International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Processing and Properties of Metal Matrix Composites

L. Siva Sankara Reddy[1], P. Thimmaiah[2], K. Narasimhulu[3]

[1,2]Department of Physics, Sri Krishnadevaraya University, Anantapur- 515003, A.P. India

[3]Department of Physics, SSA Government First Grade College (Autonomous), Ballari, Karnataka

Abstract

Growing interest in the development and emergence of metal matrix composites (MMCs) during the time period spanning the last two decades has been made possible because of its ability to offer an attractive combination of properties to include high specific strength, enhanced elevated temperature strength, structural efficiency, reliability, improved wear resistance and acceptable corrosion resistance in environments spanning a range of aggressiveness. The overall acceptable combination of mechanical properties and functional response when compared one-on-one with their conventional counterparts makes them a viable choice for selection and use in applications spanning the domains of structural engineering and functional devices. The fabrication techniques and nature of reinforcement play a critical role in the end properties of the engineered or fabricated metal matrix composites (MMCs). This review provides an adequate insight into all aspects and intricacies specific to the development, emergence and commercialization of two-phase processing of metal matrix composites (MMCs). The influence of reinforcement on microstructure development and response kinetics is briefly highlighted with specific reference to mechanical properties of the engineered composite material.

Keywords: Lightweight; Spray atomization; Rheocasting; Mechanical behavior; Automotive

I. INTRODUCTION

A composite material is a combination of two or more insoluble components having different chemical composition and often various shape [1]. The continuous phase is referred to as the matrix while the discontinuous phase is referred to as the reinforcement. These two independent components often have noticeable differences in their properties spanning mechanical, physical, electrical and even chemical. One of the components, often the matrix, will be tough and ductile while the other component, namely the reinforcing phase will be light, strong and hard and intrinsically brittle. The metal matrix is often a pure metal or its alloy counterpart and is the continuous phase while the reinforcing phase can be (i) discontinuous in the form of particulates (i.e., particles), short fibres and whisker, and (ii) continuous in the form of fibres as shown in Figure 1.

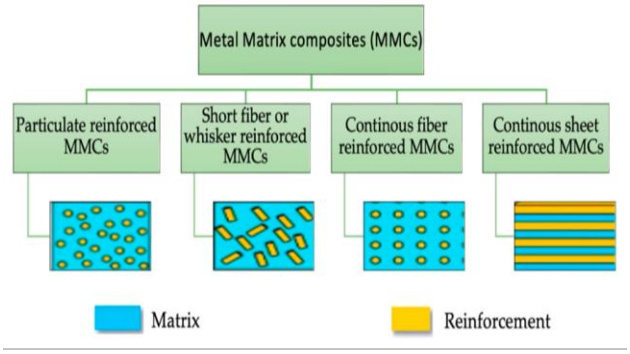

Figure 1. Classification of metal matrix composites

The primary and most desirable need if for the metal matrix composites (MMCs) to offer a healthy combination of properties to include low density, high or adequate strength both in tension and in compression, good thermal expansion characteristics, acceptable creep resistance, good resistance to friction, and overall good wear behaviour [2-4]. The challenges arising from material design, cost-effective processing, characterization and matrix-reinforcement interfacial characteristics have been systematically addressed for the family of metal matrix composites [MMCs] by several researchers in their independent studies in the time period spanning the last four decades [1980 – 2020]. Sustained research and development efforts did eventually result in the development and emergence of particulate-reinforced metal matrix composites (MMCs) as potentially viable and an economically affordable option for the purpose of selection and use in a spectrum of applications spanning the fields of military, aerospace, electronics, ground transportation, infrastructure-related industry and high-performance end products [5-7]. Noticeable advances in the domains specific to compositional design commensurate with application have been made possible through sustained research and development efforts.

The viable options for producing metal matrix composites [MMCs] were the following techniques: (a) stir casting, (b) mechanical alloying, and (c) powder metallurgy [8,9]. The reinforcing particles often tend to undergo clustering or aggregation, poor interfacial interactions between the soft and ductile metal matrix and the hard and brittle reinforcement coupled with complex manufacturing-related problems that often occur during the conventional manufacturing processes used for the synthesis of the desired metal-matrix composite [MMC]. This often results in reduced, or degraded, mechanical performance of the as-synthesized metal-matrix composite (MMC) [10,11]. In an attempt to overcome problems specific and related to processing, the technique of spray processing has often been chosen and used as a potentially viable and attractive method for the synthesis of metal matrix composites [MMCs]. The two external powder injectors placed around the melt atomizing section aids in placing the reinforcing particles well within the spray cone during processing. Both clustering and aggregation of the reinforcing particles can be successfully prevented with the help of rapid solidification of the atomized droplets [12].

To eliminate several of these problems and to concurrently increase the ability of a metal matrix composite [MMC] to be synthesized with ease a two-phase process is chosen. This includes the techniques of: (i) spray atomization and deposition processing, and (ii) rheocasting. The objective of this chapter is to examine the key factors that affect and/or exert an influence on two-phase processing, resultant microstructure of the as-synthesized composite and the conjoint influence of processing and microstructure on mechanical behaviour of both the aluminium-based composite and the magnesium-based metal matrix composite.

