Bulletin of the *Transilvania* University of Braşov
Series I: Engineering Sciences • Vol. 7 (56) No. 1 - 2014

FUNCTIONALLY GRADED ALUMINIUM ALLOYS

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Abstract: *The paper analyses the fundamentals of processing functionally graded alloys and presents the experimental results obtained by static and centrifugal casting of Al-Si, Al-Cu and Al-Zn alloys in a a centrifugally cast tube part with a length of 80 mm and outer diameter 80.The significant difference between the structures of the outer and inner layers is highlighted also by the summary quantitative analysis of the proportion of constituents in case alloys: AlCu10 , Al55Zn43Si2.*

Key words: *gradient structure, FGM, casting, aluminium alloy.*

1. Introduction

Composite materials are known as metallic or non-metallic materials with macroscopically homogenous and microscopically non-homogenous components dispersed in the structure. This category of materials has opened up new avenues for product designers, allowing for significantly evolved technical and economic solutions for complex problems. A particular and quite specialised group within the large family of composite materials is that of functionally graded materials (FGM). Since their emergence in the 1980s [4], these materials have revolutionised materials science and its related fields.

Such materials can also be found in nature, like teeth that have a very hard exterior enamel layer for wear strength and a softer interior ensuring resistance to mechanical shocks, or bamboo with a hard exterior and very soft and light elastic interior, both ensuring a tubular structure very resistant to dynamic strain. Due to the combination of very different properties bamboo is also known as „the iron tree" that has served well even as construction material for bridges of 50 m length [11].

Also in the case of metallic functionally graded materials (FGM) the microscopic chemical composition changes continuously across its section, thus determining very different functional properties at the extremities of the section of any one component [3]. It needs be pointed out that the properties of FGM are the synergetic sum of the individual properties of their component elements.

2. FGM Processing Techniques

Further on two categories of FGM will be discussed, namely materials with continuous modification of their structure and properties on one hand Figure 1, and materials the characteristics of which vary in steps Figure 2.

The multitude of processing technologies of functionally graded materials with at least one metal component can be broken

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down into two main groups: physical and metallurgical methods. Physical methods include the following technological variants:

- in solid state;
- by powder metallurgy, a procedure consisting in assembling “slices” with different characteristics by sintering;
- by vapour deposition on a support.

In both variants FGM are obtained with characteristics that change in steps.

- in melted state the most researched methods are gravitational and centrifugal.

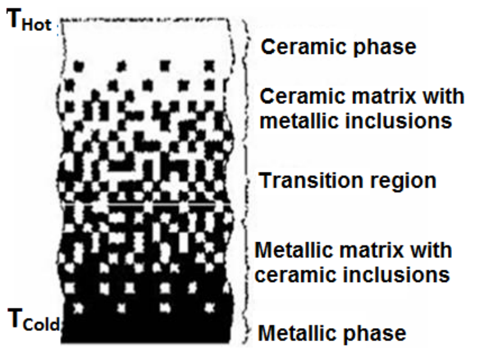


Fig. 1. *Graphic illustration of a metallic - ceramic FGM, with continuous modification of the structure* [1]

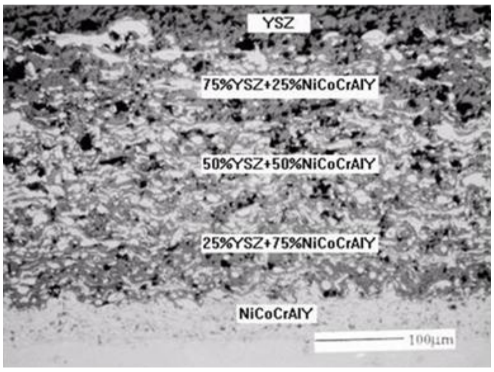


Fig. 2. *SEM structure for a metallic-ceramic FGM,with stepwise modification of the structure* [10]

Figure 3 presents the principle of gravity casting (decanting) of FGM parts, a technology known as CDC (cast-decant-cast) [5]. The process is based on the principle of low pressure casting, by depressurisation of the mould. The manufacturing cycle of the FGM part includes three stages Figure 3:

a) filling the mould with alloy A, from the left hand side compartment of the crucible and waiting for it to partially solidify;

b) by opening of the valve the not solidified melt returns to the crucible;

c) by opening of the valve of the right hand side compartment, alloy B fills the remaining empty space in the mould.

