PRODUCTION OF FG-Al-MMC BY SEMI-SOLID STIRRING AND SEQUENTIAL SQUEEZE CASTING METHODS

Nilhan URKMEZ TASKIN, Serhan KARAMAN GENÇ

Trakya University, Department of Mechanical Engineering, Edirne, Republic of Turkey,
nilhanu@trakya.edu.tr, serhankaraman@trakya.edu.tr

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Abstract

In this study, manufacturing of functionally graded ceramic reinforced aluminum matrix composite materials (FG-Al-MMC) by using direct semi-solid stirring and sequential squeeze casting method has been investigated. As a matrix material Al-7075 and as a reinforcement material SiC ceramic particles have been chosen for composite materials of FGM layers. Aluminum composite mixtures with different reinforcement ratios have been prepared by mechanically mixing SiCp reinforcements into semi-solid aluminum alloy and, FG-Al-MMC's have been produced by pouring the composite mixtures into a mold on top of each other in liquid form where each layer has been solidified under pressure. The partial melting of the previous layer due to the added liquid layer and the applied pressure cause bonding between layers with a transition region. This process has been repeated sequentially until a structure with the desired thickness and features were obtained. The structure formed between the layers with this manufacturing method was investigated by taking samples from different layers and transition regions of FG-Al-MMC. Density analyses, spectrometric analyses and optical analyses were carried out to determine the properties of FG-Al-MMC material. As a result, it is observed that successful production of functionally graded aluminum composite materials by the direct semi-solid stirring and sequential squeeze casting methods is possible.

Keywords: Functional graded materials, Al 7075, FG-Al-MMC, semi-solid stirring, squeeze casting

1. INTRODUCTION

The ever-changing technological innovations have made our technical development, progress in understanding and processing the material even more important over time. Today, scientists and engineers recognize the importance of using innovative materials for economic and environmental reasons [1]. Functionally graded materials are advanced engineering materials designed for a particular performance or function where a rating in structure and / or composition has self-tailored properties [2]. The term of functional graded material (FGM) is defined as a new group of composite materials with graded structural functions across the section. With the adoption of it as one of the 10 advanced technologies in 1992, FGM technology has reached the global level and gained an important quality [3]. Today, functional graded materials are used in many areas, for example; rocket bodies, turbine blades, military applications as a protective armor layer [4-8], fusion energy systems, tool materials as hard metal, optoelectronic tools [9], biomedical applications as implants [10] and many others. FGMs in machine elements are developed to reduce their weight, increase their wear resistance and strength and stop the spread of surface damage [11,12].

Ceramic reinforced light metals (Metal Matrix Composites) are used in the defense industry to reduce of military weapons and vehicles weight [8,13]. MMC materials also provide ballistic protection. Light metals reinforced with high-strength ceramic particles consolidate under dynamic loads and exhibit excellent strength and hardness properties. The biggest advantage of FG-MMC composites is that it contains graded functions of toughness and other material properties throughout the structure [3]. MMC materials are produced in functional grade structure in order to protect from shock waves and shock impact effects especially in military vehicles, armor applications. Numerous studies have been conducted to develop these materials for the use of metal matrix composites [8,14-17]. Some of the traditional and non-traditional methods are adapted and used for the production of FG-MMC materials. Production methods can be generally classified as liquid and solid phase methods. It is the most applied method among productions using liquid phase is centrifugal casting [18]. A liquid mixture is created with the ceramic particles mixed into the molten metal in the desired proportions, and then FGM is produced in the form of a hollow cylinder by applying the centrifugal casting method. Due to the differences in the density of the materials, a structure with a dense ceramic layer on the outer surfaces of the material section and an increasing amount of metal material towards the inner parts is obtained. FG-MMC production studies are carried out by gradually coating composite mixtures prepared in certain proportions by gradually coating the composite mixtures prepared in certain proportions by keeping the graded structure in the molten metal or by adapting the production methods and plasma spray methods of ceramic particles, which are deposited with auxiliary way such as vibration [17]. In addition to the known solidification problems encountered in monolithic materials in these materials obtained by using liquid phase, problems such as not being able to provide homogenous mixture, lumping, and pushing ceramic powders out of the material due to the ceramic material contained in the material are also encountered. The most preferred solid phase production method in FG-MMC production is powder metallurgy methods and there are many studies on this subject [19-21]. Functional grade structure is better controlled with this method [6]. However, the size of FGM materials, produced by the powder metallurgy method, is limited. In addition, the method is costly and includes highly sensitive and long processing procedures.

