Microstructure, Mechanical Properties (Strength and Hardness) and Wear Behavior of Chilled Aluminum Alloy (LM-13) Reinforced with Titanium Carbide (TiC) Metal Matrix Composites

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Abstract

This paper deals with the production of aluminum alloy (LM-13) reinforced with titanium carbide (TiC) chilled composites subject to different chilling rates to study the effect of chilling on microstructure, mechanical and tribological behavior. Metallic and non-metallic chills (25 mm thick) were used in this investigation. The specimens taken from casting blocks were tested for their microstructure, strength, hardness and wear behavior. It was found in the present investigation that chilling rate and addition of TiC reinforcement (3 to 12 wt% in steps of 3 wt%) have improved both mechanical properties (strength and hardness) and wear resistance of the composite developed. Out of the chills used, copper chill was found to be good in improving mechanical properties because of its high Volumetric Heat Capacity (VHC). It is concluded from the above investigation that type of chill and hence chilling rate, reinforcement content have an effect on mechanical properties wear behavior.

Keywords

Wear, Strength, Hardness, Chill, Solidification

1. Introduction

Aluminum alloys are known for their strength and ductility. The combination of strength and ductility adds to give aluminum alloy greater values of toughness and resistance to wear. It is well known that properties of Al alloy can be con-

trolled by controlling its composition or by adding the reinforcement.

Study on the effect of high rate heat transfer during solidification of Al alloy using water-cooled and sub-zero chills on mechanical behavior [1] concluded that a number of dendritic cells are significantly larger in the case of chilled composite than that obtained in the case of composite cast without a chill. Dendrite arm spacing was shown to be a major factor that affects ultimate tensile strength and fracture toughness. In another study on microstructure of cryogenically treated Al alloy [2], it is reported that cryogenic treatment facilitates the formation of fine grain structure and the subsequent alloying improves the wear resistance of Al composites.

It is well known that Al alloys that freeze over a wide range of temperature are difficult to feed during solidification [3] [4] [5]. The dispersed porosity caused by the pasty mode of solidification can be effectively reduced by the use of chills. Chills extract heat at a faster rate and promote directional solidification. Therefore chills are widely used by foundry engineers for the production of sound and quality castings. There have been several investigations [6] [7] [8] [9] on the influence of chills on the solidification and soundness of alloys. With the increase in the demand for quality composites, it has become essential to produce Al composites free from unsoundness.

Hence in the present investigation, the addition of reinforcement, and chilling route during solidification followed by aging were adopted to eliminate micro-porosity and to improve mechanical properties [10] [11].

Relevance of the Present Research

The objective of the present research is to examine the effect of the addition of reinforcement (TiC) on the microstructure and mechanical properties of chilled aluminum alloy (LM-13). These composites are widely used in the production of automotive parts, aerospace application, structural members, valves, flanges, motor casing, and fittings at high temperature service. Hence in the present investigation effort has been made to enhance the mechanical properties and wear behavior of Al alloy reinforced with TiC using a different route by introducing chilling effect during solidification. So for no work has been done on chill treated TiC reinforced composite during solidification. The present work is therefore under taken to fill the void.

2. Experimental Procedure

2.1. Molding, Melting and Casting

In the present research metallic and non-metallic end chills were used to get test castings. These end chills were fabricated to required size and set in CO_2 sand molds (AFS standard size 225 × 150 × 25 mm) as shown in **Figure 1**. Zircon sand coating was applied to mold to get good surface finish as well to avoid fusing of sand.

Chills used: 1) Metallic chill (copper).
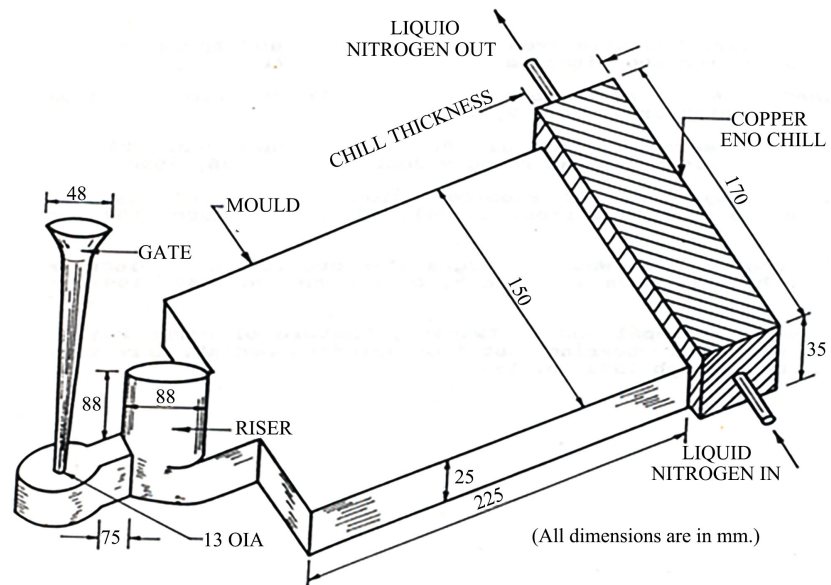
2) Non metallic chill (graphite).

