PROJECT AND CONSTRUCTION OF EQUIPMENT FOR SYNTHESIS OF PARTICULATED METAL MATRIX COMPOSITE, USING MECHANICAL STIR CASTING

Kratus Ranieri, kratusranieri@ig.com.br
Carlos Kiyan, kiyan@feg.unesp.br
Universidade Estadual Paulista – UNESP, Faculdade de Engenharia de Guaratinguetá, Departamento de Materiais e Tecnologia, Av. Dr. Ariberto Pereira da Cunha, 333 – CEP 12516-410 – Guaratinguetá – SP - Brasil

Abstract: Metal matrix composites (MMC) are now materials of both technological and economical significance. Their functional properties that combine metal and ceramic characteristics provide an important material with applications in several fields such as: ground transportation, aerospace, recreational and many others industries. Among the many techniques available to synthesize metal matrix composite, the mechanical stir casting method is attractive for its simplicity, economy and flexibility, therefore it has been object of intensive researches and patents registrations. Although the considerable amount of publications, the laboratorial devices used by the researchers to mix ceramic particles with matrix melt are poorly described. In this work emphasis is given to the design, as well as to details of the apparatus construction, in order to produce particulated metal matrix composite by mechanical stir casting. The equipment used was designed to work with low melt point alloys, operating temperature up to 1000 °C and loading about 800 g of metal. It has a system to stir the metal driven by an adjustable speed electrical motor. The oven is tubular, opened in both sides, making it possible to withdraw the crucible to the lower opening for pouring and to introduce the stirrer inside the oven by the upper opening. This technique has been used with success in order to prepare alumina composite with Al7%Si matrix. The method and the device used showed efficiency and reproducibility for particulated metal matrix composite synthesis.

Keywords*: Metal matrix composite, stir casting, alumina, Al7%Si*

1. INTRODUCTION

A metal matrix composite (MMC) combines into a single material a metallic base with a reinforced non-metallic constituent. It means that, MMCs are produced by a process other than conventional metal allowing. MMCs have been generating considerable interest within the materials community for the last 30 years. There are several reasons such as: 1) composites offer the only pathway for producing materials with tailored physical property combinations and exceptional properties can be obtained in some cases; 2) The use of metallurgical processing is the only pathway for the production of a entire classes of metallic materials; 3) MMCs offer significant improvements over their polymer matrix counterparts with regard to several properties, including tolerance of high temperature, transverse strength, chemical inertness, hardness and wear resistance. High performance aerospace, medical, communications, power semiconductor, and other industrial and commercial applications are finding advantages in the using of metal matrix composites (Miracle, 2005).

There are various manufacturing techniques available to produce MMC composites, such as: compocasting, infiltration techniques, powder metallurgy, diffusion bonding and many others ones. These techniques can't be applied in all situations and depend on the choice of matrix alloy and reinforcement materials. Usually, the manufacturing methods are classified by the physical state of the matrix: solid phase process, liquid phase process and semi-solid process. Stir casting method involves producing a melt of the matrix material, followed by the introduction of a reinforcing material into the melt to obtain dispersion through stirring. The stir can be done either in the semi-solid state or in the liquid state or both in the same processing. Compared with another processes for discontinuous MMC production, the stir casting method has some important advantages, such as easier control of matrix structure, simplicity, flexibility, applicability to large scale production, low cost of processing and near net shape (Naher et al, 2004).

The preparing of composite materials using a casting method is generally associated to ceramic particles. Therefore good wetting between the solid ceramic particles and the liquid metal is an essential condition for the generation of a satisfactory bond between these two phases. In general ceramic particles have poor wettability to molten metals and several approaches have been taken to promote wetting of reinforcement particles with a molten matrix alloy. The wettability of a solid by a liquid is indicated by the "contact angle" θ. This angle is related to three surface tensions γ_{sg}, γ_{sl}, γ_{lg} of the interfaces solid-gas, solid-liquid and liquid-gas, respectively, by the well-known Young's equation:

$$\gamma_{lg} \cos \theta = \gamma_{sg} - \gamma_{sl}$$

This means that a low contact angle is indicative of good wettability, or if $\cos \theta > 0$, than $\gamma_{sg} > \gamma_{sl}$ (Delannay et al, 1987). Hence, the wettability may be improved by decreasing the surface tension at the interface solid liquid γ_{sl}. These include: addition of alloying elements to the molten matrix; coating of the ceramic particles and thermal treatment of the ceramics particles (Hashim, 1999). The wetting process has to displace air from the internal surfaces between particles to facilitate breaking of their agglomerates during mixing. The wetting of solid particles with porous surfaces is a complex process involving several primary processes: immersion, adhesion, spreading, and capillary penetration. Various wetting mechanisms may operate simultaneously.

To best understanding, the stir casting process can be divided into two groups of events: 1) the mix of ceramics particles with the melt metal promoted by a vigorous agitation in order to obtain a homogeneous suspension of the wetted ceramics particles and 2) the composite pouring, following by the solidification of the slurry. In each group several parameters influence the particles incorporation, the homogeneity of the reinforcement distribution and the bonding between ceramic particle and the solidified matrix alloy. The mechanical properties of MMC are controlled to a large extent by these characteristics. The main variables related to these two groups of events are: a)total mixing time; b)stir speed (revolutions per minute); c)relative geometry stir rod/crucible; d)granulation, morphology and surface roughness of the particles; e)matrix alloy composition; f)particles chemical composition – indeed impurities; g)thermal route; h)cooling rate – material and geometry of the mould; i)pouring method (Prabu et al, 2006; Aniban et al, 2002; Hashim et al, 2002; Rajan et al, 2007; Aklaghi et al, 2004). Therefore, the process presents a high degree of complexity and the apparatus developed for the laboratorial studies as well as the equipment operation are critical factors for the reproducibility and the reliability of the experiments. The possibility of variation and control of such variables is an essential condition in any study concerning the stir casting process. Some of them like rotational speed, relative geometry of the stir rod/crucible, mixing time, thermal route and pouring method are directly related to the apparatus design and its operation. Consequently the equipment design must be in such a way that these variable can be controlled. In general, the devices used by the researches comprise an electric furnace, a crucible (usually clay graphite material) and a system to promote the stirring. Although these components are common to all the equipments, the geometry, size, the stir system, work temperature, power furnace and many others designed details are different and in general are poorly described. The main purpose of this work is to present and to discuss a detailed project and construction of an equipment used to study and produce metal matrix composites by the stir casting method.

2. EXPERIMENTAL

In this study, a stir caster was designed based on the following conditions: (a) easy construction; (b) low cost; (c) working temperature up to 1000°C; (d) metal load up to 1 kg; (e) easy operation; (f) flexibility to operate in several thermal routes and (g) possibility to produce compocasting and (or) specific metal alloys. The schematic drawing of the stir caster used in this work is shown in Fig. 1. This device is compounded of the following elements: 1) structure; 2) electric motor; 3) motor speed controller; 4) stirrer shaft; 5) electric furnace; 6) furnace temperature controller; 7) crucible; 8) mechanism to move the crucible – crucible actuator and 9) argon system to protect the molten metal surface against oxidation.

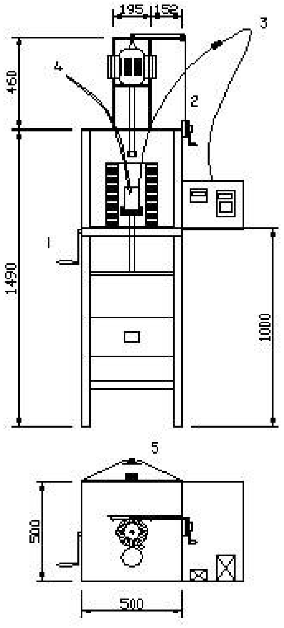

Figure 1. Schematic drawing of the apparatus [mm]: (1) crucible actuator (2) motor/shaft actuator (3) thermocouple (4) argon tube (5) fun

2.1. Structure

The structure was built on four columns of low carbon steel angle bar, 5x50x50 mm, welded to two steel tables of 5x500x500 mm. The furnace was mounted on the lower table, which has a hole making it possible to withdraw the crucible. The upper table has a hole, 5 mm diameter, to let pass the motor shaft and another hole, 20 mm diameter, allowing observation of the furnace inner.