In this study, most of the problems encountered in liquid and solid phase production methods are overcome by using semi-solid mixing method. The semi-solid mixing method is a method that has more advantages than other methods. The reinforcing material can be mixed homogeneously into the matrix material, problems such as clumping the reinforcement outside the mixture and uncontrolled segregation are not occur. In addition, the reinforcement and matrix contact briefly at relatively lower temperatures, undesirable interface reactions are reduced [22]. The squeeze casting process applied in the second stage provides better internal structure properties, reduces porosity and increasesstrength properties. Al7075 as a matrix material and SiC as a reinforcement selected for the production of FG-Al-MMC. The formed FG-Al-MMC material properties are examined using density analysis, spectrometer analysis and optical microscope analysis.

2. EXPERIMENTAL PROCESS

2.1. Material

AA7075 was chosen from 7XXX series alloys as the matrix material for the production of SiC reinforced composite materials. In this alloy; copper is the main alloying element, magnesium, chrome and zirconium are additional alloying elements and its among the aluminum alloys with the highest mechanical strength. The properties of AA7075 Aluminum alloys and SiC$_p$ reinforces are given in **Table 1, Table 2** and **Table 3**.

Table 1 Physical and mechanical properties of AA7075

Density	2.81 g/cm^3	Coefficient of linear expansion (293 K - 373 K)	23x10^{-6} K^{-1}
Elasticity module	71-72 GPa	Thermal conductivity (373 K – 673 K)	130 W/m·K
Specific heat (273 K - 373 K)	0.97 J/g·K	Resistance (293 K)	0.049x10^{-6} Ω·m

Table 2 Chemical compounds of AA7075 (wt%)

Element	**Si**	**Fe**	**Cu**	**Mg**	**Mn**	**Cr**	**Zn**	**Ti**
Minimum	-	-	1.2	2.1	-	0.18	5.1	-
Maximum	0.4	0.5	2	2.9	0.3	0.28	6.1	0.2

Table 3 Physical and mechanical properties of SiC_p

Particle	**Size** (µm)	**Density** (g/cm^3)	**Tensile strength** (GPa)	**E- Module** (GPa)
SiC	15 - 340	3.2	3.0	480

2.2. Methods

In this study, heat treatment was applied to increase the wettability of the reinforcing powders. The heat treatment of SiC particles used as reinforcing materials; After being kept in the oven at 1100 ˚C for 5 hours, they were allowed to cool at room temperature and oxidized. Aluminum composite slurries were prepared using direct semisolid stirring method. This method is described in a patent held by Urkmez Taskin and Taskin [23].

