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The as cast microstructure and mechanical properties of 10wt%TiC reinforced Al-12%Si matrix composite

Belete Sirahbizu Yigezu*, P. K. Jha, M. M. Mahapatra

Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee-247667, Uttrakhand- India

Email address

kassa2000et@yahoo.com (B. S. Yigezu)

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Abstract

In this study an attempt had been made to investigate the effect of in-situ synthesized 10 wt% TiC in the microstructure and mechanical properties of Al-12%Si matrix. The microstructures and tensile fracture characteristics of the representative composite samples were examined using scanning electron microscopy (SEM) and X-ray diffraction (XRD) techniques. The investigation revealed that fairly uniform distribution of a mixture of sub micro size and flake/needle shape Titanium Carbide (TiC) particles with some voids in few areas. In addition, Al_3Ti and Al_4C_3 intermetalic phases were observed. As compared to the matrix alloy processed in similar conditions, the 10wt% TiC reinforced composite exhibit a 66.7%, 64.6%, and 37.9% increase in 0.2% proof stress, ultimate tensile strength (UTS) and bulk hardness, respectively. On the other hand, the percentage elongation (%EL) and percentage porosity reduced by 24.1% and 37.2%, respectively. However, there is only a slight increase in elastic modulus (E), in values of 11.9%.The fractographic test analysis indicated that the fracture surfaces of both matrix and composite materials demonstrate a brittle fracture characteristics.

Keywords

Al-Si alloy, Interfacial Reactions, In-situ, Mechanical Properties, MMCs, TiC

1. Introduction

The requirement of high performance engineering materials for advanced structural applications consistently increased since the past few decades. Conventional alloys are not suitable for such advanced applications. Reinforcing monolithic metallic materials with a high strength and high stiffness secondary phases are one of the useful techniques to enhance the performance characteristics of these materials. So far considerable research work has been conducted towards the development of metal matrix composites (MMCs) with a wide range of matrix materials such as Aluminium, Magnesium, Titanium, Copper, Nickel, Iron and their alloys [1].

The ready availability, low costs, relatively low processing temperatures, low density, excellent strength, toughness, and resistance to corrosion have made the aluminium based metal matrix more popular [2]. Apart from pure aluminium, cast and wrought Al-Cu, Al-Si, Al-Mg, Al-Zn, Al-Mg-Si and Al-Si-Cu/Mg alloys are among the commonly used aluminium based matrix materials [3, 4]. Particularly, Al-Si casting alloys are widely used in the aerospace, military, and automotive industries due to their excellent casting characteristics, wear and corrosion resistance as well as high strength over weight ratio [5, 6]. Based on the amount of Si present, Al-Si alloys characterized as hypoeutectic (<11.7 wt.%), eutectic (11.7 wt.% to 12.6 wt.%) and hypereutectic (>12.6 wt.%) [7]. Near-eutectic Al-Si cast alloys particularly attractive as a result of their excellent castability and lower cost [5]. For enriching the property of Al-Si alloys, more alloying elements like Cu, Mg, etc. can be added. Alloying elements can form fine precipitates, refine grain size, modify silicon phase morphology and reduce the effects of defects and thus can usually increase both fatigue and wear resistance. Incorporating ceramic particulate reinforcement is another way of improving properties of Al-Si alloys [8].

Ceramic particulate reinforced composite is mainly attractive owing to very reasonable processing costs, easy implementation and isotropic behaviour. Particle reinforced metal matrix composite represent a group of materials where the hardness and temperature resistance of the reinforcement are combined with the ductility and toughness of matrix materials. SiC, Al_2O_3, TiB_2, B_4C, and TiC have been recognized as potential reinforcements for metal matrix composites. The dispersion of these particles enhances the elastic modulus, hardness, tensile strength and wear resistance of the alloys at room and elevated temperatures. However, these reinforcing particles significantly reduced the ductility of the matrix alloy [9, 10].

Particulate-reinforced composites conventionally prepared either by powder technology or liquid metallurgy, where the ceramic particles are directly incorporated into solid or liquid matrices, respectively [11]. Introducing ceramic particles directly to metal melts is notoriously difficult, poor wettability, particle clustering and gas entrapment are major problems [12]. In the in situ fabrication process, the reinforcing phase is synthesized within the matrix during composite fabrication. This contrasts with the conventional (ex-situ) composites where the reinforcing phase is synthesized separately and then incorporated into the matrix during melting or powder processing [13]. In situ synthesised MMCs exhibit the following advantages: (a) the reinforcements are thermodynamically stable at the matrix, leading to less degradation at elevated temperature; (b) the reinforcement-matrix interfaces are clean, resulting in a strong interfacial bonding; (c) the in situ formed reinforcing particles are finer in size and their distribution in the matrix is more uniform, yielding better mechanical properties [1].