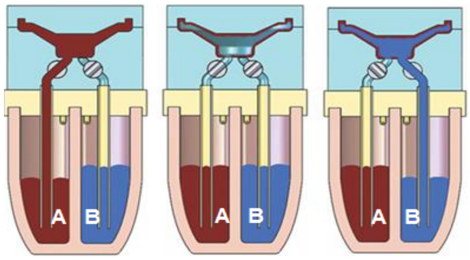


Fig. 3. *CDC casting in depressurized moulds* [5]

In the contact area of alloys A and B, because of the partial remelting of alloy A upon coming into contact with liquid alloy B, a gradient structure is generated in that the constituents of alloy B are reduced from an 100% share to 0%, being replaced by the constituents of alloy B (Figure 4).

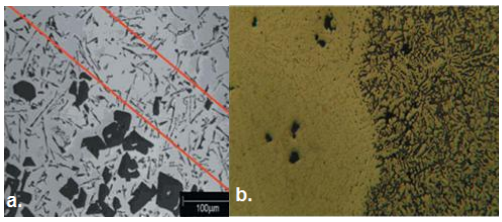


Fig. 4. *Microstructure of the transition area in a part obtained by CDC technology for the couple of alloys:* a) *Al390-A356, of 150 μm thickness;* b) *AlSi7-ZAl27* [5]

The thickness of this transition area can be adjusted by adequate selection of the working parameters: the melting temperatures of the 2 alloys; the overheating temperature of alloy B; the duration of maintaining alloy A in the mould before injecting alloy B; the cooling rate applied to the part; directing of the metallographic constituents for the two alloys etc. It is this technology that is used for manufacturing gradient structure brake disks (Figure 5) [5].

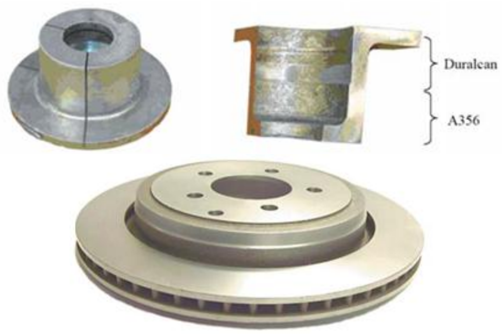


Fig. 5. *Structure gradient brake disks obtained by CDC technology* [5]

The most researched technological variant for obtaining FGM parts is centrifugal casting. Centrifugal casting generates forces 100 times greater than natural decanting of solid particles in a liquid environment (melt). By the generation of solid particles in the metal melt, this processing technology of structure gradient alloys is implemented in two variants with significantly different effects on the properties of the cast parts.

In the first variant the solid particles are present in the liquid alloy to be cast consequently to their being introduced into the melt in powder form (TiO_2, SiC, Al_2O_3, ZrO_2 etc.) or else, when a partially solidified alloy is cast, in that the solid particles are intermetallic compounds formed within the crystallisation interval.

In the second variant a homogenous melt is cast and solid particles are generated after casting, during centrifugation, a method known as in situ. Figure 6 presents the principles of these two variants.

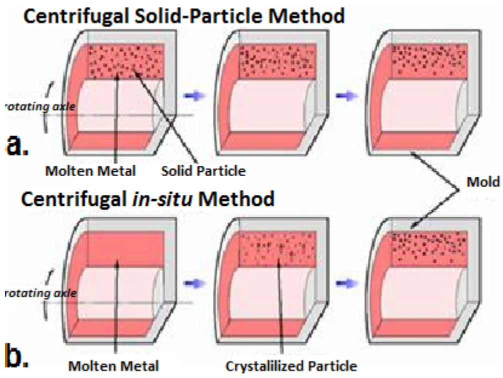


Fig. 6. *Diagram of the manufacturing technology of FGM revolution parts by centrifugal casting in two variants: a) "with solid particles"; b) "in situ"* [6]

Figure 7 presents the Al-Zr diagram in order to illustrate the differences of principle between the processing technologies of FGM materials in the two discussed variants: "with solid particles" and "in situ" [2].