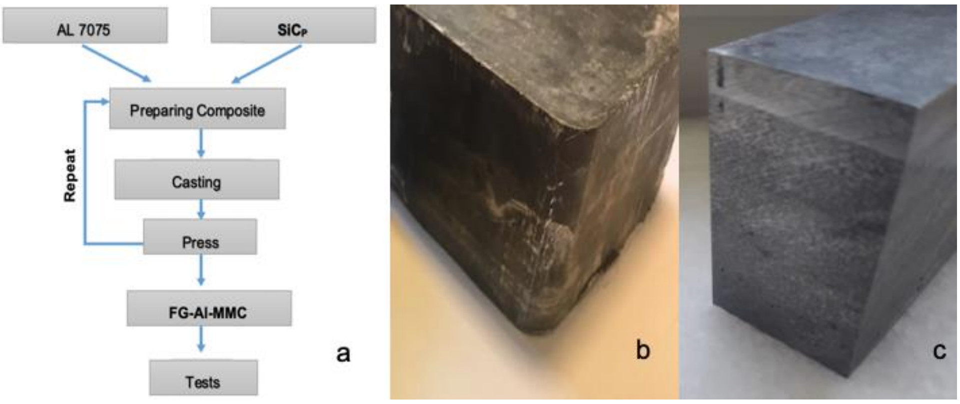

Figure 1 a) Schematic diagram of process b) produced FG-Al-MMC material c) view of layers in sample

Sequential squeeze casting operations were carried out by following the process steps described schematically in **Figure 1a**. Firstly, Al 7075 matrix material prepared in a certain volume by dividing into small pieces was poured into the mold without reinforcement and solidified under pressure. Thus, the formation of the first layer was achieved. By ensuring that the matrix material that will form the second layer remains at a semi-solid temperature, 5% by weight ceramic particle reinforcements were mixed into the matrix by means of a mechanical mixer. The composite mixture was poured on the first layer in the mold placed under the press table and solidified under pressure. In this process, while pouring the composite mixture in liquid form onto solidified aluminum, it is aimed to form partial melting by contact of the solidified aluminum material with the liquid material. After pouring the liquid material into the mold, pressure was applied and the composite mixture was solidified on the first layer. After the 5%, 10%, 15% and 20% SiCp reinforced composite mixtures were sequentially poured and solidified under pressure, the process was terminated and FG-Al-MMC material was produced (**Figures 1b** and **1c**).

2.3. Optical microscope analysis

The optical examination samples respectively were passed through 280,400, 600, 800, 1000, 1200, 2000 and 4000 mesh SiC sandpapers and then polished with 6 µm, 3 µm, 1 µm diamond paste using suitable felts. Finally, it is prepared for microstructure studies by polishing with colloidal silica. Optical images were taken respectively from 5%, 10%, 15%, 20% SiCp-reinforced layers and their transition zones.

2.4. Density analysis

Density measurements were made by cutting pieces from different regions on the layers. Densities of the samples obtained from the produced materials were calculated using metler toledo 1/1000 gr precision scale, which can measure according to Archimedes principle.

2.5. Spectrometer analysis

In order to determine the chemical composition of the produced FG-Al-MMC material, spectrometry analyses were performed on each layer of the sample. Spectrometry analyses were carried out with the X-Ray fluorescent spectrometer instrument in the TUBITAK MAM X-Rays laboratory.

3. RESULTS

3.1. Density analysis results

Density measurements of samples taken from the FG-Al-MMC sample layers and transition zones were investigated. The results are given in **Table 4**. In **Table 4** both measured density values and theoretical densities are given, and porosity amounts showing the difference between the two are also calculated. The values obtained indicate that the density increases as the reinforcement rates increase in the layers. This is an expected result. The density in the transition zones higher than the values measured in the upper and lower layers; Partial melting occurs in this region during production, indicating that the two layers mix well locally. The fact that it is low indicates that pores have formed in this region or the reinforcements have left this area during melting. In microscopic examinations, no separation was observed in this transition zone and it indicates that the pore formation is intense. When passing from 15% SiCp reinforced layer to 20% SiCp reinforced layer, the high pore quantity in the transition zone that is formed confirms the density measurement results as shown in **Table 4**.

