Predicting the influence of process parameters on tensile strength of AA6061/TiC aluminum matrix composites produced using stir casting

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Abstract

Stir casting is an economical method to produce aluminum matrix composites (AMCs). In this work, stir casting was used to produce AA6061/15wt. % TiC AMCs. An empirical relationship was developed to predict the effect of stir casting parameters on the ultimate tensile strength (UTS) of AA6061/TiC AMCs. A central composite rotatable design consisting of four factors and five levels was used to minimize the number of experiments i.e. castings. The factors considered were stirrer speed, stirring time, blade angle and casting temperature. The effect of those factors on the UTS of AA6061/TiC AMCs was derived using the developed empirical relationship and elucidated using microstructural characterization. Each factor significantly influenced the UTS. A higher or lower values of those factors resulted in poor tensile strength. The variation in the UTS was attributed to porosity content, cluster formation, segregation of TiC particles at the grain boundaries and homogenous distribution in the aluminum matrix. The UTS was high when the porosity content was low and the distribution was homogenous. The present work concludes that a careful selection and control of stir casting parameters are necessary to reduce porosity content and obtain uniform distribution to improve the load bearing capacity of the AA6061/TiC AMCs.

Key words: Aluminum Matrix Composites; Stir Casting; Titanium Carbide; Tensile Strength.

1. Introduction

Aluminum alloys reinforced with various particulates, universally called as aluminum matrix composites (AMCs) has been the subject of much research in the past two decades owing to their superior properties. Conventional monolithic aluminum alloys fails to meet the rising demand for high performance in many applications. AMCs have the right combination of properties such as higher stiffness, superior strength, improved resistance to wear and low coefficient of thermal expansion which promote them as a potential alternative material to replace aluminum alloys. The utilization of AMCs exhibits an increasing trend in various industries including aerospace, automotive, marine and nuclear [1–4]. A range of carbide, oxide, boride and nitride particles have been used as particulate reinforcements to produce AMCs. Among them TiC is as interesting ceramic particulate which possesses high hardness and elastic modulus, low density, good wettability with molten aluminum and its low chemical reactivity. The introduction of TiC particles into the aluminum matrix significantly improves the high temperature properties. In addition, TiC particle is a grain refiner and provides nucleation sites during solidification of AMCs [5–9].

Stir casting is the most commonly used method for the production of AMCs compared to other methods. The aluminum alloy is melted completely in an electrical furnace attached with an impeller or stirrer. The furnace is usually provided with an inert gas atmosphere to avoid contamination. The stirrer is switched on and the aluminum melt is stirred to form a vortex. The ceramic particles are fed at a constant rate at the periphery of the vortex. The ceramic particles mix with the molten aluminum to form an aluminum composite melt. After sufficient amount of stirring, the aluminum composite melt is poured into a mould for solidification [10,11]. Stir casting is an economical method to produce AMCs and suitable for mass production. Stir casting is simple and yield near net shape components. Products having many features and irregular contours can be made using stir casting [12]. Hitherto, stir casting has been effectively applied to produce AMCs reinforced with SiC [13], Al_2O_3 [14], TiC [15], B_4C [16], SiO_2 [17], AlN [18], Si_3N_4 [19], TiB_2 [20], WC [21], fly ash [22] particulates and CNT [23]. The selection of process parameters is crucial to obtain sound AMCs. Because, stir cast AMCs are susceptible to micro porosity, poor distribution, interfacial reaction and decomposition of ceramic particles [24,25].

A large number of literatures are available on the production of AMCs using stir casting. Nevertheless, the effect of process parameters is reported in limited number of literatures [26–37]. Nai and Gupta [26] found an increase in the homogeneity of particle distribution with an increase in stirring speed in AA1050/SiC AMCs. Naher et al [27] simulated the influence of stirring speed, stirring time and blade angle using water/glycerol solutions. Akhlaghi et al [28] studied the effect of casting temperature on particle distribution and porosity of A356/SiC AMCs. Prabu et al [29] noticed poor particle distribution and clustering at lower stirring speed with lower stirring time in A384/SiC AMCs. Ravi et al [30] investigated the effect of stir casting variables through a water based model. Amirkhanlou and Niroumand [31] obtained improved distribution of the reinforcement particles and properties at lower casting temperature in A356/SiC AMCs. Zhang et al [32] investigated the influence of stirring speed, stirring time and casting temperature on the microstructure of Al-