In the past few decades number of researchers investigates the microstructure, interfacial reactions and mechanical properties of various aluminium alloy based in-situ synthesised TiC reinforced composites [1, 11-13, 15]. However, there is no much work reported particularly on the enhancement of mechanical properties of Al-12%Si alloy by reinforcing with in situ synthesized TiC. The aim of the present study is therefore to investigate the possibilities of enhancing the properties of Al-12%Si alloy by incorporating in-situ developed TiC.

2. Materials and Experimental Details

2.1. Materials and Preparation of Composites

In this study Al+12%Si alloy was used as a matrix and commercially pure titanium and activated charcoal as reinforcement materials. Al-12% Si/TiC composites were fabricated by melting the Al-12%Si matrix in the muffle furnace with graphite crucible. When the temperature of the molten aluminium alloy reaches 800^{0}C, commercially pure titanium and activated charcoal was added and the melt temperature increased to 1200 ^{0}C and hold for 30 min. The amount of titanium and activated charcoal incorporated in the matrix melt was in account of achieving the desired wt% of TiC. The melting process was carried out under the cover of flux (50% KF + 50% NaF) to remove the oxide film from the molten metal surface and to act as a protective barrier to gas absorption. Small amount of degasser (C_2Cl_6) was also added to remove the dissolved hydrogen gas from the melt. Finally, the melt was poured into steel mould of size 35 x 35 x 260 mm^3. Representative samples were cut from various sections of the as cast ingots for metallographic examinations, mechanical property test and wear test. Table 1 shows the chemical composition of the matrix material.

Table 1. *Chemical composition of Al-12%Si matrix.*

Element	Cu	Mg	Si	Zn	Mn	Fe	Al
Wt%	0.24	2.85	12.0	0.50	0.39	1.21	Balance

2.2. Microstructural Characterization

Initially one surface of the specimens were polished gradually using 120 to 1200 grit SiC emery papers followed by velvet cloth with Al_2O_3 suspension on a disc polisher. Finally samples were etched using Keller's reagent (2.5%HNO_3, 1.5%HCl, 1%HF and 95%H_2O by volume). Microstructural characterization was done using optical microscope (OM), scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX). X-ray diffraction (XRD) analysis was also carried out for confirming the formation of TiC and other phase analysis.

2.3. Mechanical Property Test

Vickers bulk hardness at load of 5 kg was carried out on the composite samples after polishing with a fine grained emery papers. Each test was repeated seven times and the mean has been reported as the hardness. Representative tensile specimens from different parts of the cast ingot were machined at 5.0 mm diameter and 25 mm gage length. After machining, the gage surface of the specimens was mechanically polished using 400 and 600 grained emery papers to remove scratches and machining marks. Three test specimens were used for each run and the mean value were reported as a result. The 0.2% proof stress, ultimate tensile strength (UTS), elastic modulus (E) and percentage elongation (%EL) were extracted from the stress-strain curves of the examined material. The fracture surfaces of the representative tensile test specimens were subsequently examined by SEM to determine the failure mechanisms. The percentage of porosity present in the test material also determined based on the Archimedes principle.

3. Results and Discussion

3.1. Microstructure Analysis

The microstructure of the matrix material consists of dark white dendritic silicon and a white grey plate shape which is rich in aluminium. Silicon has a diamond crystal structure and is consequently very brittle. The XRD pattern confirmed that alpha-Al and primary silicon exists in considerable amount. The presence of large amount of alpha-Al and primary silicon has detrimental effect on the mechanical property of the material. The microstructure and XRD pattern of the Al-12%Si/10wt%TiC composite prepared at 1200^0C and 30 min reaction time exhibit a reasonably uniform distribution of a mixture of needle/flake shape Al_3Ti and sub microns size TiC with some voids in few areas. It has been also observed that considerable amount of Al_4C_3 and Al_5FeSi intermetalic phases were formed. The formation of Al_3Ti and Al_4C_3 may be due to the insufficient processing temperature and incomplete reaction between Al, Ti and C. As per the findings of Y ¨Ucel [14], the precipitation of Al_4C_3 gets underway before complete conversion of Ti into TiC. Hence, it is best from a practical standpoint, to terminate processing before the dissolved Ti is totally consumed in order to avoid the risk of getting some Al_4C_3 in the cast plate. Unreacted Ti which crystallizes in the form of Al_3Ti needles upon solidification, on the other hand, can be tolerated when it is present in the melt only in very small quantities. The formation of Al_5FeSi intermetalic phase may associated with the presence of considerable amount of Fe as impurity (as shown in Table 1) and the interaction of the stirrer blade with the super heated molten metal during mechanical string. Iron is well known as an undesirable impurity in aluminium alloys and forms an intermetallic phase in the casting. The morphology of Fe-rich phases, particularly β-Al5FeSi phase plays an important role in reducing mechanical properties of the castings.

