

# Stir Casting of in-situ Al 6061TiB<sub>2</sub> Metal Matrix Composite Synthesized with Different Reaction Holding Times

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**Abstract**— Conventional casting of Aluminium (Al) Metal Matrix Composite (MMC) faces certain disadvantages such as non-uniform distribution of the reinforcement particles in the metal matrix, insufficient wetting of particles by the liquid metal and segregation of the reinforcement particles in the matrix phase resulting in poor tensile strength, low hardness and other inferior mechanical properties. These problems can be solved by an effective casting method viz. stir casting which promotes uniform distribution of the reinforcement particles in the matrix phase, good wetting of particles by the liquid matrix metal and improvement of tensile strength and hardness which are essential mechanical properties required for engineering applications in the fields of transportation, construction and aerospace. Aluminium is one of the light metals and its alloys are used for developing many metal matrix composites due to its favorable mechanical properties such as low weight, good corrosion resistance and high electrical and thermal conductivities etc. The strength and hardness of aluminium alloy can be increased by introducing TiB<sub>2</sub>, the reinforcement phase in the liquid aluminium alloy matrix at a temperature above its melting point. In the present study, an attempt was made to fabricate in-situ Al6061-TiB<sub>2</sub> metal matrix composite by incorporating halide salts such as potassium hexafluorotitanate (K<sub>2</sub>TiF<sub>6</sub>) and potassium tetrafluoroborate (KBF<sub>4</sub>) in the aluminium alloy melt at 850°C. In order to investigate the degree of in-situ reaction during the formation of Al6061-TiB<sub>2</sub> metal matrix composite the melt was maintained at 850°C with different reaction holding times (RHTs).

**Keywords**—Stir casting, Aluminium alloys, Al6061-TiB<sub>2</sub> Metal Matrix composite, In-situ, Reaction Holding Time (RHT).

## I. INTRODUCTION

In a stir casting process, the reinforcing phases (usually in powder form) are distributed into molten Aluminum by mechanical stirring. Stir casting of metal matrix composites was initiated in 1968, when S. Ray introduced alumina particles into aluminum melt by stirring molten aluminum alloys containing the ceramic powders [1]. Mechanical stirring in the furnace is a key element of this process. The resultant molten alloy, with ceramic particles, can then be used for die casting, permanent mold casting, or sand casting. Stir casting is suitable for manufacturing composites with up to 30% volume fractions of reinforcement [2, 3]. The cast composites are sometimes further extruded to reduce porosity, refine the microstructure, and homogenize the distribution of the

reinforcement. A major concern associated with the stir casting process is the segregation of reinforcing particles which is caused by the surfacing or settling of the reinforcement particles during the melting and casting processes. The final distribution of the particles in the solid depends on material properties and process parameters such as the wetting condition of the particles with the melt, strength of mixing, relative density, and rate of solidification. The distribution of the particles in the molten matrix depends on the geometry of the mechanical stirrer, stirring parameters, placement of the mechanical stirrer in the melt, melting temperature, and the characteristics of the particles added [4, 5]. An interesting recent development in stir casting is a two-step mixing process. In this process, the matrix material is heated to above its liquidus temperature so that the metal is totally melted. The melt is then cooled down to a temperature between the liquidus and solidus points and kept in a semi-solid state. At this stage, the preheated particles are added and mixed. The slurry is again heated to a fully liquid state and mixed thoroughly. This two-step mixing process has been used in the fabrication of aluminum A356 and 6061 matrix composites reinforced with SiC particles. The resulting microstructure has been found to be more uniform than that processed with conventional stirring. The effectiveness of this two-step processing method is mainly attributed to its ability to break the gas layer around the particle surface. Particles usually have a thin layer of gas absorbed on their surface, which impedes wetting between the particles and molten metals. Compared with conventional stirring, the mixing of the particles in the semi-solid state can more effectively break the gas layer because the high melt viscosity produces a more abrasive action on the particle surface. Hence, the breaking of the gas layer improves the effectiveness of the subsequent mixing in a fully liquid state. Stir casting allows for the use of conventional metal processing methods with the addition of an appropriate stirring system such as mechanical stirring; ultrasonic or electromagnetic stirring; or centrifugal force stirring [6]. The major merit of stir casting is its applicability to large quantity production. Among all the well-established metal matrix composite fabrication methods, stir casting is the most economical (Compared to other methods, stir casting costs as little as one third to one tenth for mass production