6.8Mg/SiC AMcs. Li-na et al [33] detected an increase in the homogeneity of reinforcement and tensile properties with decreasing the stirring temperature and increasing the stirring time in AA6061/(ABO_w+SiC_p) hybrid AMCs. Sajjadi et al [34] showed that lower casting temperature provided proper distribution and higher mechanical properties in A356/ Al_2O_3 AMCs. Du et al [35] established an empirical relationship between the stirrer speed and radial distribution of particles in A356/SiC AMCs. Akbari et al [36] observed an increased porosity content with an increase in stirring time in A356/Al_2O_3 AMCs. Khosravi et al [37] reported an increase in the porosity content with an increase in stirring speed and casting temperature in A356/SiC AMCs.

Most of the published literatures concentrated on the effect of few process parameters with limited number of experiments. The process parameters were chosen randomly and their effects were studied based on microscopic observation. No numerical or empirical relationships were developed to predict the properties over a wide range of process parameters. Therefore, the objective of the present work is to produce AA6061/TiC AMCs using stir casting and develop an empirical relationship incorporating the stir casting variables to predict the tensile strength. The effect of stir casting variables on the tensile strength is deduced from the developed empirical relationship and correlated with the observed microstructure. The experiments i.e castings were carried out as per central composite design (CCD) adopting statistical approach. Several investigators effectively applied CCD for various manufacturing processes to precisely predict the influence of process parameters on the responses [38–42].

2. Experimental Procedure

2.1. Identification of Process Parameters

The stir casting parameters which influence the microstructure and mechanical properties of AMCs are shown in Fig. 1. The key parameters which appreciably influence the properties of AMCs are stirrer speed (S), stirring time (T), blade angle (A) and casting temperature (K). These parameters were chosen for the present study based on literature survey [26–37].

2.2. Finding the Limits of the Process Parameters

The limits of each factor were decided based on trial castings to avoid macro porosity, settling of TiC particles at the bottom of the crucible, decomposition of TiC particles and abnormal stirring i.e. splash. The upper and lower limit of a factor was coded as +2 and -2 respectively for the convenience of recording and processing experimental data. The intermediate values were calculated from the following relationship

$$X_i = 2[2X - (X_{max} + X_{min})] / (X_{max} - X_{min}) \quad (1)$$

where X_i is the required coded value of a variable X; X is any value of the variable from X_{min} to X_{max}; X_{min} is the lowest level of the variable; X_{max} is the highest level of the variable. The chosen levels and selected process parameters with their units and notations are presented in Table 1. Other casting parameters maintained constant values are furnished in Table 2.

2.3. Developing the Design Matrix

A four factor, five level central composite rotatable factorial design consisting of 31 sets of coded conditions with seven center points as presented in Table 3 was selected to carry out the experiments. A comprehensive account of the design matrix is available elsewhere [43, 44].

2.4. Casting of AMCs as per Design Matrix

Aluminum alloy AA6061 was used as matrix material in this work. Measured quantity of AA6061 rods were placed inside the furnace. The chemical composition of AA6061 aluminum alloy is presented in Table 4. The stir casting equipment (M/s Swamequip, Chennai, INDIA) is an electrical resistance furnace attached with a bottom pouring arrangement. Hence, after solidification the top and bottom portion of the casting will fairly represent the corresponding distribution at the top and bottom portion of the crucible prior to pouring. The bottom pouring method drastically reduces the time to transfer the composite melt to the mould and avoids the change in distribution of particles [15]. The mechanical stirrer was positioned into the aluminum melt at 2/3 of the total height of aluminum melt. The mechanical stirrer was made of graphite material. TiC particles were gradually fed into periphery of the vortex using a feeding mechanism. The morphology of the TiC particles is depicted in Fig. 2. The average size of TiC particles was 2 μm. Hashim et al [24] reported that particles of size less than 10 μm will suspend in the aluminum melt for a long time least influenced by gravity. TiC particles were preheated to improve wettability in addition to magnesium incorporation into the aluminum melt. The furnace was provided with an argon rich atmosphere to prevent aluminum oxide formation. The temperature of the furnace was recorded using a thermocouple. The composite melt was then poured into a preheated die. Castings were taken by changing the process parameters as per the experimental design.