Table 4 Density measurement results

SiC$_p$ (wt%)	**Layers**	**Measured density** (g/cm^3)	**Theoretical density** (g/cm^3)	**Porosity (%)**
0%	1. Layer	2.787	2.81	1.079
0%-5%	Transition zone of 1-2 layers	2.790	---	---
5%	2. Layer	2.799	2.83	1.433
5%-10%	Transition zone of 2-3 layers	2.805	---	
10%	3. Layer	2.812	2.85	1.423
10%-15%	Transition zone of 3-4 layers	2.845	---	---
15%	4. Layer	2.840	2.87	1.105
15%-20%	Transition zone of 4-5 layers	2.831	---	---
20%	5. Layer	2.848	2.89	1.581

Ram Prabhu, produced functional graded composite materials made of 6% and 9% SiCp reinforced 7075 Aluminum alloy using the centrifugal casting method and examined their characteristics. Since the density of the SiC particles (3.21 g/cm^3) is greater than the matrix material (2.81 g/cm^3), it confirmed the determination that the density of the material will increase as the reinforcement rate increases [24]. The density results seen in **Table 4**, increase with the increasing reinforcement rate in accordance with the literature. In the study, the rate of porosity was found above 3% in 9% SiCp reinforced FGM. As the reason that the measured density values are lower than the theoretical density values and the porosity is high. In the liquid matrix material, it is stated that the aggregation and gas compaction increases with the increase of reinforcement particles and therefore the porosity values increase in these regions. In this study, in theFG-Al-MMC material we obtained by applying semi-solid mixing and sequential squeeze casting, the rate of porosity in the 20% SiCp reinforced region was measured around 1.5% and it was observed that the method could form less porous structure [19,20]. In addition, in FG-Al-MMC material, it has been observed that porosity increases with increasing reinforcement rate, but both the rate in this increase and the functional graded transition in terms of microstructure are better than in centrifugal casting [24,21].

3.2. Spectrometer analysis results

In spectrometer analysis results, layers with different reinforcement ratios and SiCp ratios in these layers are clearly seen in **Table 5**. While the ratios of the other elements do not change significantly, the change in the Si element in the composition of the SiCp used as a reinforcing material appears to increase in proportion to the reinforcement rate of this element.

Table 5 Spectrometer analysis results (wt%)

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
1. Layer	0.0610	0.0254	0.516	0.0287	1.57	0.257	4.00	93.4
2. Layer	2.42	0.639	1.21	0.0817	2.69	0.159	4.57	88.1
3. Layer	6.42	0.831	1.45	0.167	2.80	0.241	4.79	83.1
4. Layer	14.32	0.798	1.69	0.0441	2.38	0.200	5.50	74.8
5. Layer	20.84	1.03	1.60	0.0253	2.01	0.190	4.94	68.7

3.3. Optical Microscope Analysis Results

Optical microscope images, respectively was taken from 0%, 5%, 10%, 15%, 20% SiCp reinforced layers and their combination zones. The images shown with a, c, d and g in **Figure 2**. belong to the intermediate regions (transition zone) and b, d, f, h are main regions (layers). Respectively a = 0%-5% SiCp transition zone, b = 5% SiCp layer, c = 5%-10% SiCp transition zone, d = 10% SiCp layer, e = 10%-15% SiCp transition zone, f = 15% SiCp layer, g = 15%-20% SiCp transition zone, h = 20% SiCp layer.