[7, 8]. For that reason, stir casting is currently the most popular commercial method of producing aluminum based composites.

Metal matrix composites (MMCs) first emerged as a distinct technology in an era when improved performance for advanced military systems provided a primary motivation for materials development [9]. MMCs have emerged as an important class of materials for structural, wear, thermal, transportation and electrical applications, primarily as a result of their ability to exhibit superior strength-to-weight and strength-to-cost ratio when compared to equivalent monolithic commercial alloys [10]. Important MMC applications in the ground transportation (auto and rail), thermal management, aerospace, industrial, recreational and infrastructure industries have been enabled by functional properties that include high structural efficiency, excellent wear resistance and attractive thermal and electrical characteristics [11].

Aluminium matrix Composites (AMCs) have found extensive use in many engineering applications because of their high specific modulus, strength, hardness and stiffness, excellent wear resistance, low-heat expansion coefficient, stability of properties at elevated temperature, reduced density and competitive fabrication cost. The development of these materials has been driven by the aerospace and automotive industries for both nonstructural and structural applications [12].

Al based composite reinforced by hard ceramic particles have become more and more attractive in the research of structural composites. The addition of ceramic particles such as TiB<sub>2</sub>, SiC, Al<sub>2</sub>O<sub>3</sub>, and B<sub>4</sub>C to an aluminium based matrix does not considerably change the density of the material but instead it usually leads to a significant rise in specific strength and modulus of composite. This improvement of composite plays a role as weight saving material for use in structural applications [13]. Aluminium alloy Al 6061 is widely used in numerous engineering applications including transport and construction where superior mechanical properties such as tensile strength, hardness etc. are essentially required. Its superior corrosion resistance makes it a suitable candidate material for marine structural applications. The demand for lighter weight, cost effective and high performance materials for use in a spectrum of structural and non-structural applications have resulted in the need for fabrication of metal matrix composites (MMCs) of various types [14].

The composite prepared by ex - situ method suffers thermodynamic instability between matrix and reinforcements thus limiting their ambient and high temperature mechanical properties. The major challenges in processing of ex-situ MMC is the thermodynamic instability of ceramic reinforcing phases with the matrix. This is due to poor wetting between matrix and reinforcement. Ex-situ process possesses drawbacks like agglomeration, poor wetting and heterogeneity in microstructure [15]. Fabrication of in-situ composite involves synthesis of reinforcing phases directly within the

matrix. This approach is in contrast to ex-situ composite where the reinforcements are synthesized separately and then introduced into the matrix during a secondary process such as melting, infiltration (or) powder processing [16]. The main problem lies in ex-situ composite is thermodynamic instability of reinforcing ceramic phases with the matrix [17]. This problem can be solved by using in-situ technique. And also there are several potential advantages associated with in-situ composite such as thermodynamic stability, kinetic control of the reaction, reduced size and uniform distribution of the reinforcing particles, good interfacial bond and economy in processing [18]. Using the in-situ approach MMCs with wide range of matrix materials (Al, Fe, Cu, Pb, Ni and Ti) and the second phase particles (borides, carbides, nitrides and oxides) can be produced [19].