2.5. Recording the Response

Tensile specimens were prepared as per ASTM E8M standard having a gauge length, width and thickness of 40 mm, 7 mm and 6 mm respectively. Six tensile specimens were prepared from each casting from various locations. The mean value of each set of six specimens was taken into account (Table 3) for developing an empirical relationship. The ultimate tensile strength (UTS) was estimated using a computerized universal testing machine.

2.6. Development of Empirical Relationship

The response functions representing the UTS of AA6061/TiC AMCs are functions of stirrer speed (S), stirring time (T), blade angle (A) and casting temperature (K) which can be expressed as

$$UTS = f\,(S, T, A, K) \tag{2}$$

The second order polynomial regression equation used to represent the response '*Y*' for *k* factors is given by

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k} b_{ij} x_i x_j \tag{3}$$

The selected polynomial for four factors could be expressed for the response as:

$$UTS = b_0 + b_1 S + b_2 T + b_3 A + b_4 K + b_{11} S^2 + b_{22} T^2 + b_{33} A^2 + b_{44} K^2 + b_{12} ST + b_{13} SA + b_{14} SK + b_{23} TA + b_{24} TK + b_{34} AK \tag{4}$$

where b_0 is the average of responses and $b_1, b_2, \ldots b_4, b_{11}, b_{22}, \ldots b_{44}$ are the response coefficients that depend on respective main and interaction effects of parameters. The coefficients were calculated using the software SYSTAT 12. The empirical relationship was developed after determining the coefficients. All the coefficients were tested for their significance level at 95 % confidence level. The insignificant coefficients were eliminated without affecting the accuracy of the empirical relationships using student t-test. The significant coefficients were taken into account to construct the final empirical relationship. The final developed empirical relationship with processing factors in coded form is given below.

$$\text{UTS (MPa)} = 233.286 + 0.167S - 0.667T + 1.5A + 1.833K - 15.217S^2 - 12.342T^2 - 12.967A^2 - 8.842K^2 \quad (5)$$

2.7. Checking the Adequacy of the Empirical Relationships

The statistical results of the developed empirical relationship are presented in Table 5. The predicted empirical relationship values will precisely match with the experimental results if the R - square value is 1. Higher values of 'R-Square' and lower values of standard error (SE) indicate that the empirical relationship is adequate. The adequacy of the developed empirical relationship was analyzed using analysis of variance (ANOVA) technique which is presented in Table 6. The value of calculated F ratios was higher than that of the tabulated values at 95 % confidence level. Hence, the developed empirical relationship is adequate. Further, the scatter diagram as presented in Fig. 3 show that the actual and predicted values are scattered both sides and close to 45° line which confirm the adequacy of the empirical relationship.

2.8. Microstructural Characterization

Specimens were prepared from selected castings. They were polished using standard metallographic technique and etched with Keller's reagent. The etched specimens were observed using scanning electron microscope (SEM, JEOL-JSM-6390) and field emission scanning electron microscope (FESEM, CARL ZEISS-SIGMA HV).

3. Results and discussion

The effects of process parameters such as stirrer speed, stirring time, blade angle and casting temperature on the UTS of AA6061/TiC AMCs were deduced from the developed empirical relationship. The predicted trends obtained for each process parameter are represented in Fig. 4, 7, 10 and 13. The effects of process parameters on the UTS of AA6061/TiC AMCs and the possible causes are expounded in the following sections. It is desirable to achieve homogenous distribution to obtain higher tensile strength.

3.1. Effect of stirrer speed

The predicted effect of stirrer speed on the UTS of AA6061/TiC AMCs is shown in Fig. 4 for a constant stirring time (15 min), blade angle (30^O) and casting temperature (800^OC). The UTS increases as stirrer speed increases and reaches a maximum at 300 rpm. Further increase in stirrer speed leads to the reduction of UTS.

The rotation of the stirrer creates a vortex within the aluminum melt as well as disperses the fed particles into the aluminum melt by setting up centrifugal currents. A vortex formation is essential to incorporate the reinforcement particles. The size of vortex formed limits the degree of particle mixing and its dispersion into the melt. The magnitude of the circulating currents generated during the stirring should be strong enough to keep the particles in suspension for longer duration. The stirring speed influences both the size of vortex and the magnitude of the circulating current linearly. A deep vortex and high stirring speed result in turbulence and suction of air bubbles. This is an undesirable situation and leads to gas entrapment. The study of micrographs aids to correlate the effect of stirrer speed on tensile behavior.