Figure 1. Experimental setup for production of chilled composite.

LM-13 aluminum alloy was melted in an induction furnace and when the melt was superheated to 720°C to which the reinforcement was added for 3 wt% to 12 wt% in steps of 3 wt% and stirred with an impeller rotating at 350 rpm. Finally it was taken into a preheated ladle containing calcium silicide (which acts as deoxidizing agent) during pouring. This TiC reinforcement treated molten composite was then poured into the mold containing different end chills. After solidification all the test castings were heat treated (aging) for 5 hours and finally these castings were cleaned and cut to prepare specimens. Chemical composition and properties of LM-13 Al alloy used in the present investigation is shown in **Table 1** and **Table 2** and properties of TiC in **Table 3**.

TiC was purchase from "Amorphous Materials Ltd., England and LM-13 aluminum alloy from "Hindustan Metallurgicals", India.

2.2. Testing

2.2.1. Metallographic Examination
The specimens for micro structural studies were polished according to ASTM metallurgical standards and fine polishing was done using alumina powder and diamond paste. The specimens were etched with 3% Nital to evolve grain boundaries. Micro-structural studies were done using Olympus optical metallurgical microscope. SEM (Jeol make) was used to study the fractured surface in tension test and wear morphology of the worn surface.

2.2.2. Tensile and Hardness Tests
Tension tests were conducted at ambient temperature (26°C) on computerized universal testing machine of 60 ton capacity in the load range of 0 - 600 kN. The specimens for mechanical tests were taken at three different locations along the length of the casting (at 15 mm, 110 mm and 210 mm from chill end) and were

Table 1. Chemical composition of the matrix alloy (LM 13).

Elements	Zn	Mg	Si	Ni	Fe	Mn	Al
by wt%	0.5	1.0	12	2.0	0.5	1.0	Bal

Table 2. Properties of LM-13 aluminum alloy.

Property	UTS (MPa)	Hardness (HRB)	Melting point O˚C	Density (gm/cc)	Structure
	155	150	698	2.7	FCC

Table 3. Properties of titanium carbide (TiC).

Density g/cc	Hardness (HRB)	Melting point (˚C)	Type of Structure	Color
4.93	280	3160	Cubic	Black

prepared according to AFS standards. Rockwell hardness (HRB) for the samples was measured using ZWICK-Roll ZHR hardness tester with a load of 100 kg-f using ball indenter of size 1/16 inch in diameter. The values reported in both these tests are the average of three repetitions on the same sample at the same location.

2.2.3. Tribological Test

Wear test for the samples are conducted using pin on disc computerized DUCOM make sliding wear testing machine. The specimen is a pin of size 6 mm in diameter and 25 mm long where as the disc is of alloy steel having hardness of HRC 62. Before the test the surface of the pin was cleaned with acetone and volume loss method (LVDT attached to the specimen to measure change in length) was adopted in the present investigation. Test was carried out by applying normal load on pin from 10 to 30 N in steps of 10 N at different disc speeds.

