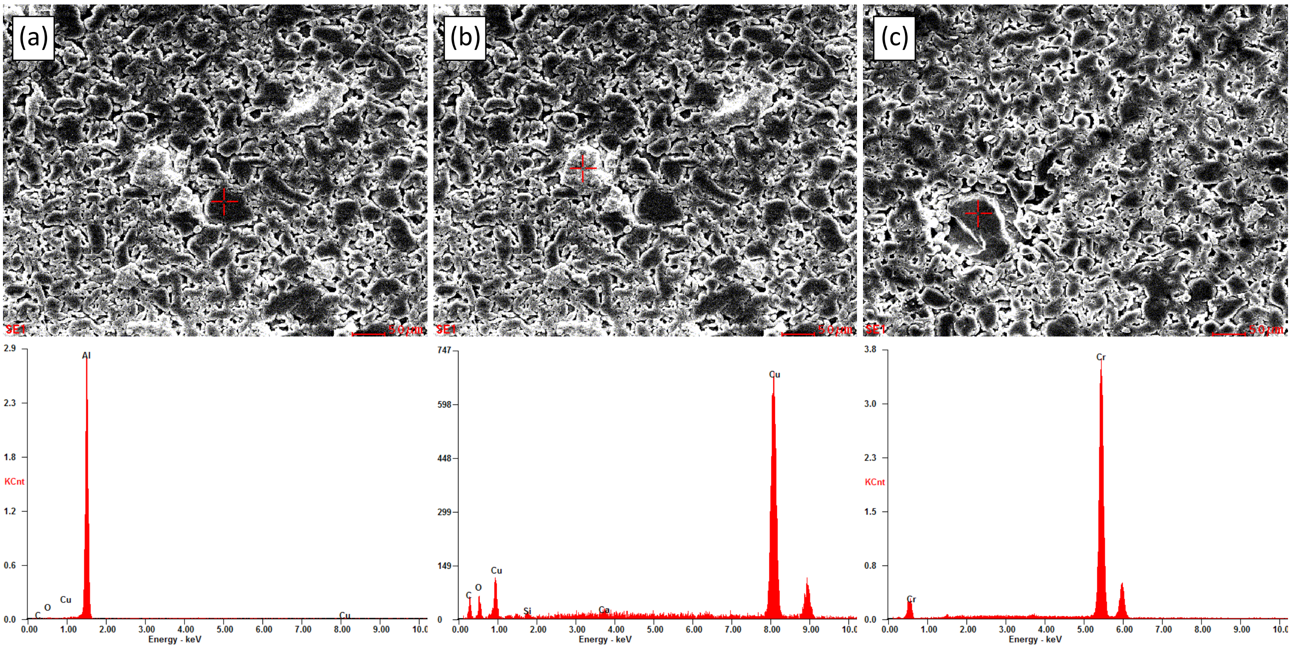

Figure 2. EDX analysis of composite C3W to differentiate: (a) Al, (b) Cu and (d) Cr particles

which means water exhibits a higher cooling rate of the composite in comparison to oil. Despite a lower cooling rate, the porosity of oil-quenched composites was higher than that of water-quenched composites. This may be attributed to the polluted reinforcement/matrix interfaces, due to which the resistance provided by interfaces to particle deformation was lower for oil-quenched composites [20,21,23].

3.2 Mechanical behaviour

As stated earlier, compressive strength and Vickers hardness were evaluated to assess the mechanical behaviour. Figure 3 shows the variation of compressive strength with the weight content of Cr.

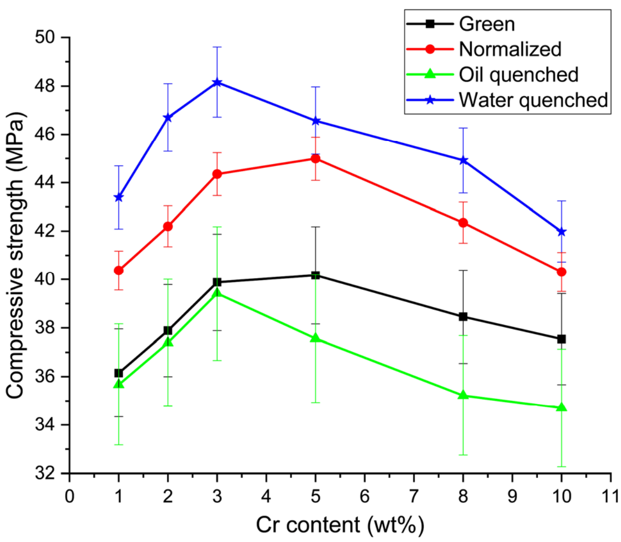

Figure 3. Variation of compression strength of composites with Cr content and quenching medium