Fig. 5 shows representative micrographs of AA6061/TiC AMCs at various stirring speeds. It is evident from these micrographs that the stirring speed influences the distribution of TiC particles and the formation of porosity. The distribution is poor and hetrogenous at lower stirrer speed of 100 rpm (Fig. 5a). Some regions do not have the dispersion of TiC particles which are known as particle free regions. Cluster of TiC particles are observed in some other regions. The micrograph is a mixture of particle free regions, clusters and fairly distributed regions. The stirrer speed is insufficient to disperse the particles sufficiently into the melt. The micrograph at stirrer speed of 300 rpm (Fig. 5b) depicts a finer distribution of TiC particles. The increase in stirrer speed increases the centrifugal current within the aluminum melt which in turn disintegrates the TiC clusters into homogenously distributed particles. The vortex created is an optimum one to achieve homogenous distribution. The micrograph at stirrer speed of 500 rpm (Fig. 5c) shows further improved distribution of TiC particles in the aluminum matrix. The increase in stirrer speed from 100 rpm to 500 rpm increases the average interparticle distance. But regions of porosity are found in the micrograph. The porosities observed in stir cast AMCs are of four types; (a) porosity associated with individual particle; (b) porosity associated with particle clusters; (c) micro porosity in the aluminum matrix and (d) gas porosity [26]. The shape of the porosity is observed to be spherical in nature which confirms gas porosity. The vortex formed at stirrer speed of 500 rpm is vigorous and sucks atmosphere air into the aluminum melt due to higher pressure difference. The height of the vortex nearly reaches the stirrer blade. This result agrees to the findings of Ravi et al [30]. The gas porosities are not observed at stirrer speed of 100 rpm and 300 rpm for the constant cooling rate. The amount of gas sucked is more at 500 rpm which does not relieve completely during solidification. The entrapped gases formed gas porosity in the AMC casting.

3.2. Effect of stirring time

The predicted effect of stirring time on the UTS of AA6061/TiC AMCs is depicted in Fig. 6 for a constant stirring speed (300 rpm), blade angle (30^{O}) and casting temperature (800^{O}C). The UTS increases as stirrer time increases and reaches maximum at 15 min. Further increase in stirrer time leads to the reduction of UTS.

The creation of vortex by the stirrer rotation draws the particles into the aluminum melt. The fed particles will not disperse into all regions of the aluminum melt at once. The dispersion is a function of time [29]. The particles need to be subjected to constant centrifugal currents over a definite period of time to achieve dispersion all through the aluminum melt. Conversely, the vortex has the tendency to suck the air into the aluminum melt. The amount of air sucked depends on the stirring time. A longer stirring time will lead to excessive air entrapment resulting in porosity in the casting. The observation of micrographs of AA6061/TiC AMC casting at various stirring time will reveal the effect of stirring time.

Fig. 7 depicts representative micrographs of AA6061/TiC AMCs at various stirring time. The variations in the micrographs clearly indicate the effect of stirring time. The micrograph (Fig. 7a) at stirring time of 5 min presents large number of clusters. Particle free regions also observed. The microstructure is highly heterogeneous. A stirring time of 5 min is insufficient to disperse the TiC particles throughout the aluminum matrix. TiC particles remain closer to each other in the aluminum melt which form clusters. The micrograph (Fig. 7b) at stirring time of 15 min shows a homogenous distribution of TiC particles in the aluminum matrix. No clusters are visible. The average interparticle distance increases. The increase in stirring time produces finer distribution of particles. As the stirring time increases, the centrifugal currents within the molten aluminum collapse the clusters. The particles in the clusters are driven away to particle free regions. As a result, the distribution improves over stirring time. The micrograph (Fig. 7c) at stirring time of 30 min depicts improved distribution of TiC particles at the cost of porosity. The increase in stirring speed further 15 min improves the distribution to some extent. But various types of porosities as discussed earlier in sec 3.1 are noticed. The formation of porosity in cast AMCs is influenced by a number of parameters such as gas entrapment during stirring, air bubbles entering the composite melt, water vapor on the surface of the ceramic particles, hydrogen evolution and solidification shrinkage. Longer stirring time produces more agitation in the molten composite which increases the tendency to form more porosity [36]. Hence, a longer stirring time is detrimental to the desired microstructure. The obtained results indicate that there is an optimum range of stirring time to achieve uniform distribution with least porosity. If stirring continues beyond the optimum range, the gas absorbability of the molten aluminum will increase. Thus, the formation of porosity becomes unavoidable. The preferential nucleation and growth of gas bubbles during solidification lead to various kind of porosities.