Among the various reinforcing particles TiB<sub>2</sub> is particularly attractive because it exhibits high elastic modulus and hardness as well as good thermal conductivity. Compared to Al-SiC, the Al-TiB<sub>2</sub> MMC has better high temperature properties [20]. The incorporation of TiB<sub>2</sub> particles in the matrix by in-situ processing offer special advantages such as clean matrix-particle interface resulting in effective load transfer and minimizing wear rates [18].

The present study was to fabricate in-situ Al6061-TiB<sub>2</sub> metal matrix composite by incorporating halide salts such as potassium hexafluorotitanate (K<sub>2</sub>TiF<sub>6</sub>) and potassium tetrafluoroborate (KBF<sub>4</sub>) in the aluminium alloy melt at 850<sup>o</sup>C. In order to investigate the degree of in-situ reaction during the formation of Al6061-TiB<sub>2</sub> metal matrix composite, the melt was maintained at 850<sup>o</sup>C with different reaction holding times (RHTs).

## II. EXPERIMENTAL PROCEEDURE

Aluminium alloy Al6061 was used as the matrix phase and the reinforcement phase was TiB<sub>2</sub> which was formed by introducing halide salts viz. potassium hexafluorotitanate (K<sub>2</sub>TiF<sub>6</sub>) and potassium tetrafluoroborate (KBF<sub>4</sub>) into the molten alloy at 850<sup>o</sup>C.

### PROCESSING:

Al6061 alloy was first melted in a graphite crucible using an electrical resistance furnace to a temperature of 850<sup>o</sup>C and then the halide salts namely potassium hexafluorotitanate (K<sub>2</sub>TiF<sub>6</sub>) and potassium tetrafluoroborate (KBF<sub>4</sub>) were added to the molten alloy in accordance with the atomic ratio Ti/2B. Using a mild steel stirrer coated with zirconia for avoiding possible contamination, the melt was stirred at 600 rpm and maintained for different reaction holding times in steps of 15 minutes up to 45 minutes to investigate the degree of reaction and the growth behavior of TiB<sub>2</sub>. After the predetermined period of reaction holding time, the cryolite slag formed during the chemical reaction between the halide salts and the molten aluminium alloy was skimmed thoroughly before pouring the molten composite into the die. The composite was cast into rods of 16 mm diameter. Various examinations and tests such as metallographic examination, tests for the measurement of

tensile properties and hardness were carried out as the part of characterization of the composites prepared with different reaction holding times.

### III. RESULTS AND DISCUSSION

#### *Microstructure*

Specimens of the cast base alloy and the composites with different reaction holding times were prepared for the microscopic examination to evaluate the microstructure. They were ground, polished and suitably etched and the examination was conducted by an optical microscope. Figure 1 shows the optical micrographs of the Al6061-TiB<sub>2</sub> composites with different reaction holding times up to 45 minutes in steps of 15 minutes. A uniform distribution of reinforcement particles in the matrix phase is observed from these micrographs. There is good bonding between the matrix and the reinforcement phases as there is no gap between them.

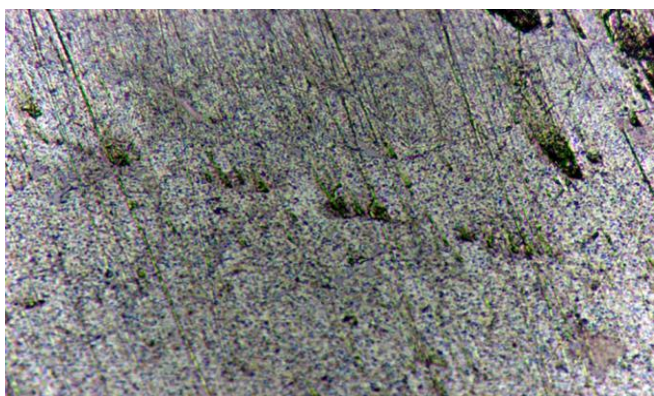


Fig.1.a. Micrograph of Al 6061 alloy as cast (100X)

