Effect of Thermo-Mechanical Processing and Heat Treatment on the Tribological Characteristics of Al Based MMC's

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Abstract: This paper reports on effect of forging and Heat Treatment on Tribological characteristics of aluminium alloy-silicon nitride. Cast aluminium alloy and composite were subjected to open die hot forging process. Alloy and its composites were examined to characteristics hardness and wear test under both primary and secondary processing conditions. Effect of heat treatment on hardness and tribological behaviour were also studied. Microstructure shows even spreading of particles in cast & forged conditions. hot forged alloy and composite shows a noticeable improvement in wear resistance and COF compare to their primary counter parts. Heat treatment has a considerable effect on hardness, friction and wear characteristics of composites.

1. Introduction

Presently, Al composites are tender than conventionally available alloys in most of the applications because of its advantageous properties like higher strength, fatigue resistance, low density etc. Hence, Al composites are more suitable or recommended for aerospace applications which undergo repetitive loads [1,2]. Al based composites are having significant demand particularly in aerospace and automobile areas due to their excellent and enhanced properties. Silicon carbide, Al2O3, Si3N4, TiO2 etc are categorized as types of reinforcements which are available in the form of fibers, whiskers and particulates. Out of all available composites, the most obedient is particle reinforcing material due to their isotropic properties and cheaper [3]. Al composites with discontinuously reinforced Al shows enhanced characteristic over other conventional one [4].

In this study, an attempt has been made to develop the composite using Si3N4 as a reinforcement using stir casting technique which is simplest technique to develop MMC's which is followed by Forging. Also an attempt has been made to conduct tribological experiments and to get the results of both cast & forged composites. From the literature, many experts paid attention towards improvement of quality & properties of metal matrix composites and their needs using different reinforcement materials. Only meager information is available on forged and heat treatment of developed composites. In the light of the above, this research focuses on synthesis & characterization of hot forged & heat treated Al6061- Si3N4 metal matrix composites.
2. Experimental details

Al6061 alloy has been selected as matrix due to its huge range of applications in engineering sector. Al6061 alloy ingots were procured from M/s Fenfe Metallurgicals, Bangalore, India. Al6061 has its chemical composition used for this research as described in Table 1. Silicon Nitride particles of size 10-30 microns were used as reinforcement.

Al6061-10wt%Si₃N₄ composite was manufactured by stir casting route using 6KW electrical resistance furnace. Prior to composite preparation, the surface of the Si₃N₄ particles were coated with nickel using electroless nickel deposition to get better wettability in aluminum molten metal. Both cast matrix alloy and composite has been subjected to forging at 500°C with help of hydraulic hammer. More details on electroless nickel coating, composite preparation and hot forging can be found in our earlier published works [1, 2].

| Elements | Si  | Fe  | Cu  | Mn  | Ni  | Pb  | Zn  | Ti  | Sn  | Mg  | Cr  | Al  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Percentage | 0.43 | 0.43 | 0.24 | 0.139 | <0.05 | 0.024 | 0.006 | 0.022 | 0.001 | 0.802 | 0.184 | Balance |

Aluminium alloy and composites were processed by primary & secondary techniques were heat treated using muffle furnace at solutionsing temperature of 550°C for a duration of 2 hrs. Solutionised alloy & composites were quenched using air, water and ice as quenching media. Ageing was performed at a temperature of 175°C at various ageing duration in the range of 4 to 10 hrs.

The sample dimensions used for Microhardness test was 10mm thickness and 20mm diameter and ASTM E92 test method was followed for conducting the experiment. Pin on disc instrument was employed to characterize wear rate and friction coefficient of alloy & its composites as per ASTM G99 standard method. Test samples of dimensions 8mm φ and 20mm length. Test were conducted by changing load and sliding velocities in the range of 20-100N and 0.314-1.547m/s respectively.
3. Results and discussion

3.1 Microstructure studies

Fig 1(a) & 1(b) depicts the SEM of cast and forged Al6061-10wt%Si3N4 composites. It is observed that Si3N4 powders homogenously dispersed all over aluminium alloy. SEM of forged systems shows that Si3N4 powders aligned in the path of metal flow at the time of forging.

![Figure 1(a). Cast Al6061-Si3N4 composites](image1)

![Figure 1(b). Forged Al6061-Si3N4 composites](image2)

Fig 2(a) shows SEM of intermetallic precipitates after solutionising and quenching in water media followed by artificial ageing. Fig 2(b) shows the EDAX pattern of the precipitates. It confirms the presence of elements like Mg, Si, and Fe.

![Figure 2. SEM (a) and EDAX (b) pattern of intermetallic precipitates in Al6061-10wt%Si3N4 composites solutionised and quenched in water media followed by artificial aging.](image3)
3.2 Microhardness

Fig 3 shows the variation of microhardness with addition of Si₃N₄ in aluminium alloy. With the addition of Si₃N₄ particles into matrix alloy, a severe development is observed. A considerable increase can be seen by adding ceramic reinforcement into aluminium alloy. The bulk hardness will always enhances with addition of reinforcement into matrix alloy [5, 6]. There exists mismatch in CTE of alloy & ceramic particles. This aspect is responsible for increase in the density of dislocations which results in elevated hardness [7]. When compared with cast alloy, an improvement of 83% and 90% is observed by cast and forged composites respectively.