3.3. Effect of blade angle

The predicted effect of blade angle on the UTS of AA6061/TiC AMCs is depicted in Fig. 8 for a constant stirring speed (300 rpm), stirring time (15 min) and casting temperature ($800^{O}C$). The UTS increases as blade angle increases and reaches maximum at 30^{O}. Further increase in blade angle leads to the reduction of UTS.

The currents generated by the stirrer rotation determine the distribution of particles within the melt. The axial and radial variation of the currents should be within a shorter range to achieve homogeneous distribution of particles. Previous studied indicated that an optimum inclination of the stirrer blade is required to disperse the particles uniformly into the melt [27,30,45,46]. A vertical stirrer blade resulted in sedimentation of particles near the wall and bottom of the crucible. The stirrer blade angle refers to the inclination of the blade with respect to the horizontal plane which is perpendicular to the axis of the crucible. The blade angle directly influences the angular flow i.e. velocity of the melt and causes a variation in the axial and radial currents. The details of the micrographs at various blade angles will help to understand the effect of blade of angle.

Fig. 9 shows representative micrographs of AA6061/TiC AMCs at various blade angles. The micrographs are not alike which gives confirmation to the effect of blade angle. The micrograph (Fig. 9a) at blade angle of 0^{O} presents many clusters of TiC particles as well as particle free regions. TiC particles are grouped in selected regions and other regions are left unreinforced. The vortex developed at blade angle of 0^{O} is shallow but sufficient for particle incorporation. The rate of particle mixing is slow. The angular velocity of the aluminum melt is relatively low to induce currents of required magnitude. The low centrifugal currents lead to poor distribution and formation of clusters. The micrograph reveals that a flat and horizontal blade does not produce desired distribution. The micrograph (Fig. 9b) at blade angle of 30^{O} depicts a homogenous distribution of TiC particles in the aluminum matrix. The clusters of TiC particles are not seen. The result indicates that tilting the stirrer blade from the horizontal position yields good distribution. The increase in blade angle increases the angular velocity of the aluminum melt and improves the centrifugal currents within the melt. The higher currents aid to break up the clusters in the aluminum melt and results in homogenous distribution. Thus, the dispersion rates increase with increasing the blade angle. Fig. 9c and d respectively describe the micrographs observed at the top and the bottom of the casting at blade angle of 60^{O}. The distribution of TiC particles across the depth of the casting from top to bottom is not constant. Hardly few TiC particles are observed (Fig. 9c) at the top of the casting. On the other hand, TiC particles are distributed homogenously at the bottom of the casting. But the distribution is stratified. The interparticle distance is too short at the bottom compared to the micrograph (Fig. 9b) at blade angle 30^{O}. It points out that more TiC particles are pushed towards the bottom of the crucible. The angular velocity is too high at blade angle of 60^{O} leading to huge axial variation of the current. The molten aluminum above and below the stirrer undergoes differential centrifugal currents. Similar observations were reported in the literatures by Naher et al [27] and Ravi et al [30]. The flow of aluminum melt becomes analogous to an intense swirl dragging the TiC particles towards bottom. Porosities are also noticed in the micrographs in Fig. 9c and b. The swirl motion draws more air into the aluminum melt which are not relieved during solidification. The air entrapment leads to internal micro voids known as porosity. The blade angle of 30^{O} is an optimum one to obtain the desired distribution.

3.4. Effect of casting temperature

The predicted effect of casting temperature on the UTS of AA6061/TiC AMCs is depicted in Fig. 10 for a constant stirring speed (300 rpm), stirring time (15 min), and blade angle (30^{O}). The UTS increases as casting temperature increases and reaches maximum at 800^{O}C. Further increase in casting temperature leads to the reduction of UTS.