It can be seen from Figure 3 that water-quenched composites exhibited the highest compressive strength, followed by normalised, green and oil-quenched composites. The lowest strength of oil-quenched composites may be attributed to the contamination of the particle/matrix interface by the oil and the highest porosity. Figure 4 shows the fracture surfaces of 5 wt. % Cr filled normalised, oil-quenched and water-quenched composites.

It can be seen from Figure 4b that the fracture surface of composite C5O did not exhibit any kind of particle deformation and the cracks propagated through the particles interfaces. This signifies that oil contaminated the interfaces, which decreased the interfacial and hence the overall strength of the composites. The particle deformation can be seen for composites C5N and C5W, as shown in Figures 4a and 4c, respectively, and is more pronounced in C5N compared to C5W. Despite the higher porosity of water-quenched composites, they showed higher compressive strength as compared to normalised composites. The higher strength of water-quenched composites may be attributed to the enhanced dislocation density strengthening effect owing to an increase in dislocation density due to the generation of additional dislocations because the matrix and reinforcement exhibit significantly different coefficients of thermal expansion (CTE), i.e. Al: 23×10^{-6} 1/K, Cu: 17×10^{-6} 1/K and Cr: 6×10^{-6} 1/K.

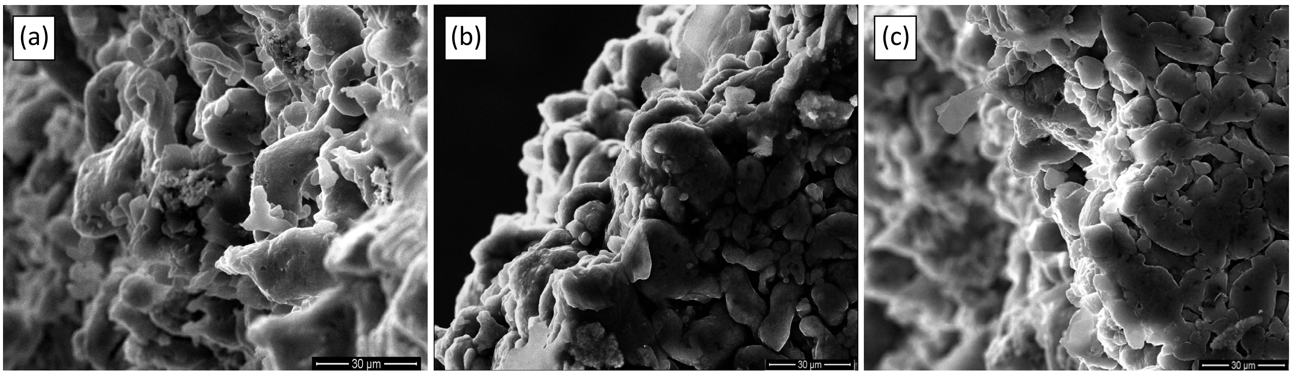

Figure 4. Fracture surfaces of composite: (a) C5N, (b) C5O and (c) C5W

Moreover, the generation of additional dislocations also depends upon the radial heat flux [24]. The water-quenching built up a higher heat flux compared to normalising, which also increased the strength. Furthermore, the generation of additional dislocations also depends upon the content of reinforcement particles [25,26]. The generated dislocations due to CTE mismatch increase with the increase in reinforcement volume fraction and accumulate in the interphase region of reinforcement/matrix rather than distributing in the matrix [25-27]. Therefore, the composites showed increased strength with an increasing Cr content. Moreover, the increase in reinforcement content also decreased the spacing among reinforcement particles and hence, higher strength is obtained due to the Orowan loops mechanism [28]. Furthermore, the application of an external load led to plastic deformation, causing Orowan loops to exert back stress on dislocation sources, which also increases strength [29]. However, the agglomeration of reinforcement particles at high Cr content reduced the interconnecting bonds between reinforcement and matrix, resulting in a decrease in strength [30], as shown in Figure 3. The Vickers hardness also followed almost the same trend as that of strength, as shown in Figure 5, except for the oil-quenched composites, which showed a decreasing trend with an increase in Cr content.