Fig 3 shows the influence of quenching media on the microhardness of aluminium alloy and Al6061-Si₃N₄ composites. The maximum hardness has resulted on ice quenching under identical heat treatment condition. The least improvement of hardness has resulted on Air quenching. However, comparing the results of ice and air quenched samples, a moderate level of improvement can be seen over water quenched samples. An improvement of 11%, 18%, 37% is noticed in air quenching, water quenching and ice quenching respectively. The fact behind the increase in the hardness value is due to intermetallic precipitates Mg₂Si that are formed in alloy and Al6061-Si₃N₄ system [6]. Further the advantage of solution treatment is that it makes the cast structure uniform and reduces the segregation of alloying elements. As the rapid cooling helps in maintaining super saturated solid solution in alloy, ice quenched samples exhibits peak hardness.
3.3 COF

Fig 4 shows the dissimilarity of COF of as cast, hot forged and heat treated as cast & heat treated hot forged composites with addition of Si$_3$N$_4$ particles. It is clear that addition of Si$_3$N$_4$ particles, the COF of composites is reduced in both cast and forged Al6061-10wt%Si$_3$N$_4$. The coefficient of friction is reduced by 20% and 25% in cast and forged Al6061-10wt%Si$_3$N$_4$ composites. This drop in co-efficient of friction of Al6061-Si$_3$N$_4$ composites with addition of Si$_3$N$_4$ can be credited to enhancement in anti frictional behavior of reinforced particles that are capable of withstand the load [1].

![Figure 4. Variation of coefficient of friction and Effect of heat treatment on as cast and hot forged Al6061 alloy and Al6061-Si$_3$N$_4$ composites.](image)

During wear testing, the friction takes place between Si$_3$N$_4$ particles and steel surface due to lower coefficient of friction. The uniform dispersion of Si$_3$N$_4$ particles, its exceptional bond strength and clear boundaries among matrix and reinforcement is reason for reduction in coefficient of friction. The drop in COF is also due to the smaller particles sizes of Si$_3$N$_4$. Si$_3$N$_4$ exhibits superior tribological characteristics when it is exposed to atmospheric conditions. During sliding action Si$_3$N$_4$ particles reacts with water either in gaseous form or in liquid condition and forms silica (SiO$_2$) which is an amorphous hydrated film that can significantly alter frictional characteristics at interface of test pin & steel disc [8].

It is found that the heat treatment has reflective influence on COF value for matrix alloy and its composites in both cast and forged systems. on the other hand, with only cast alloy and its composites, have poor COF compared to forged alloy even after heat treatment.
3.4 Wear
Fig 5 shows the dissimilarity of wear rate with more fraction of Si₃N₄ particles in matrix alloy in as cast and hot forged conditions. It is seen that increased content of reinforcement in matrix alloy decreased the wear rate. Out of all the research studies, the wear rate of hot forged alloy and its composites are much lower than their corresponding cast alloy and its composites. A maximum of 42% and 49% reduction is observed in cast and forged Al6061-10wt%Si₃N₄ composites respectively.

As a result of ceramic coating the casting defects are expected to less which is further confirmed by micrographs [9-11]. Presence of Si₃N₄ minimises the actual contact area of matrix contributing to lower wear rate [5], which in turn increases the ability to convey the load from matrix to reinforcement [12].

![Figure 5. Effect of reinforcement on wear rate of as cast and hot forged Al6061 alloy and Al6061-Si₃N₄ composite](image)

The lower wear rate of forged systems compared with cast systems can be credited to enhancement in the hardness. Superior hardness results in reduction of wear rate as proposed [13,14]. The reduction in the wear rates of forged systems can also be attributed to heavy plastic working, due to dynamic recrystallisation during forging which end up with excellent grain size [15]. The hardness and strength of the composites increases with finer grain size which also reduces the wear rate, also exhibit excellent bonding relationship between matrix and reinforcement subsequent to hot forging process. This can be considered as a major factor which have more effect on wear characteristics [16].
Fig 6 describes the influence of heat treatment on adhesive wear rate of aluminium composites and Al6061-Si₃N₄ samples. It is seen that heat treatment have reflective effect on the wear rate of composites. Maximum of 37% and 57% reduction in wear rate is reported in cast and hot forged Al6061-10wt%Si₃N₄ systems respectively.

It can be noticed that the heat treatment has a remarkable influence on hardness in aluminium alloy & composites as discussed in previous sections, which leads to superior wear resistance of the heat treated systems.

4. Conclusion

- Al6061-Si₃N₄ composite manufactured by stir casting route was hot forged successfully.
- Aluminium alloy & its composite processed under forging conditions exhibit higher wear resistance compared with cast conditions.
- Microstructure shows the Si₃N₄ powders are homogeneously dispersed all over aluminum alloy and are aligned in the path of metal flow after forging.
- Heat Treated alloy and composites exhibits higher microhardness, better wear resistance and lower COF compared to unheat treated ones.
- Among all the quenching media, ice quenched samples shows higher hardness & wear resistance with lower COF.
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