The casting temperature exerts its influence in number of ways including viscosity of the molten aluminum, gas absorbability, cooling rate of the casting and reactivity between reinforcement particle and the aluminum [28,47,48]. The viscosity of the molten aluminum is directly proportional to the casting temperature. The change in viscosity results in the following. At lower viscosity, it is difficult to stir the aluminum properly. Particle movement within the molten aluminum particularly vertical motion towards the bottom of the crucible known as settling depends on the viscosity. If the viscosity is high, the movement of particle within the aluminum melt will be high and it will be difficult to secure homogeneous distribution. The increase in casting temperature increases the risk of higher gas absorption. The cooling rate is inversionally proportional to the casting temperature. Higher cooling rate produces reasonable distribution of particles and porosity. The chances of interfacial reaction are more at very high casting temperature. In the light of these effects, the micrographs at various casting temperature are discussed subsequently.

Fig. 11 shows representative micrographs of AA6061/TiC AMCs at various casting temperatures. The micrograph (Fig. 11a) at casting temperature of 630^{O}C shows regions of TiC clusters. Little porosity is also observed. The binary phase equilibrium diagram of aluminum alloy AA6061 is given in Fig. 12a [49,50]. The magnesium and silicon in this aluminum alloy combines to form Mg_2Si. The amount of Mg_2Si was calculated using the chemical composition provided in table 4 and was estimated to be 1.49. The Mg_2Si percentage of the AA6061 used in this work is marked as a vertical line in Fig. 12a. The liquidus and solidus temperature was estimated to be 655^{O}C and 595^{O}C respectively. The alloy remains in a semi solid state within this region. Stir casting at semi solid state is called as compo casting or slurry casting or rheocasting [34,51,52]. There are contrary trends published by different investigators on compo casting. Some reported improved distribution and lower porosity [32,34,53] and vice versa [28,33]. The liquid fraction of the aluminum alloy within the freezing range was computed using lever's rule from Fig. 12a and presented in Fig. 12b. The liquid fraction at the casting temperature of 630^{O}C is 20%. Yet it was possible to stir the semi solid slurry with difficulty and incorporate the particles. The distribution of TiC particles is related to the friction of the semi solid slurry which depends upon the viscosity. The viscosity is relatively low at 630^{O}C. The low viscosity is favorable to avoid vertical movement of particles. But the frictional resistance is too high which makes it impossible to distribute the TiC particles all through the slurry homogenously. The weak currents within the slurry do not assist to disperse the particles causing the formation of clusters. The presence of small amount of porosity can be explained as follows. The gas absorbed by the semi solid slurry is low compared to molten aluminum. A substantial portion of the semi solid slurry is solidified at the instant of transferring to the mould. The possibility of solidification shrinkage related porosities are remote. Since, the viscosity of the slurry is high; it cannot vent all the absorbed gas similar to a fully molten aluminum. Further, the solidification rate is high at 630^{O}C due to lower latent heat and high solid fraction. These two factors reduce the available time for the gas to escape resulting in porosity. The micrograph (Fig. 11b) at casting temperature of 830^{O}C presents homogeneous distribution of TiC particles. The increase in casting temperature from 630^{O}C to 830^{O}C decreases the viscosity of the molten aluminum. The decrease in viscosity enhances the ease of stirring and improves the centrifugal currents in the melt. The clusters are scattered in the melt to form homogenous distribution. The cooling rate at 830^{O}C is optimum which allows sufficient time to relieve the absorbed gases. The porosity in the casting is low. The micrograph (Fig. 11c) at casting temperature of 1030^{O}C depicts the distribution of TiC particles in the aluminum matrix. Most of the TiC particles are segregated at the grain boundary. The distribution is highly intergranular. Regions of porosity also noticed in the micrograph. The rise in casting temperature from 830^{O}C to 1030^{O}C further decreases the viscosity of the melt. The particles gain high energy at this elevated temperature and cause them to move faster and easier within the melt. The free movement of the particle in the melt is rapid. The cooling rate at 1030^{O}C is slow compared to other casting temperatures used in this work. The distribution of second phase particles in a melt depends on three phenomena; (a) buoyant motion of the particles, (b) pushing of the particles by the moving solidification front, and (c) convection current in the melt [54]. Observing the distribution of TiC particles along the grain boundaries, it can be concluded that the particles are pushed by the solidification front leading to segregation in the interdendritic regions.