3.3 Tribological behaviour

The tribological behaviour of the composites was characterised by the pin-on-disc tribometer. Figures 6 and 7 show the composites' friction and wear behaviour, respectively. It can be seen from Figure 6 that the coefficient of friction decreases with an increase in the Cr weight content, regardless of the applied load. This may be attributed to the increase in hardness with an increase in Cr content, which results in a decrease in the extent of asperity penetration with increased Cr content. This led to a decrease in the deformation component of friction, which tends to decrease the coefficient of friction. The decrease in abrasion marks due to an increase in Cr content can be seen in Figures 8a and 8b. Moreover, the thermal conductivity of Cr is lower than that of Cu and Al, which is why the temperature rise of the contact surface was higher in the case of higher Cr content due to less heat transfer. Although it increases the adhesion component of friction, the heat accumulation at the surface of Cr particles led to their debonding from the matrix. The debonded Cr particles prevented direct contact between the contact surfaces. Hence, the coefficient of friction decreased with an increase in Cr content. The sites of debonded particles can be seen in Figure 8b.

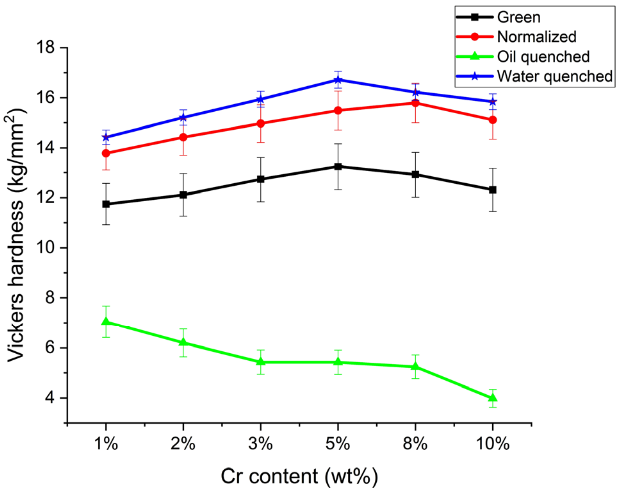

Figure 5. Variation of hardness of composites with Cr content and quenching medium

Unlike the coefficient of friction, the wear of composites increased when the Cr content was higher than a particular amount, as can be seen in Figure 7. The first decrease in wear, up to a certain Cr content was mainly attributed to the increase in hardness, which increased the abrasion resistance.