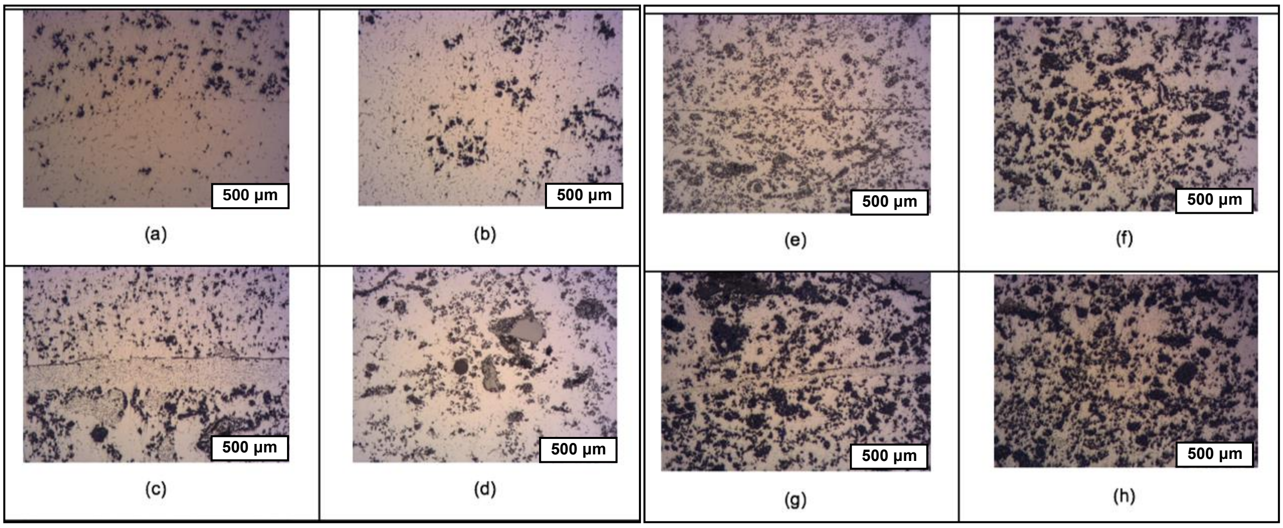

Figure 2 Optical microscope images

In **Figure 2a**, it is observed that in the transition zone of the layers with 0% and 5% SiCp reinforcement, the line is almost lost, there are no large pores and oxide layers, and good bonding is achieved. In **Figure 2c**, there is a partial diffusion region where there is no line in the junction area, and adhesion is observed where there is a line. Generally, it is observed that there is some clumping in the main regions.

2. CONCLUSION

- Semi-solid stirring and the sequential squeeze casting technique were applied together and the production of functional graded aluminum composite materials has been successfully realized by pouring the composite mixture with five different reinforcement ratios and solidifying it under pressure.
- By mixing the SiCp reinforcements into the semi-solid aluminum alloys mechanically, aluminum composite material mixtures with different reinforcement ratios can be obtained homogeneously.
- FG-Al-MMC material was produced by creating transition zones between the layers. FGMs with different functions can be produced by this method by changing the number and thickness of the layers.
- In sequential squeeze casting, the process should be carried out in an inert gas environment in order to prevent or minimize the formation of oxide layers that will prevent liquid diffusion between the two layers.

REFERENCES

[1] JOSHI, R.K. Graphene oxide: the new membrane material. *Appl. Mater Today*. 2015, vol. 1, pp. 1–12.

[2] KAWASAKI, A., WATANABE, R. Concept and P/M fabrication of functionally gradient materials. *Ceram. Int*. 1997, vol. 23, no. 1, pp. 73–83.

[3] KNOPPERS, G.E., GUNNINK, J.W., VAN DEN HOUT, J., VAN VLIET, W.P. The reality of functionally graded material products. In *7th CIRP International Conference on Intelligent Computation in Manufacturing*. 2010.

[4] LENGAUER, W., DREYER, K. Functionally graded hard metals. *J. of Alloys and Comp*. 2002, vol. 338, pp. 194–212.

[5] DOBRZANSKI, L.A., KLOC-PTASZNA, A., MATULA, G. Gradient Tool WC/HS6-5-2 materials produced using the powder metallurgy method. *Archives of Materials Science and Engineering*. 2008, vol. 31, no. 1, pp. 9-12.

[6] PRCHLIK, L., SAMPATH, S., GUTLEBER, J., BANCKE, G., RUFF, A.W. Friction and wear properties of WC-Co and Mo-Mo2C based functionally graded materials. *Wear*. 2001, vol. 249, pp. 1103–1115.

[7] GOMES, J.R., RIBERIO, A.R., VIEIRA, A.C., MIRANDA, A.S., ROCHA, L.A. Wear mechanisms in FG aluminum matrix composites: Effect of the lubrication by an aqueous solution. *Mat. Sci. and Eng*. 2005, pp. 33-38.