3.5. Microstructure-tensile strength relationship

The predicted trends (Fig. 4,6,8 and 10) of UTS against various stir casting parameters are correlated to the observed micrographs (Fig. 5,7,9 and 11) in this section.

The factor which predominantly influence the strength of AMCs are the porosity content, grain size, distribution of second phase particles, shape and size of reinforcement particles and presence of intermetallic compounds due to interfacial reaction or decomposition. The grain size was not taken into account to correlate with UTS. It was established by early stage investigators that the grain size of cast AMCs does not appreciably contribute to the strength [55]. The shape and size of the TiC particle (Fig. 2) is fixed same for all experiments. There is no variation in shape and size of TiC particles after stir casting comparing Fig. 2 with Fig. 5,7,9 and 11. This indicates that there is no decomposition of TiC particle during stir casting. Fig. 13a shows the micrograph of AA6061/TiC AMCs at casting temperature of $1030^{O}C$ in higher magnification. The particle shape and size are similar to initial conditions. The interface between the TiC particle and the aluminum matrix is clean. No interfacial reaction products are detected at the interface. This confirms that TiC particles are thermodynamically stable throughout the range of temperatures used in this study. The XRD of AA6061/TiC AMCs at casting temperature of $1030^{O}C$ is presented in Fig. 14. The XRD consists of peaks of aluminum and TiC. Peaks of possible interfacial reaction compounds such as Al_3Ti, Al_3C_4 were not detected. The XRD further confirms the integrity of TiC particles during stir casting. The XRD did not show peaks of oxides such as Al_2O_3. The inert furnace atmosphere prevented the formation of oxide inclusions in the casting. The UTS of AA6061/TiC AMCs was found to be high when the microstructure is characterized with homogenous distribution of TiC particles in the aluminum matrix with minimum porosity content. The uniform distribution promotes Orowan strengthening of the AMC [56]. Llyod [55] concluded that Orowan strengthening operates in AMCs reinforced with second phase particles of size less than 5 μm. The operation of Orowan mechanism involves the interaction between dislocations and reinforcements. During solidification of the AMC, strain fields are created around TiC particles due to the difference in the thermal expansion coefficient between the aluminum alloy and TiC particle. The motion of dislocations during tensile loading is hindered by the strain fields associated with TiC particles which causes the dislocations to bow around the particles. Thus, orowon loops are created around TiC particles and impedes the progress of dislocations. Hence, the value of UTS is high for AA6061/TiC castings having homogenous distribution of TiC particles. The UTS of AA6061/TiC AMCs was observed to be lower for castings having porosity, clusters and intergranular distribution. Porosity content reduces the available cross sectional area to resist the tensile load. A porosity site creates stress concentration and tends to increase the localized strain [57]. It sets up non uniform stress fields and initiates cracks. TiC particle clusters are sites for damage buildup. The interface between the particles in the cluster is weak as depicted in Fig. 13b. These weak interfaces are most favorable sites for crack initiation during tensile loading. The strain localization within a particle cluster leads to premature fracture. The intergranular distribution represents segregation of TiC particles at the grain boundary. The magnified view of segregation is shown in Fig. 13c. Several weak interfaces between particles are identified which act as potential sites for crack initiation.

4. Conclusions

In the present work, AA6061/15wt. % TiC AMCs were produced successfully using the stir casting method. An empirical relationship incorporating the stir casting parameters was developed to predict the UTS. The various stir casting parameters such as stirrer speed, stirring time, blade angle and casting temperature considerably influenced the UTS. A lower or higher combination of those parameters resulted in lower UTS. This was attributed to the formation of porosity, cluster of particles and segregation of TiC particles at the grain boundaries. An intermediate range of parameters yielded castings with homogeneous distribution of TiC particles and minimum porosity content. The UTS was high when the porosity content was low and the distribution was homogenous. The present research work revealed an existence of optimum range of parameters to produce AA6061/15wt. % TiC AMCs with high UTS. The selection and control of stir casting parameters are essential to minimize porosity content and achieve uniform distribution to enhance the load bearing capacity of the AMCs.

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