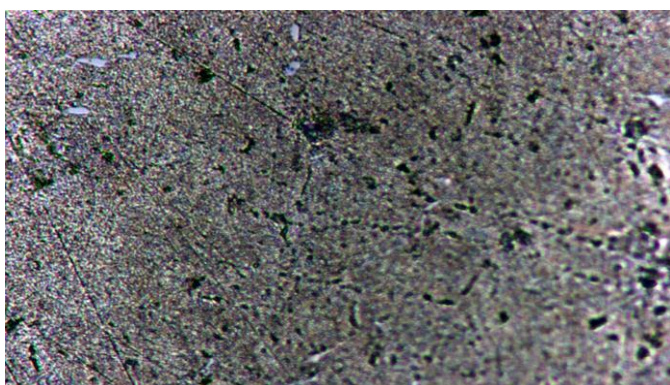


Fig.1.b. Micrograph of Al 6061-TiB<sub>2</sub> with 15 minutes' Reaction Holding Time (100X)

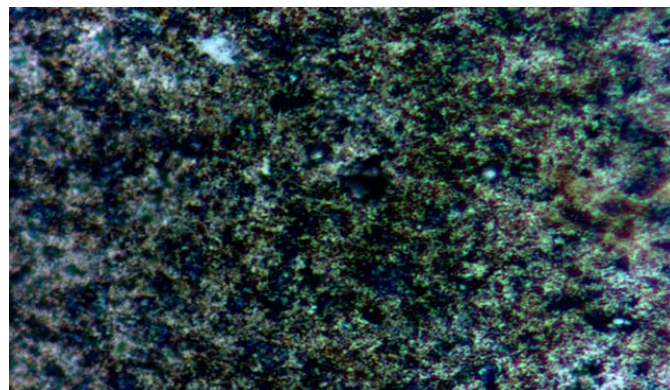


Fig.1.c. Micrograph of Al 6061-TiB<sub>2</sub> with 30 minutes' Reaction Holding Time (100X)

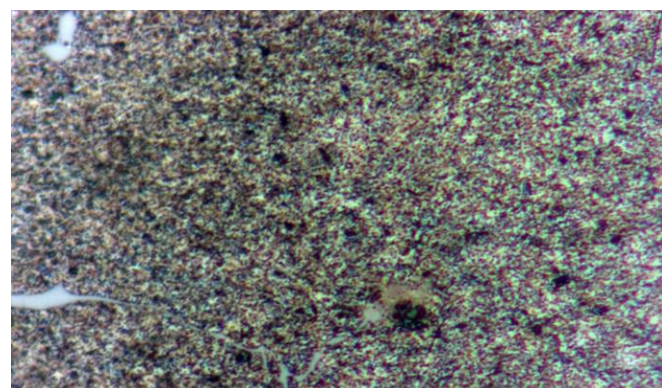


Fig.1.d. Micrograph of Al6061-TiB<sub>2</sub> with 45 minutes' Reaction Holding Time (100X)

Fig.1. Optical Micrographs of Al 6061 as cast and Al6061-TiB<sub>2</sub> with Different Reaction Holding times

#### *Tensile strength*

For measuring tensile properties, tensile test specimens were prepared as shown in Figure 2 as per ASTM E8 standard and the tensile tests were carried out by using a Hounsfield Tensometer at room temperature under constant strain rate. The tensile test results for various samples with different reaction holding times are shown in TABLE 1. The tensile properties of the composites are compared with the results of the base alloy Al6061.