2.2. Electric furnace

The designed furnace is a tubular shaped one with 3960 W – 220V, opened in both ends. A spiral shaped Kantal A1 wire was coiled around a PVC tube with 160 mm diameter. This assembly was put into a cylindrical shaped mold and hydrated high alumina refractory concrete (85% wg alumina) was poured around it, embedded in the Kantal wire. Fifteen days later, the mold was removed and the concrete was dried at room temperature in ten days. Then the wiring furnace was connected and the following fired process was carried out:

First step - heated up to 100° C in 2 h

Second step – hold on at 100° C for 22 h

Third step – heated up and hold on at 600 °C for 48 h

During the first step the PVC tube becomes softened and can be removed. The furnace was put on the lower steel table, fitted with the table hole, recovered with an insulator refractory mineral mantle and surrounded by an low-carbon steel galvanized sheet. An annular shaped refractory concrete slab was used to close the top furnace side. Two refractory covers were used to close both the top and the bottom furnace openings. The top cover is simply supported under the annular concrete and the bottom cover is attached to the crucible actuator. The furnace temperature is controlled by a solid-state power relay driven by a thermo regulator. One calibrated K type mineral insulated thermocouple put into a blind-drilled hole made at the crucible wall provided the control input to a thermo regulator temperature controller. To assure an efficient refrigeration of the solid-state relay, it was mounted under an aluminum plate with 5x20x50 mm fixed at the structure and air cooled by a little fan.

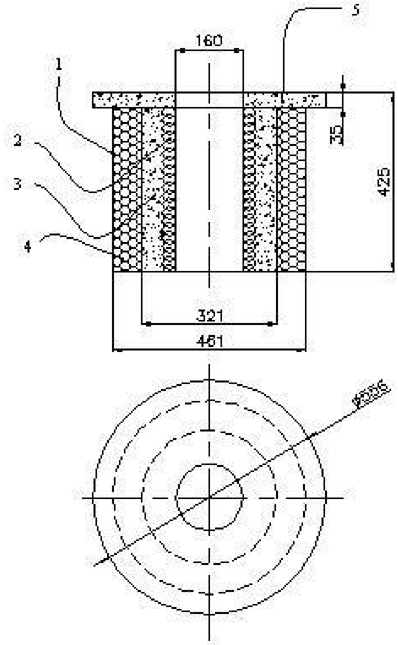

Figure 2. Electric furnace [mm]: (1) steel sheet (2) Kantal A1 wire (3) refractory concrete (4) mineral mantle

2.3. Electric motor

The electric A.C. motor is 0,25 CV, 2 poles, 220V. Figure 1, detail 2, shows an actuator mechanism witch allows a vertical movement of the motor/stir shaft assembly. This mechanism is necessary because the blades are introduced in the metal after its melt. In addition it is good to hold on the electric motor most of the time far from the furnace heat. Otherwise some problem arises from this system related to get a perfect alignment between the stir rod and the crucible center. The motor rotational speed can be changed from 0 to 3600 rpm by a reversing power frequency with a protection against mechanical interlocking.

2.4. Stirrer rod

The stirrer rod was lathe-turned from a low steel bar and coupled to the motor shaft by an inner hole with 25 mm diameter, 460 mm height, made in one of the end rod and fixed by an inner screw. During this experimental work, a two flat bladed stirrer was chosen. The blade was fixed by mechanical pressure on a tear made in the stirrer end. When working with aluminum and aluminum alloys the stirrer was protect against chemical dissolution with a specific paint. Both the shaft and the blades can be changed. Attention was taken during machining and fastening of the stirrer and the motor shaft to assure a good balancing. Although the motor driven can work on rotation speeds from 0 to 3600 rpm, rotational speeds upper to 800 rpm are difficult to reach due to mechanical vibrations on the shaft. A way to overcome this difficult is to support the shaft end on a hole made on the crucible bottom. By lifting the stirrer shaft this hole permits a quick metal pouring at low temperatures. It is a usual proceeding in compocastings experiments.