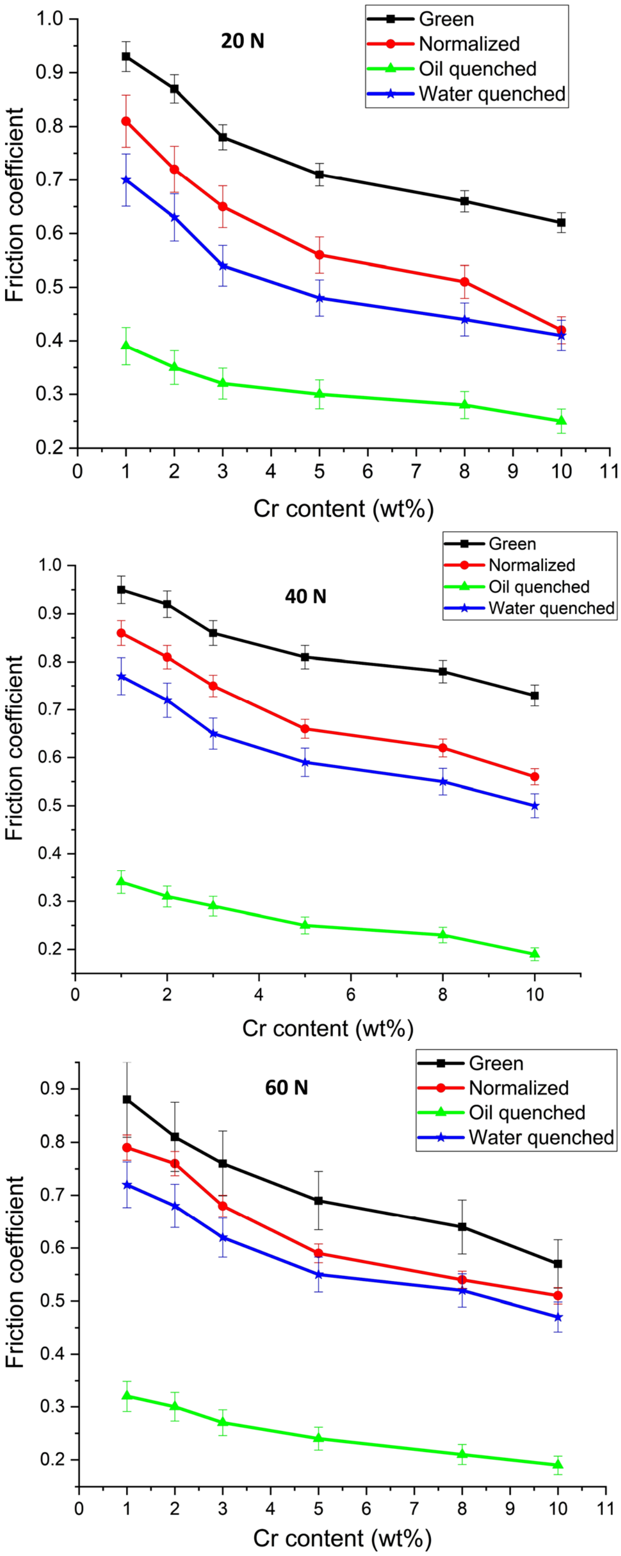

Figure 6. Variation of coefficient of friction of composites with Cr content and quenching medium for different normal loads

However, when the Cr content was higher than a particular amount, the increase in temperature led to an increase in adhesive wear, as can be noticed in Figure 8. In addition, the debonding of Cr particles also contributed to the wear. Furthermore, three-body abrasive wear also occurred due to the debonding of Cr particles. Therefore, wear increased at higher Cr content. The increase in adhesive wear and debonding of Cr particles are shown in Figure 8 for composites with 5 and 10 wt. % Cr and different quenching mediums.