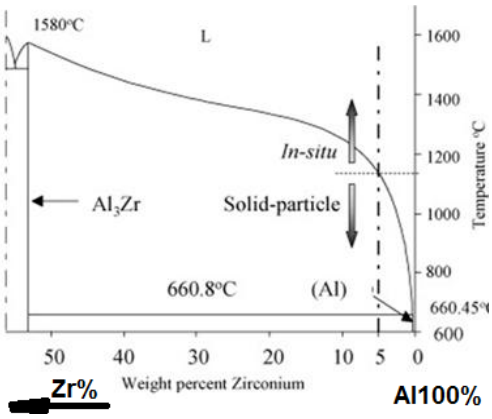


Fig. 7. *Al-Zr equilibrium phase diagram* [2]

If the alloy of the composition indicated in the equilibrium phase diagram is cast at a temperature below the liquidus one, the melt will contain Al_3Zr crystals; hence the FGM will be obtained in the variant "with solid particles". The centrifugal force will act instantaneously upon the intermetallic separations in suspension in the liquid alloy used for casting. The pre-formed crystals will move massively towards the exterior of the revolution part, generating a layer very rich in intermetallic compounds, the sizes of the intermetallic inclusions varying in a very large range.

If the same chemical composition is cast at a temperature above the liquidus line, the crystals of the intermetallic compound Al_3Zr are generated after introducing the melt into the mould; hence the FGM will be obtained in the "*in situ*" variant.

In this variant of processing the solid Al_3Zr particles are formed (germinate and grow) during the centrifugation process. Thus the displacement of these crystals towards the exterior of the part will be less intense at the beginning of centrifugation, mostly because of their sizes. The motion of solid particles in a viscous liquid environment commences only when their size exceeds a certain critical dimension (Figure 8).

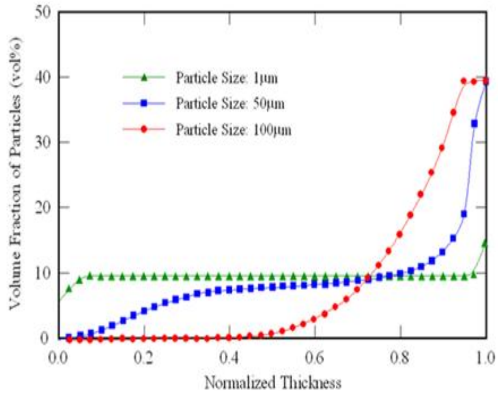


Fig. 8. *Influence of the size of the TiO_2 particles on their distribution under the effect of the centrifugal force in the casting process of aluminium alloys* [7]

In this case in the structure of the cast part the variation gradient of the intermetallic separations concentration from the interior towards the exterior is significantly more uniform than in the processing variant "with solid particles" (Figure 9).

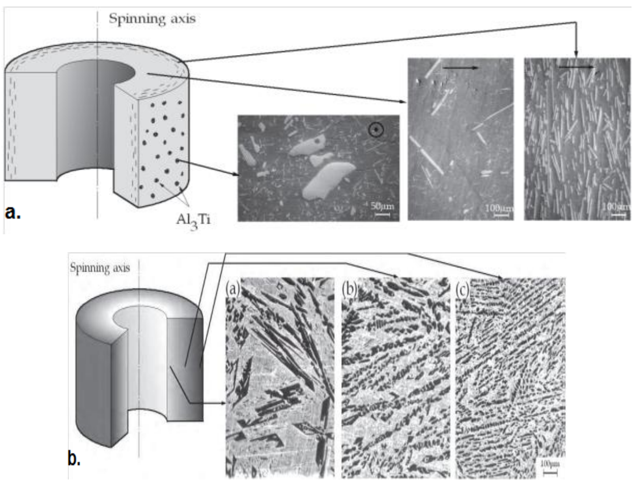


Fig. 9. *Al-Al_3Ti FGM structures obtained by centrifugation with AlTi5 alloy: a) "with solid particles"; b) "in situ"* [8]