The other observation was the formation of porosity in the matrix as well as composite materials. Normally, porosity occurs during solidification by two primary causes, the evolution of hydrogen and the inadequate feeding of the volume contraction during the phase change. This kind of defect can be detrimental to the mechanical properties of materials due to a decrease in the load bearing area. It has been suggested that nucleation of pores in cast aluminium alloys is unlikely to occur in practice in the case of both homogeneous and heterogeneous nucleation due to the extremely high pressure required. Oxide films and Fe-rich phases therefore might lead to the formation of pores in the castings. The SEM micrograph and the XRD pattern of the Al-12%Si matrix and the as cast Al-12%Si/10wt%TiC composite are shown in Fig. 1 -4.

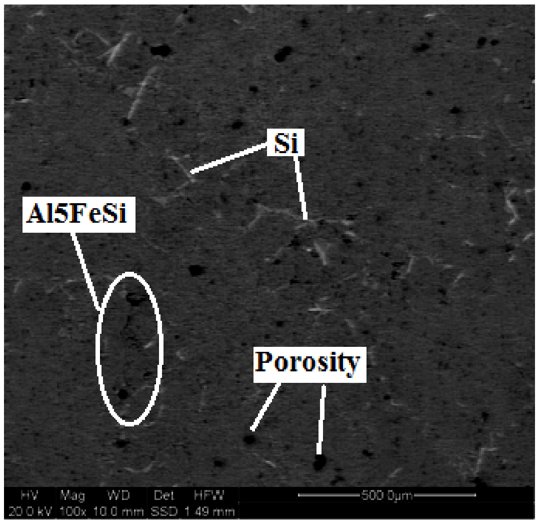

Fig. 1. *the SEM micrograph of Al-12%Si matrix.*

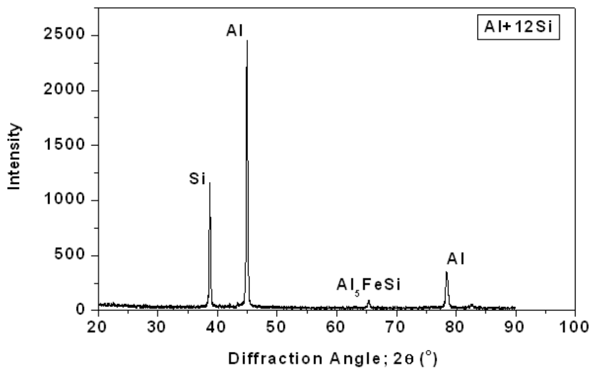

Fig. 2. *The XRD pattern of the Al-12%Si matrix*

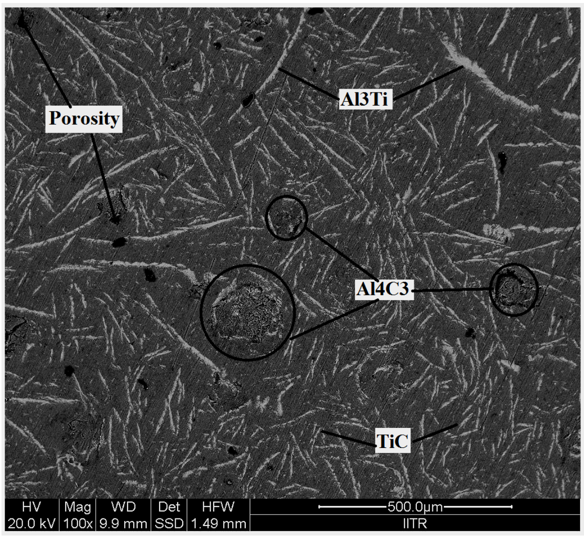

Fig. 3. *the SEM micrograph of the as cast Al-12%Si/10wt%TiC composites.*

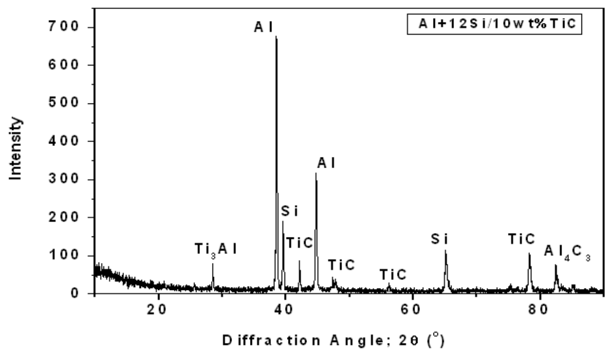

Fig. 4. *The XRD pattern of the Al-12%Si/10wt%TiC*

3.2. Mechanical Properties Test Analysis

Fig. 5 shows the results of mechanical property tests of the experimental composite and its matrix. The results revealed that 0.2% proof stress, ultimate tensile strength (UTS) and hardness value (HV) of the Al-12%Si/10wt%TiC composite increased by 66.7%, 64.6%, and 37.9% respectively. However, there is only a slight increase in elastic modulus (E) which is only 11.9%. These considerable changes in the mechanical property of the composite may be associated with the hard ceramic nature of TiC and its grain refining property. The remarkable difference in expansion coefficient between matrix and strengthening phase has also its own contribution. When a particulate reinforcement introduced into a molten alloy matrix, there is usually a significant increase in the mechanical properties of the composite due to the aggregate properties of the distinct characteristics of matrix and reinforcement [15]. It has also been known that the finer the grain of the matrix the higher the strength of the composite. As has been proved in literature, grain refining strengthening effect can be shown in two aspects: firstly, nucleation sites of aluminium matrix will increase with the formation of TiC particles and the aluminium nuclei can grow from the crystallographic plane of TiC which is the nucleation substrate. Secondly, the grain growth can be effectively restricted by the strengthening particles, thus the matrix microstructure is refined [16].