3. Results and Discussions

## 3.1. Micro Structural Observation of the Composite

3.1.1. Solidification Pattern

Figures 2(a)-(c) shows microstructure of the composite using different chills, Figure 2(d) and Figure 2(e) shows eutectic cell count (at low magnification at 50×) and Figure 2(e) and Figure 2(f) shows Dendrite Arm Spacing (DAS) of graphite chilled and copper chilled composite. The differences in associated TiC distribution, its randomness, length and its matrix structure (as shown in Figures 2(a)-(c)) for the various specimens cast were analyzed and correlated to the temperature of eutectic formation. Faster cooling produces fine, highly oriented dendrites, while slow cooling produces large, coarse dendrites. Solidification over a temperature range is the primary requirement for dendrite growth. Pri-

mary austenite dendrites readily grow from the liquidus down to the eutectic temperature. Growth of dendrites may also continue concurrently with the eutectic as the temperature decreases through eutectic range to the solidus. Thus, under cooling in case of copper chilled composite may lead to longer dendrites and higher interaction. Hence, the eutectic cells solidify around these austenite dendrites and in this manner the entire microstructure is affected by the number and size of the dendrites.
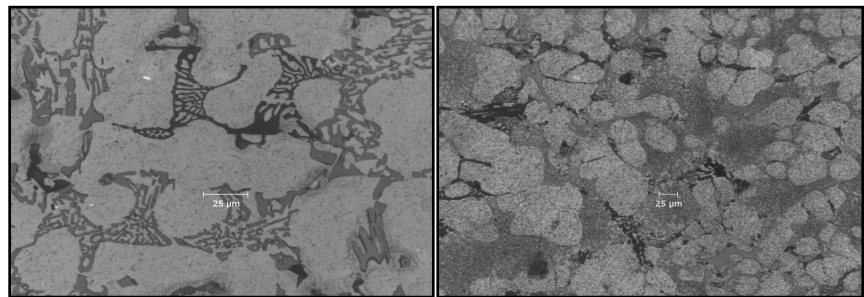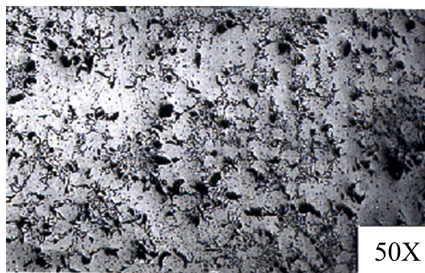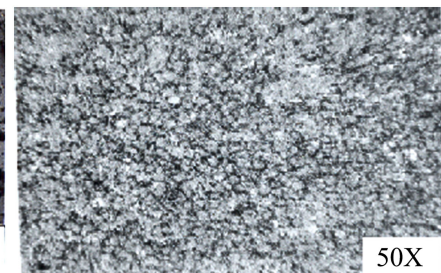

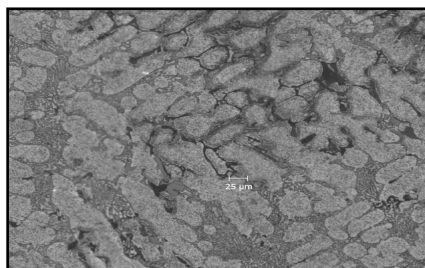(a) Copper chilled (500×)   (b) Graphite chilled (500×)
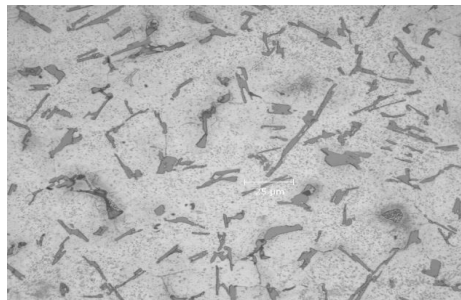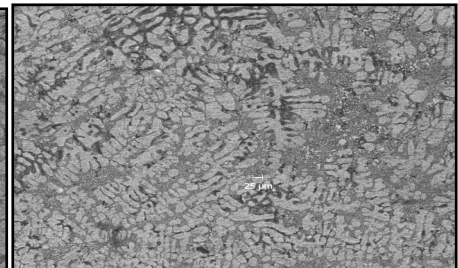
(c) Matrix alloy (LM-134)

(d) Copper chilled composite   (e) Graphite chilled composite

(f) Graphite chilled (500×)   (g) Copper chilled (500×)

Figure 2. Microstructure (a to c), eutectic cell (d and e) and dendrite arm spacing (f and g) of different composites (9 wt% reinforcement).

Therefore the general picture of solidification of graphite chilled (non metallic) composite and copper chilled composite (metallic) with various eutectic cells, dendrite arm spacing, graphite shapes and matrix structures (as shown in **Figures 2(a)-(g)**) can be summarized as follows: The solidification of the composite resulting from sand casting without a chill starts from a small number of nuclei as compared with chilled composites, a phenomenon indicated by eutectic cell count (see **Figure 2(d)** and **Figure 2(e)**). Since the growth condition in the liquid are favorable, these nuclei start growing as soon as temperature below the equilibrium temperature in case of graphite chilled MMC and with maximum under cooling in the case of copper chilled composite.