3. Analysis of the Phenomena Contributing to Obtain FGM Parts

Based on the above discussed aspects it follows that an important parameter in processing FGM alloys by centrifugal casting is the decanting time (τ) of the solid particles in the melt. This parameter is computed by Stokes' modified equation:

$$\tau = \frac{9 \cdot \eta \cdot H}{2 \cdot r^2 \cdot (\rho_S - \rho_L) \cdot a}, \quad (1)$$

where: H is the wall thickness of the cast cylinder, [m]; ρ_S, ρ_L - density of the solid and the liquid phases [kg/m^3]; η - coefficient of dynamic viscosity [N·s/m^2]; r - solid phase radius [m]; a - centrifugal acceleration [m/s^2].

The centrifugal acceleration is computed by Equation (2):

$$a = 4\pi^2 \cdot n^2 \cdot R_m, \quad (2)$$

where: n is the speed of rotation [rps]; R_m - medium radius of the cast cylinder, [m].

Processing FGM alloys by centrifugal casting aims at decreasing the duration of decanting due to the intervention of the centrifugal force (F_c), which is significantly greater than the force determined by gravitational acceleration (F_g). The ratio (G) of the two forces is computed by Equation (3):

$$G = \frac{F_c}{F_g} = \frac{m \cdot a}{m \cdot g} = \frac{4 \cdot \pi \cdot n^2 \cdot R_m}{9.81}. \quad (3)$$

It can be noticed that for a part of 10 cm average diameter, modification of the rotational speed in the interval of 750÷3000 rpm, causes a centrifugal force 30÷500 times greater than gravity.

Another parameter that determines the heat conditions at centrifugation is the solidification interval for the processed composition. The working temperature has to be adjusted such as to fall within this interval for well determined durations, such as to generate a pre-defined proportion of intermetallic compounds (in case of the "*in situ*" variant), as well as to adjust the duration of action of the centrifugal force, in view of controlled decanting of the solid particles. The solidification intervals of the studied aluminium alloys can be compared by means of the overlapped diagrams of equilibrium (Figure 10).

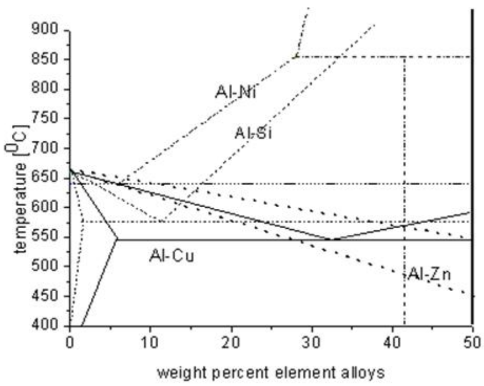


Fig. 10. *Comparison of the solidification intervals for the alloys of the systems*: *Al-Cu, Al-Si, Al-Ni, Al-Zn*

In the processing of FGM materials by centrifugal casting a great diversity of separated types of phases can be observed: in hypereutectic Al-Ni alloys the intermetallic phase Al_3Ni; in hypereutectic Al-Si alloys primary silicon; in hypoeutectic Al-Cu alloys the intermetallic compound Al_2Cu embedded in the eutectic, and in Al-Zn alloys the solid solution rich in zinc, which consequently to the phase transformation will have a heterogeneous eutectoid type structure in solid phase.

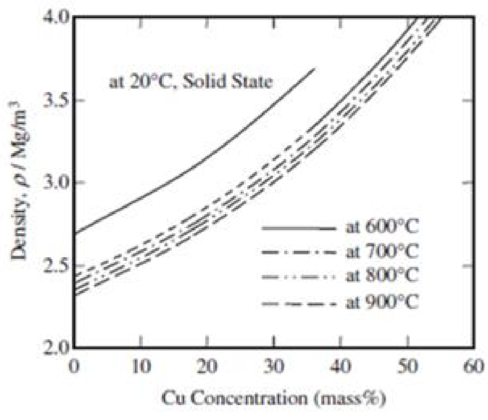


Fig. 11. *Density of Al-Cu alloys in liquid state at different temperatures and in solid state at a temperature of 20 °C* [9]