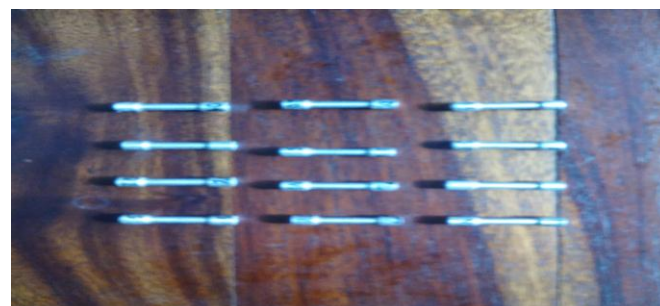


Fig. 2: Tensile Test specimens of alloy and composites for measuring tensile properties

Compared with Al6061 alloy, the composite has a higher tensile strength but with lower ductility. The increase of tensile strength in the case of composite is due to the uniform distribution of  $TiB_2$  in the matrix. The stress value increases with reaction holding time up to 30 minutes and then it decreases. This implies that the optimum reaction holding time of the halide salts in the base alloy is 30 minutes. The percentage elongation of the base alloy and the composites with different reaction holding times are also shown in TABLE 1.

TABLE-1: TENSILE PROPERTIES OF COMPOSITES WITH DIFFERENT RHTs

Material	RHT (Min)	YS (MPa)	UTS (MPa)	Elongation (%)
Al 6061 (as cast)	0	122	146	22.13
Al6061-TiB <sub>2</sub>	15	134	156	18.24
Al 6061-TiB <sub>2</sub>	30	142	160	16.34
Al 6061-TiB <sub>2</sub>	45	141	157	16.46

It decreases with the reaction holding time up to 30 minutes and then it increases slightly. Compared to the base alloy, the decrease of percentage elongation of the composite is due to the presence of  $TiB_2$  particles in the matrix giving rise to increase in hardness.

#### Hardness

Test specimens were prepared from base alloy and the composites for the measurements of their hardness which were carried out using Brinell hardness tester to assess the influence of different reaction holding times during which the salt-metal reaction took place. The Brinell hardness test results obtained for the base alloy and the composites with different reaction holding times at different locations over the surface are shown in TABLE 2.

TABLE2: HARDNESS OF ALLOY AND COMPOSITES

Material	RHT (Min)	Hardness (BHN)
Al 6061(as cast)	0	88
Al 6061-TiB <sub>2</sub>	15	107
Al 6061-TiB <sub>2</sub>	30	116
Al 6061-TiB <sub>2</sub>	45	114

It is clear that the presence of  $TiB_2$  reinforcement particles in the Al6061 alloy matrix increases the hardness of the composites up to 30 minutes' reaction holding time with a decrease in hardness for the next 15 minutes' time. The reduction in hardness is due to the increase of micro porosities due to higher reaction holding time at the temperature of the melt. It can be concluded that the increase of micro porosities and hence the reduction in

hardness is due to the absorption of gases by the aluminium melt at 850°C. Besides, the percentage of elongation reduced significantly up to the same level of reaction holding time. The  $TiB_2$  particles in the Al 6061 alloy matrix increased the hardness as these reinforcement particles are harder than Al 6061 alloy.

#### IV. CONCLUSIONS

Based on the present investigation, it can be concluded the following:

1. By incorporating halide salts, potassium hexafluorotitanate ( $K_2TiF_6$ ) and potassium tetrafluoroborate ( $KBF_4$ ) in the Al 6061 alloy at 850°C Al 6061-TiB<sub>2</sub> metal matrix composites were synthesized successfully.
2. Good 'wetting' of the reinforcement particles by the liquid melt was made to be possible by the Stir casting method.
3. TiB<sub>2</sub> reinforcement phase was made to achieve a uniform distribution in the Al 6061 matrix phase by the combined effects of both the Stir casting and the In-situ methods.
4. The amount of cryolite slag formed during the reaction between molten alloy and the halide salts increases with increase in reaction holding time.
5. With increase in reaction holding time, there was an increase in tensile strength and hardness of the composite up to 30 minutes' reaction holding time followed by a decrease in both tensile strength and hardness for the next higher level of 15 minutes' reaction holding time.
6. A similar opposite trend was seen in the case of percentage of elongation and ductility of the composite with increase in reaction holding time up to 30 minutes.

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