3.1.2. Dendrite Formation

Results of the investigation indicate that the minimum eutectic temperature can be used as a measure of under-cooling that reflects DAS (**Figure 2(f)** and **Figure 2(g)**), the number of cells (**Figure 2(d)** and **Figure 2(e)**) precipitated and the chilling tendency of the composite. Higher dendritic interaction areas in the case of chilled composites reflect the interweaving of dendrite through eutectic cells that effectively tie the eutectic cells together. Since dendrites are formed from primary eutectic phase, they have a higher tensile strength. Here, due to chilling, nucleation and dendrites directly form from the melt.

3.2. Mechanical Behavior (Strength and Hardness) of Composite

Table 4 and **Table 5** shows the results of mechanical properties (UTS and hardness) of various chilled composites developed. From **Table 4** and **Table 5** it is observed that addition of reinforcement beyond 9 wt% do not improve mechanical properties and hence further discussions will be based on the composite containing 9 wt% reinforcement. Results of mechanical properties indicate that strength and hardness both depends on the type of chill used for casting as well as the reinforcement content present. It is also observed from **Table 4** and **Table 5** that strength and hardness of the composite (containing 9 wt% reinforcement) cast with copper chill is found to be superior compared to graphite chilled composites. Improvement in strength and hardness in the case of copper chilling is because of high volumetric heat capacity (VHC) of the chill which has resulted in fine grain structure of the matrix (see **Figure 2(a)**) during solidification and the reinforcement content in the composite. It is finally observed that addition of 9 wt% reinforcement to Al alloy (LM-13) matrix and copper chilling increases the strength by 11.6% and hardness by 21.3% near the chill end. Note that UTS and hardness of LM-13 Al alloy are 155 N/mm^2 (Mpa) and 150 HRB respectively.

Figure 3(a) and **Figure 3(b)** shows SEM fractographs of copper chilled and graphite chilled specimens failed in tension testing. It is seen from the fractographs that copper chilled composite has fine grain structure with large dimples as compared with graphite chilled MMC which has shallow dimples. It is also observed that the mode of fracture has changed from moderately ductile graphite chilled) to cleavage in the case of copper chilled composite.

Table 4. UTS (Mpa) of various chilled composites developed.

wt% reinforcement	3	6	9	12
Copper chilled	163	169	173	170
Graphite chilled	152	155	161	160

Table 5. Hardness (HRB) of various chilled composites developed.

wt% reinforcement	3	6	9	12
Copper chilled	163	171	182	181
Graphite chilled	159	163	170	170

(a) Copper chilled composite   (b) Graphite chilled composite
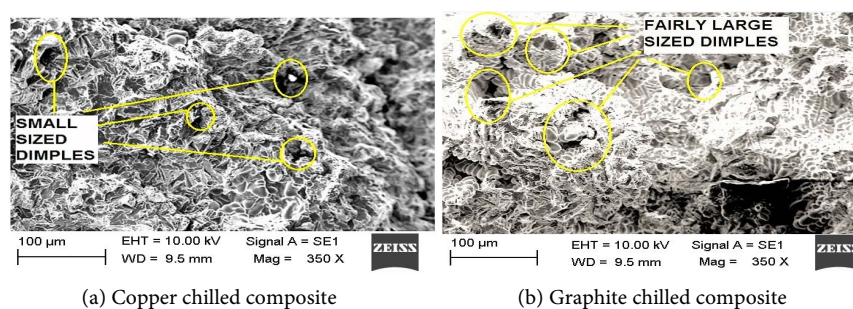
Figure 3. SEM of fractured surface of composite (9 wt% reinforcement) failed in tension.

3.3. Tribological Behavior of the Composite

Results of mechanical properties of the chilled composite developed indicate that, hardness was maximum in the case of composite containing 9 wt% reinforcement hence all further discussions will be based on this chilled composite.

3.3.1. Relationship between Microstructure and Wear

In the two body abrasion, the major portion of the load applied during testing is transferred to the specimen and the wear of the material took place under high stress condition [12]. This is supported by the experimental results, as evident by the increase in transition load from severe to mild wear with the chilling rate [13]. These explanations are in line with earlier reports of Moustafa [14] that have shown an increase in the load for transition from mild to severe wear.