The other important reason for the enhancement of the property of the composite is since metal matrix composites normally prepared at high temperature that causes to the formation of high thermal mismatch stress in the following cooling process due to the notable difference of expansion coefficient between matrix and strengthening phase. Relaxation process will take place when mismatch stress is higher than the yield stress of matrix and that gives rise to high density location in the matrix which causes to increase matrix yield strength of the composite [16].

On the other hand, the composite material demonstrates a 24.1% and 37.2% reduction in the percentage elongation (%EL) and percentage porosity, respectively. This may be attributed to the presence of porosity and the high hardness property of TiC. It is well known that if the strength of the matrix increases the ductility will decrease. It has been claimed that the presence of a hard ceramic phase is prone to localized crack initiation and increased embrittlement effect due to local stress concentration sites at the reinforcement-matrix interface. The introduction of this hard secondary ceramic phase creates slip regions [17]. Moreover, the reinforcing particulates resist the passage of dislocations either by creating stress fields in the matrix or by inducing large differences in the elastic behaviour between the matrix and the dispersoid [18].

The presences of porosity and weak intermetalic phases like Al_3Ti, Al_4C_3 and Al_5FeSi severely affect the ductility of the composites. During the production process of MMCs, some porosity is normal, because of gas entrapment during vigorous stirring, air bubbles entering the slurry either independently or as an air envelope to the reinforcement particles, water vapour on the surface of the particles, hydrogen evaluation, shrinkage during solidification, and volume fraction of reinforcement material. The presence of porosity consequently decreases most of the mechanical properties of cast MMCs. Failures initiated from the pores within the matrix material, particle fracture and reinforcement-matrix interface are due to voids coalescence, reduction of ductility, and reduced MMC cross section [19, 20] The Al_4C_3 intermetalic phase is certainly not a desirable constituent in the composite as it is a brittle compound which decomposes readily when exposed to atmospheric moisture. Similarly, the Fe-rich phases, particularly β-Al5FeSi phase, play an important role in reducing mechanical properties of the material.

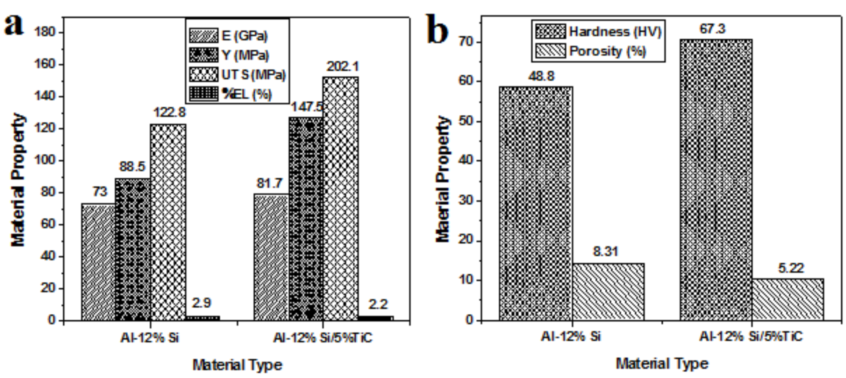

Fig. 5. *(a)-Variation of ultimate tensile strength, elastic modulus and % elongation; (b) bulk hardness and % porosity as a function of material type.*