The complexity of the physical phenomena and of the phase transformations during centrifugation of liquid alloys in order to obtain FGM parts are revealed by the analysis conducted on the Al-3%Cu alloy [9]. In relation to the separation of the solid and liquid phases the variation of their density needs to be considered, depending on temperature - the diagram of Figure 11 and Equation (4) - as well as on the composition that is modified along the liquidus and solidus lines, according to Equations (5) and (6):

$$\rho_T = \frac{\rho_0}{(1+\alpha \cdot \Delta T)^3}, \quad (4)$$

$$C_L = C_0(1 - f_S)^{k-1}, \quad (5)$$

$$\overline{C_S} = \frac{C_0}{V_S}\{1-(1-V_S)^k\}. \quad (6)$$

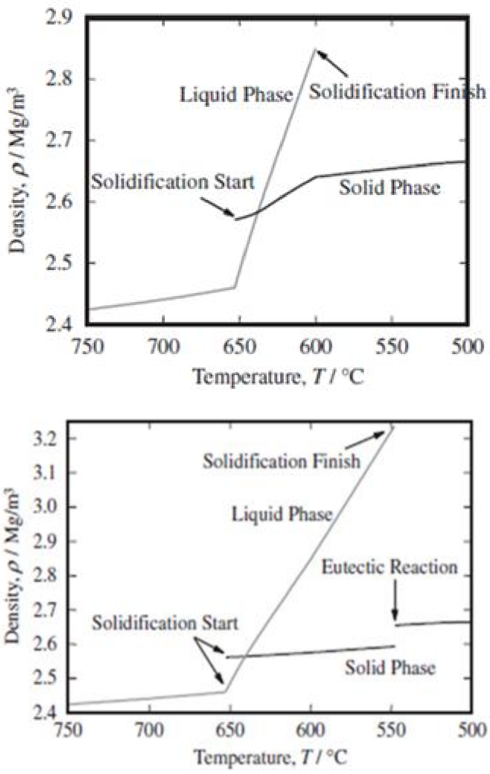


Fig. 12. *Variation of the density of the liquid and the solid phases in the solidification of an Al-3%Cu alloy: a) at equilibrium, b) at non-equilibrium* [9]

The diagrams shown in Figure 12 illustrate the results of the computations for the case of solidification at equilibrium and at non-equilibrium, with no diffusion in solid state, with the point of maximum solubility of copper in aluminium at eutectic temperature being displaced to the left, at approximately 1.5% Cu.

4. Experimental Determinations, Results

The experimental determinations were conducted along two directions. At first observations focused on the intensity of the interactions between two layers of melts with different compositions, determined by decantation and diffusion. Prismatic samples of 100 x 20 x 50 mm were cast in refractory moulds, such as to increase the duration of solidification. The liquid alloy was cast into the mould by means of a feeder positioned at the centre of the long side, at half height of the sample.

First the eutectoid Zn-Al alloy was cast, followed by the eutectic AlSi12 alloy. Vertical test pieces for microstructural analyses were cut from the obtained prism (Figure 13).

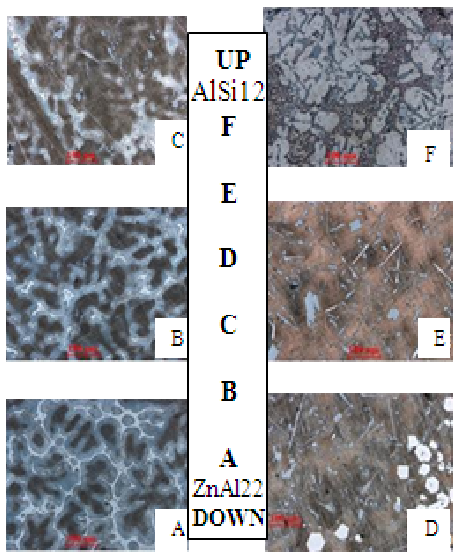


Fig. 13. *Evolution of the structure the two layers of alloys, overlapping in molten state*

It needs pointing out that by casting alloy ZnAl22 over the AlSi12, the two compositions were completely mixed.

Experimental determinations for obtaining FGM alloys by centrifugal casting were conducted by means of the installation shown in Figure 14a. The chill allows the casting of cylindrical tube-shaped parts of 80 mm length and 80 mm exterior diameter. The thickness of the wall is adjusted by dosing the liquid alloy, and can reach a maximum of 15 mm.