2.5. Crucible actuator

The crucible is charged with solid metal outside of the furnace and after the processing it must be drawn to composite pouring. In order to move the crucible in a vertical direction an actuator was designed. The system consists of an inverted “T” structure coupled at two lateral tube sliding guides driven by crank and steel cable allowing only vertical movement. The upper side of the inverted “T” holds a crucible support made like a telescoping drawtube. This lifting mechanism was used to extract the crucible and to facilitate its cleaning and replacement.

2.6 System for metal surface protection

Metals like aluminum and aluminum alloys, which have strongly affinity with oxygen, must be insulated from atmosphere. In order to protect the liquid metal, argon was directly blown under the metal surface, originating an argon layer circumscribed by the crucible walls, the liquid metal and the atmosphere. Flow of about 2 l/min was observed as a good level.

3. RESULTS AND DISCUSSION

Figure 3 shows a micrography of a representative sample of a A356 matrix composite reinforced with 5 % wg alumina powders range from 75 µm to 150 µm. The metallographic preparation followed the steps: cutting by diamond wheel at 150 rpm; manual grinding using 1000 and 1500 abrasive paper and water as lubrificant; polishing with alumina emulsion 1µm and finishing with aqueous suspension colloidal silica; unetching conditions. Cautions were taken during the process mentioned above to avoid failures or particles pulling out. One can distinguish three phases: (i) the darker one is the alumina particle; (ii) the white phase is contaminations resulting from reactions between the aluminium alloy and the stainless steel crucible wall and (iii) the dark gray is the A356 matrix.

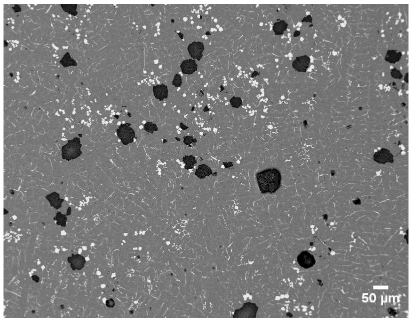

Figure 3 – Microstructure of A356 matrix composite reinforced with alumina powder (SEM)

The device operation is simple to liquid state processing but demands an experienced operator in semi solid processing. In this case it is necessary to cool up the melted alloy to a temperature between the *liquidus* and *solidu*s lines. The device used has not a refrigeration system and the metal cooling is made by turning off the furnace and by opening its top cover. Therefore the cooling rate is not controlled, depends on the room temperature and the operator must “know” the exactly instant to turn on the furnace to avoid a complete alloy solidification. A356 matrix composites were produced in this way and many attempts had to be done until satisfactory results were obtained.

In order to improve the design of the equipment and its operation some considerations may be done. As already mentioned the designed equipment has a rotational speed limit of 800 rpm owing to the dynamic unbalance of the shaft.

The height of the shaft is set by the crucible position into the oven and by the requirement of placing the motor far from the radiant heat furnace. The greater the shaft more difficulty is the perfect alignment and balancing of the system. The alternative to overcome this limitation may be by fixing the shaft extremity on a hole opened on the inner surface at the bottom of the crucible, working like a pivot bearing. The authors believe it would be better to work up to 1500 rpm.

The method to build the embedded wire furnace is an easy method, although it is time consuming and in case of resistance breaking, there is no possibility of replacing the electrical element. In spite of this, it is the cheapest method; furthermore the embedded wire is more protected against corrosion, which can shorten the wire life considerably

The argon system shows efficiency to processing time up to 40 minutes with aluminium alloys. Above this value oxidation reaction products can be observed. Any other solution will be more expensive.

4. CONCLUSIONS

An equipment was designed and built for metal matrix composite synthesis both semi solid and liquid state routes. The furnace, the metal surface protection and all the others systems work well, showing efficiency and repeatability. The main factors that influence the processing could be controlled. Al 7% Si alloy reinforced with alumina particles was successfully obtained without any addition of a wetting agent. Also special Al – Nb alloys were processed and good homogenized was found.

5. ACKNOWLEDGEMENTS

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