[8] KLEPONIS, D.S., MIHALCIN, A.L., FILBEY, G.L., WEAPONS, JR. Material design paradigms for optimal functional gradient armors. In *14th Engineering Mechanics Conference*. University of Texas at Austin. 2000.

[9] WOSKO, M., PASZKIEWICZ, B., PIASECKI, T., SZYSZKA, A., PASZKIEWICZ, R., TLACZALA, M. Applications of functionally graded materials in optoelectronic devices. *Optica Applicate*. 2005, vol. 35, no. 3, pp. 25-35.

[10] POMPE, W., WORCH, H., EPPLE, M., FRIESS, W., GELINSKY, M., GREIL, P. Functionally graded materials for biomedical applications. *Materials Science and Engineering*. 2003, vol. A362, pp. 40–60.

[11] SURESH, S., MORTENSEN, A. *Fundamentals of FGMs: Processing and thermomechanical behavior of graded metals and metal-ceramic composites*. London. IOM Communications Ltd.198.

[12] KOIZUMI, M., FGM activities in Japan. *Composites B: Eng*. 1997, vol. 28, no. 1–2, pp. 1–4.

[13] KILIÇ, C. Sıkıştırma döküm yöntemiyle üretilmiş ve soğuk haddelenmiş AlMg3/SiCp kompozitinin aşınma özelliklerinin incelenmesi. 2008.

[14] CHIN, E.S.C. Army focused research team on functionally graded armor composites. Materials Science and Engineering. 1999, vol. A259, pp. 155–161.

[15] GONCALVES, D.P., DE MELO, F.C.L., KLEIN, A.N., AL-QURESHI, H.A. Analysis and investigation of ballistic impact on ceramic/metal composite armour. *Int. J. of Machine Tools & Manufacture*. 2004, vol. 44, pp. 307–316.

[16] GOOCH, W.A., BURKINS, M.S. *Development and ballistic testing of a functionally gradient ceramic/ metal applique. Cost effective application of titanium alloys in military platforms*. 2001.

[17] ZHONGTAO, Z., TINGJU, L., HONGYUN, Y., JIAN, Z., JIE, L. Preparation of Al/Si functionally graded materials using ultrasonic separation method. *China Foundry*. 2008, vol. 5, no. 3, pp.194-198.

[18] WATANABE, Y., KAWAMOTO, A., MATSUDA, K. Particle size distributions in functionally graded materials fabricated by the centrifugal solid-particle method. Composites Science and Technology. 2002, pp. 881–888.

[19] LI, T., LI, Q., FULH, J.Y.H. Two-material powder injection molding of functionally graded WC–Co components. Int. Journal of Refractory Metals & Hard Materials. 2009, vol. 27, pp. 95–100.

[20] KIEBACK, B., NEUBRAND, A., RIEDEL, H. Processing techniques for functionally graded materials. Materials Science and Engineering. 2003, vol. A362, pp. 81–105.

[21] LI, S.B., XIE, J.X. Processing and microstructure of functionally graded W/Cu composites fabricated by multi-billet extrusion using mechanically alloyed powders. Comp. Sci. and Tech.2006, pp. 2329- 2336.

[22] ÜRKMEZ TAŞKIN N., TAŞKIN V., YURCI M.E. Alüminyum Esaslı Kompozit Malzeme Üretimi İçin Doğrudan Yarı Katı Karıştırma Yöntemi. 13. Uluslar Arası Malzeme Sempozyumu Pamukkale Üniversitesi. Turkey. 2010.

[23] TASKIN, N.U., TASKIN, V. Continuous composite metal foam production and method and device for stirring particle reinforced composite metal. European Patent No. 3083105. European Patent Office. 2017.

[24] RAM PRABHU,T. Processing And Properties Evaluation Of Functionally Continuous Graded 7075 Al Alloy/Sic Composites. Archives of Civil Mechanical Engineering. 2017, vol. 17, pp. 20-31.