The hard TiC reinforcement particles in chilled composite act as protuberances in the aluminum matrix and bear the major portion of load and as a consequence, protect the composite from wear. This leads to the reduction of wear rate of chilled composites due to reinforcement of TiC particles in the matrix of al alloy. The wear rate is significantly dependent on the applied load, microstructure and hardness of the material. The cutting efficiency of the disc particles increases with an increase in the applied load. As a result, more material is removed at higher loads and hence the wear rate increases with an applied load. The depth and width of cutting grooves also depends on the hardness of the material [15]. The hardness of the graphite chilled composite is lower than that of the copper chilled composites and hence, the wear rate of chilled composites

becomes lower than that of the graphite chilled composite. Therefore, the chances of fracturing of TiC particles in the matrix are less in the case of copper chilled composites. This led to considerably higher wear resistance of the copper chilled composites even at a high load regime. As a result, the removal of a material vis-à-vis the wear rate of the material is governed by deformation parameters, microstructure and hardness. Thus by increasing the strength and hardness between matrix (effect of chilling) and the presence TiC particles, the cutting efficiency of the hard disc particles is reduced.

3.3.2. Relationship between Load, Hardness and Wear

It is well known that the wear rate of the material decreases with hardness irrespective of the applied load. SEM studies of the copper chilled composites tested at different loads reveal that, at lower load (10 N), the variation of wear rate with hardness was marginal, but at higher load (30 N) considerable wear with hardness was noted. At lower load, mainly cutting type wear takes place and the subsurface deformation is negligible [16]. The TiC particles remain intact within the matrix alloy and protect the specimen surface more effectively. Thus, at lower load, the surface deformation behavior is negligible. At higher load, both cutting and ploughing types of mechanisms are operating and the subsurface deformation becomes considerably high. Because of subsurface deformation, transverse and longitudinal cracks are generated on the wear surface [17]. Subsequently, because of cold working, the subsurface is also working hardened [18]. The subsurface deformation is governed by the mechanical properties such as hardness, ductility and strength, which are again influenced by the microstructure and distribution of hard TiC particles. These may cause considerable reduction in the wear rate with an increase in hardness and strength when tests are conducted at higher applied load. The sub surface deformation of the graphite chilled composite may vary because of different matrix micro-structure and mechanical properties. In addition to the initial hardness of the copper chilled composite, after a few cycles of motion of the sample against the abrasive media, the hardness of the wear surface of different samples increases. Apart from this, since the TiC particles are very fine and they may have the tendency to break into small particles and spread over the wear surface thus protecting the matrix alloy from severe wear.

3.3.3. Friction and Wear

Results of the wear test shows the variation in volume loss of the composite as a function of sliding distance tested at loads 10, 20 and 30 N respectively. At the lowest load (10 N) in mild wear regime with a high coefficient of friction was always found for all the chilled composites tested. At higher loads (30 N), the copper chilled composites exhibited severe wear with a better wear resistance than the graphite chilled composite. However, graphite chilled composite tested at all loads underwent large volume loss during the early stages of the test. After sliding for some distance, the volume loss increased approximately linear with

sliding distance. The sliding distance for transition from severe to mild wear could be identified by two factors: Firstly, by abrupt and steep reduction in the frictional force, and secondly, by change in the magnitude of displacement of pin specimen [19]. Based on these measurements, the wear curves are characterized by two distinct lines of different slopes, which correspond to severe and mild wear conditions. Composite, cast using copper chill showed steady state mild wear from the beginning of the test. At no point during the tests was severe wear noticed. It was also observed that, the sliding distance and volume loss during the severe wear regime decreases with an increase the chilling rate. In the case of composites cast with copper chill, severe wear did not occur at all. These wear rates in the severe wear regime was calculated by dividing the volume loss by the sliding distance of severe wear. In the severe wear regime, wear rates of composites decrease with increasing the chilling rate. The transition to lower wear rates (mild wear regime) is accelerated with increasing in heat capacity of the chill. It is obvious that chilling effectively prevents the time/distance required for transition from severe to mild wear.