3.3. Fractographic Test Analysis

According to literature, there are three modes of failure typically occur in metal matrix composites: (i) cracking of the reinforcing particles; (ii) partial debonding at the particle/matrix interface resulting in the nucleation of voids; and (iii) the growth and coalescence of voids in the matrix. The particular failure modes that are observed and the process of evolution of the failure depend broadly on processing, matrix microstructure and reinforcement morphology and distribution in addition to the stress state [21]. The micrograph of the matrix and composite materials fracture surface are shown in Figure 6. It has been observed that both materials fractured in the same brittle fashion without appreciable dimple formation. This may be attributed to the brittle nature of the eutectic Al-Si matrix alloy. The mechanical properties of the Al-Si alloy are dependent on the size, shape and distribution of eutectic and primary silicon particles. Small, spherical, uniformly distributed silicon particles enhance the strength properties of Al-Si alloys. On the contrary, the presence of large amount of alpha -Al and primary silicon may detrimental to the mechanical properties [16]. Some voids are also noticed in the composite sample, this may be due to the fracture of the reinforcement particles. It is well known that fracture of ductile materials occurs by void nucleation, growth and coalescence stages. The fracture nucleation events play a dominant role in the ductility of these materials. The interfacial strength of the reinforcement/matrix control the strain required for void nucleation [22].

The other possible reason for the brittle fracture nature of the TiC reinforced composite may be due to the presence of weak intermetalic phases like Al_3Ti, Al_4C_3 and Al_5FeSi. Earlier study by Poza et al.1995 [22] demonstrate that the engineering alloys always contain inclusions and second-phase particles, either added to improve the mechanical behaviour or not eliminated during processing and remaining as impurities. Their presence activates a different fracture mechanism, the material failing by the nucleation, growth and coalescence of voids and the overall tensile ductility is reduced. The particles act as void nucleation sites during deformation by particle fracture or by interfacial decohesion and these voids subsequently grow by plastic straining. Final fracture occurs suddenly by localized necking of the intervoid matrix.

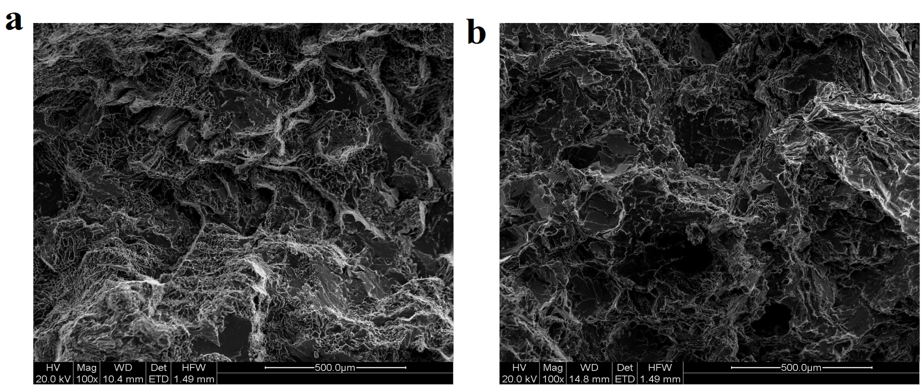

Fig. 6. *SEM micrograph of the tensile fracture surface of: (a) Al-12% Si matrix; (b) Al-12% Si/5%TiC composite*

4. Conclusion

From the present study the following conclusions can be drawn:

1. Al-12%Si/10%TiC in-situ composite were successfully synthesised by a direct reaction process.
2. The SEM and XRD analysis revealed that the distribution of TiC is reasonably uniform in accompany with some voids in few areas. In addition, Al_3Ti and Al_4C_3 intermetalic phases were observed along with TiC particles.
3. As compared to the matrix alloy processed in similar conditions, the 10wt% TiC reinforced composite exhibit a 66.7%, 64.6%, and 37.9% increase in 0.2% proof stress, ultimate tensile strength (UTS) and bulk hardness, respectively. On the other hand, the percentage elongation (%EL) and percentage porosity reduced by 24.1% and 37.2%, respectively. However, there is only a slight increase in elastic modulus (E), in values of 11.9%.
4. The SEM tensile fracture surfaces study revealed that the fracture surfaces of both reinforcement and composite materials have a similar brittle fractured feature.

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