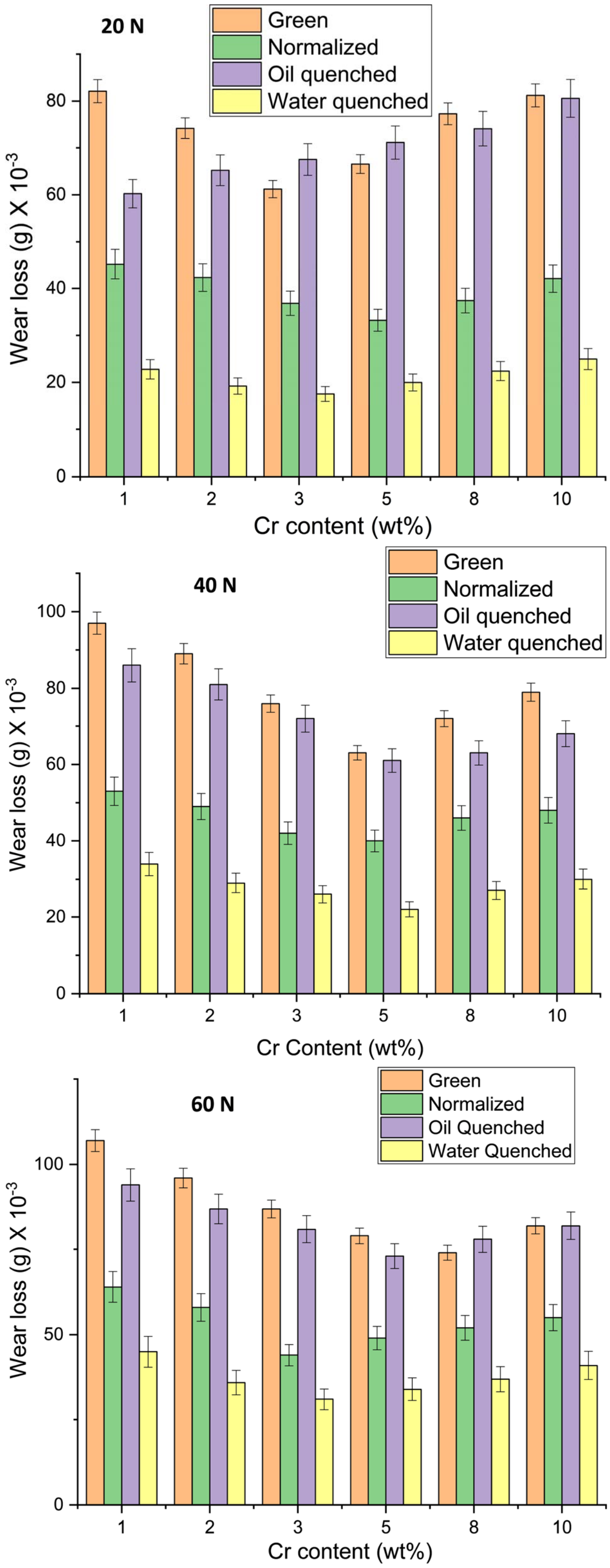

Figure 7. Variation of wear of composites with Cr content and quenching medium for different normal loads

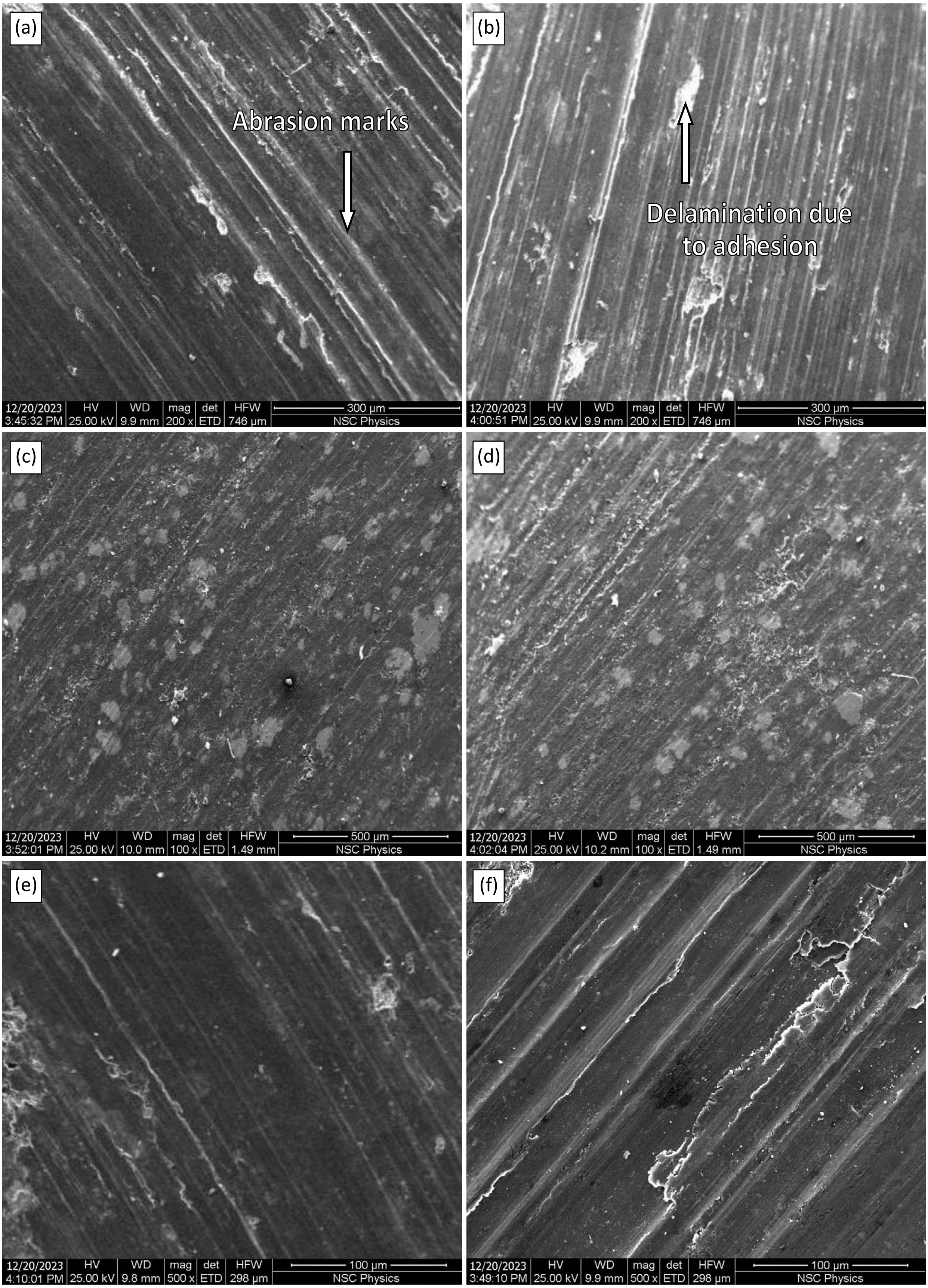

Figure 8. Worm surface (SEM image) of composite: (a) C5N, (b) C10N, (c) C5O, (d) C10O, (e) C5W and (f) C10W