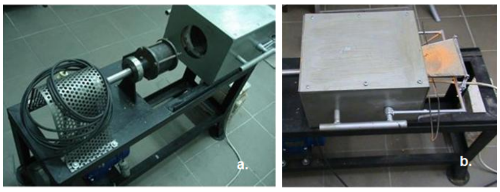


Fig. 14. *Experimental installation for obtaining FGM parts by centrifugal casting: a) general view; b) chill pre-heating phase*

An electric tubular kiln was used for preheating of the chill. The casting chute is shown in Figure 14b illustrating the technological phase of chill pre-heating. The rotation speed of the chill can be adjusted in steps: 750, 1500 and 3000 rpm.

Figure 15 presents the cast part and the obtaining of samples for structural analyses.

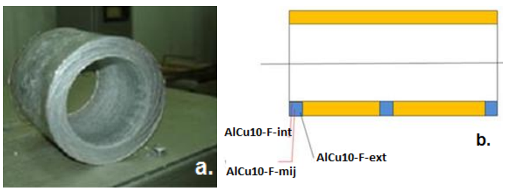
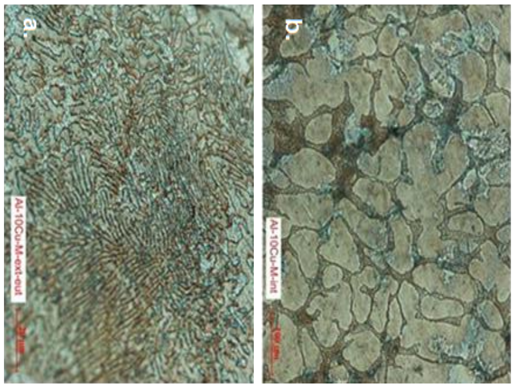


Fig. 15. *Cast part (a) and obtaining of samples (b)*

Alloy AlCu10 was processed under the following conditions: melting temperature ≈750 ^{0}C; chill temperature ≈450 ^{0}C; rotation speed ≈1500 rot/min; dimensions of the cast part: L = 80 mm, D_{ext} = 80 mm and D_{int} = 55 mm. The effect of the centrifugal force on the generation of gradient structures is highlighted in the micrographs shown in Figure 16.



a) b)

Fig. 16. *Microstructure of centrifugally cast AlCu10 alloy: a) in the outer layer; b) in the inner layer*

The structure of the outer layer is eutectic (Figure 16a) what indicates that the outer layer was enriched in copper during centrifugation of the melt. The significant structural difference between the outer and inner layers is significant also if we consider the generation of quasi-eutectic caused by the high cooling rate.

The significant difference between the structures of the two layers is highlighted also by the summary quantitative analysis of the proportion of constituents. Figure 16 shows that the structure is 100% eutectic. By applying the rule of inverse segments for AlCu10 the proportion of eutectic at eutectic temperature is 30%, and 16% at environment.

The processing of Al55Zn43Si2 alloy was aimed at obtaining an FGM with an interior layer based on solid solution and high breaking strength, and an exterior layer consisting of a mechanical mix (eutectoid) with very good tribological properties. Figure 17 shows the microstructures obtained for the outer and inner layers. By enriching the outer layer of zinc increases the proportion of eutectoid.

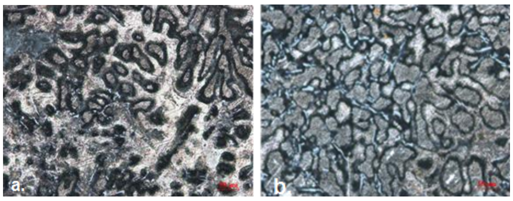


Fig. 17. *Microstructure of centrifugally cast Al55Zn43Si2 alloy: a) in the outer layer; b) in the inner layer*

5. Conclusions

The theoretical computations as well as the experimental results confirm the possibility of obtaining gradient structure revolution parts by centrifugal casting, in the case of both intermetallic compound generation (Al-Cu system) and solid solution crystallisation (Al-Zn system).

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