The mean steady state values of the coefficient of friction (μ) as a function of sliding speed tested at loads 10, 20 and 30 N are studied for both the graphite chilled and the copper chilled composites. At the lowest applied load of 10 N and at the lowest sliding speed of 0.3 m/sec a very high coefficient of friction about 1.0 was measured for the graphite chilled composite in the mild wear regime and for the copper chilled composites it was reduced to around 0.76. At intermediate sliding speed (1.2 m/sec) the coefficient of friction decreases in the mild wear regime and finally at higher sliding speeds (1.8 m/sec) all the steels displayed the same frictional behavior with coefficient of friction value around 0.55. With an applied load of 20 N and at the lowest sliding speed a high coefficient of friction of 0.92 was measured for the graphite chilled composite in the mild wear regime, whereas for the copper chilled composites it was decreased to 0.7 - 0.87. At the highest applied load of 30 N and at the lowest sliding speed a high coefficient of friction of 0.9 was measured for the graphite chilled composite which displayed a mild wear regime , whereas the copper chilled composites at the same sliding speed was decreased down to 0.6 - 0.8. At intermediate sliding speed the trend is that, a high coefficient of friction was measured in the mild wear regime and decrease to lower values of 0.35 - 0.5. At the highest sliding speed all the chilled composites displayed the same frictional behavior with a lower value of coefficient of friction around 0.55 independently from the applied load the wear regime.

3.3.4. SEM Analysis of the Worn Surface

Figure 4(a) and Figure 4(b)) shows SEM photograph of the worn surfaces of the graphite chilled and copper chilled composites in the mild wear regime. It is observed that for the composite cast using graphite chill, worn surface was completely smooth and flat and contained wear tracks in the direction of sliding. In addition, the signature of plastic flow is not at all observed in the subsurface. In
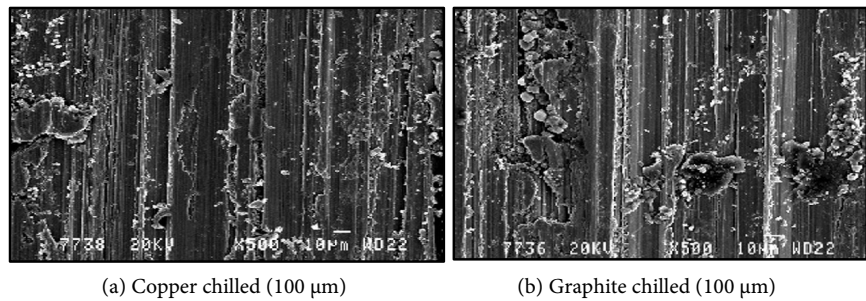
(a) Copper chilled (100 μm)   (b) Graphite chilled (100 μm)

Figure 4. SEM photomicrograph of worn surface of various composites (9 wt% reinforcement) in the mild wear regime.

contrast, the worn surface of composite cast using copper chill was found to be rough. Microscopic examination of its subsurface shows fragmentation and their uniform dispersion on the entire worn surface and, as a result, plastic flow is very limited. Further, in the case of copper chilled composite, the surface found to be very rough with a characteristic brittle fracture. The subsurface region consisted of fragments of crushed TiC (indicated by an arrow in **Figure 4(b)**). This shows that mild wear is dominated in composite cast using copper chill. A very thin tribo-induced layer was formed on the entire surface and, in addition some TiC particle was projected onto the surface. The lengths of the crushed TiC particles were measured for more than 10 fragments on the several cross sectional micrographs. The mean length was found to be 8 μm (ranging from 4.5 to 12 μm) for copper chilled composites. From these detailed observations, it becomes obvious that the reinforcement present were crushed into small fragments and a thin layer is formed on the smooth surface containing wear tracks confirming abrasive wear in the mild wear regime.

4. Summary and Conclusions

In this research, characterization of wear behavior of graphite chilled composites and copper chilled composites cast using high rate heat transfer during solidification was studied. The results can be summarized as follows.

1) Microstructure of the copper chilled composite is finer than that of the graphite chilled composite with random orientation of TiC particles in matrix alloy.

2) Strength, hardness and wear resistance of the copper chilled composites are superior to those of the graphite chilled composites. It was found that these properties increase with an increase in TiC particles in fine chilled matrix alloy.

3) At lower load copper chilled composites exhibited mild wear regime with high coefficient of friction and at higher loads they exhibited severe wear with better wear resistance than the graphite chilled composite.

4) Size of the wear debris decreases because of rapid crack propagation of a brittle body under compression whereas the size of the TiC fragmentation remains approximately the same.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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