Regardless of the applied load, oil-quenched composites showed the lowest coefficient of friction, while green composites showed the highest coefficient of friction. The lower coefficient of friction for oil-quenched composites was mainly attributed to their lowest hardness, as depicted in

Figure 5. Moreover, the oil-quenched composites exhibited the highest porosity. Thus, entrapped oil was forced to come out from the pores due to the creation of partial negative pressure during sliding, which lubricated the contact surface and decreased the coefficient of friction. Moreover, the coefficient of friction of green composites was highest, followed by normalised and then water-quenched composites. This may be attributed to their hardness trend, which followed the same pattern. The composites with higher hardness resisted the penetration of asperities in the counter-surface, thereby showing a lower coefficient of friction. The decreasing extent of abrasion furrows with the increase in hardness of the composites can be seen in Figure 8.

The wear of green, normalised and water-quenched composites also followed the same trend as the coefficient of friction, as can be seen in Figure 7. The wear behaviour of these composites can be explained in the same way as the coefficient of friction. However, the wear of oil-quenched composites was higher than that of normalised and water-quenched composites. This was mainly attributed to the contamination of the particle/matrix interface by the oil, which decreased interfacial strength, as explained earlier.

Similar types of quenching medium effects were noticed by Li et al. [31] for high chromium cast iron. The authors showed that a high cooling rate exhibits good wear resistance and hardness, whereas a low cooling rate yields lower hardness and wear resistance values. In another study, Panichkin et al. [32] showed that the same cooling rate in chromium iron may yield different hardness and wear resistance values if the holding temperatures differ. Thus, the quenching medium and holding temperatures significantly affect the hardness and wear properties of chromium-containing materials.

Although it is difficult to generalise the effect of load clearly, the coefficient of friction of green, normalised and water-quenched composites showed an increase when the load was increased from 20 to 40 N and decreased when the load was increased further to 60 N. The first increase in the coefficient of friction may be attributed to the deeper penetration of asperities as the load increases. The temperature of contact conjunctions also increases with the increase in load, resulting in an increase in the adhesion component of friction, and hence the coefficient of friction. However, a further increase in load (and thereby contact temperature) may lead to the debonding of reinforcement particles, which decreases the coefficient of friction at high loads.

The oil-quenched composites showed a decrease in the coefficient of friction with the increase in load, which may be attributed to the low hardness and weak particle/matrix interface. The composites (whether green, normalised, oil-quenched or water-quenched) showed an increase in wear with an increase in load.

4. Conclusion

The present study investigated chromium-reinforced Al/Cu dual matrix composites with variations in reinforcement content, normal load and quenching medium. The following conclusion can be drawn from the present study.

The water-quenched composites exhibited the highest compressive strength, followed by the normalised, green and oil-quenched composites. The lowest strength of oil-quenched composites was attributed to a weak interface due to interface contamination by the oil and high porosity. The highest strength of water-quenched composites was mainly attributed to the enhanced dislocation density strengthening effect. The highest strength was obtained for 3 wt. % Cr in the case of water- and oil-quenched composites, and 5 wt. % Cr in the case of normalised and green composites.

The water-quenched composites exhibited the highest hardness, and the oil-quenched composites exhibited the lowest hardness.

The coefficient of friction decreased with an increase in Cr content, irrespective of load and quenching medium. This was mainly attributed to the combined effect of an increase in hardness and a decrease in thermal conductivity with an increase in Cr content.

The oil-quenched composites showed the lowest coefficient of friction, whereas their wear was higher than normalised and water-quenched composites.

The water-quenched composites exhibited the lowest wear, whereas their coefficient of friction was higher than that of oil-quenched composites.

The adhesion tendency increased, whereas the abrasion tendency decreased with an increase in Cr content.

Based on the present investigation, it can be concluded that 5 wt. % Cr-reinforced water-quenched composites exhibited optimum mechanical and tribological characteristics in the investigated environment and conditions.

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