II. FABRICATION OF METAL MATRIX COMPOSITES

Final properties of the as-synthesized metal matrix composites [MMCs] are often decided and/or dictated by the processing technique that is chosen and used for the specific composite [13]. For a comprehensive evaluation of the MMCs, a few techniques have been researched upon and progressively developed during the past few decades very much in conformance with the prevailing trend. The processing techniques were subsequently classified based entirely on temperature of the metal matrix during processing [14]. The processing and resultant fabrication of metal-matrix composites [MMCs] at both the experimental stage and industrial or commercial stage.

Based on this two-phase processing concept, the following three techniques were found to be technically viable and economically affordable and hence the most prominent:

(a) Spray atomization and deposition
(b) Rheocasting
(c) Osprey deposition

Spray Atomization and Deposition Processing

The spray atomization and deposition processing is a semi-liquid synthesis technique that has been preferentially used for the purposes of processing discontinuously-reinforced metal-matrix composite [MMC]. In this specific technique, the metal matrix in the semi-solid state and the desired reinforcement are thoroughly mixed. This processing technique offers several unique properties that vary from solid to liquid and two-phase processing. In this technique, both mixing and consolidation are finished in a single operation, which is by far the most important and key aspect specific to this technique.

Rheocasting process

In the technique of rheocasting [15], a semi solid slurry is developed from the molten alloy through shearing action and the reinforcement particles are often trapped during the solidification process. To ensure shaping of the desired component, the resultant slurry is often transferred to a die. The key aspects specific to the technique of rheocasting are the following: (i) in-house scrap, (ii) energy saving recycling, and (iii) feed stock like special solid billet, which is often required for the technique of thixocasting. Due to a healthy combination of overall cost effectiveness coupled with high productivity for manufacturing of the semi-solid metal (SSM) [16], this processing technique has stood out to be the most prominent fabrication technique during recent years. By a careful addition of the reinforcing particles to the partially solid alloy, it is possible to prevent both the settling and agglomeration of the reinforcing particles by this technique.

The Osprey Deposition Process

In the Osprey deposition process, the reinforcing particulates are in touch with the molten alloy and the resultant mixture is carefully atomized using inert gas jets during synthesis of the metal-matrix composite [17]. In the form of reinforced metal matrix billets, the final sprayed mixture is collected on the surface. The Canadian aluminium company [ALCAN] was the first to introduce this method as an extrapolation of the Osprey process [18]. This processing technique was essentially a combination of both blending and consolidation steps specific to the powder metallurgy process. This has made possible observable strides in the synthesis, development and emergence of metal-matrix composites [MMCs].

III. PROPERTIES OF METAL MATRIX COMPOSITES

The Chaorun and co-workers [19] produced silicon carbide particulate [SiCp] reinforced aluminium alloy 7075-based composites using the technique of spray atomization and deposition processing. In an attempt to evaluate the proposed technique, the microstructure and mechanical behaviour of test specimens of the as-synthesized composite were compared one-on-one with the conventional spray formed aluminium alloy 7055. Microstructure of the as-synthesized aluminium alloy 7055 - SiCp metal-matrix composite [MMC] had near equiaxed shaped grains with an overall fine structure. The microstructure of the as-synthesized aluminium alloy 7055/SiCp composite had grains with an average size of 16µm, which was noticeably smaller than that of the spray formed aluminium alloy 7055 counter-part (about 24µm).

An observable improvement in mechanical properties of the spray formed or spray processed composite, i.e., MMC, due to the refined grain size, has been both observed and recorded in an earlier study [20]. A schematic of the spray deposition processing technique along with optical micrographs of the as-synthesized aluminium alloy based metal matrix composite are shown in Figure 2. The reinforcing silicon carbide (SiC) particulates were distributed uniformly through the metal matrix [Figure 2 (b) and Figure 2 (c)). Further, there was no evidence of an agglomeration of the reinforcing silicon carbide particulates, which could be detrimental to achieving improved properties of the composite.

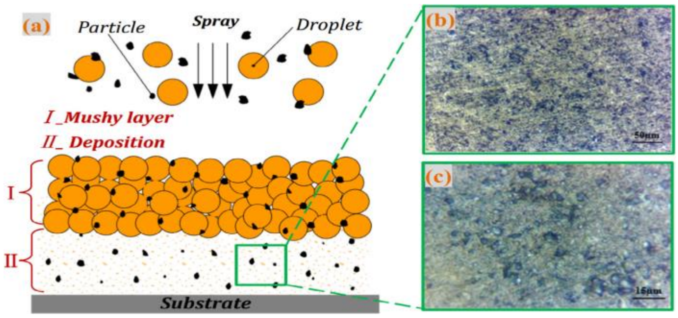

Figure 2. (a) A schematic of the spray deposition process. (b) Optical micrographs showing microstructure of the as-synthesized 7055-SiCp composite, and (c) High magnification observation of (b).

The XRD curves and the strain versus stress response in compression for the 7055-SiCp composite and the unreinforced counterpart, i.e., aluminium alloy 7055, at room temperature [27o C]. The second precipitate phase that was present in the microstructure was the η phase (MgZn2). A nominal increase of 4.64% for the compression peak strength i.e., 687.5 MPa, was observed for the 7055-SiCp composite when compared one-on-one with the spray formed aluminium alloy 7055. Further, this provides convincing evidence for two-phase atomization and deposition processing to be safely considered as one of the most prominent processing techniques proposed for the family of metal matrix composites [MMCs]

Yang and co-workers [21] did conduct an exhaustive study of the Al7055/SiCp composites using the technique of spray deposition. The volume fraction of the reinforcing silicon carbide particles

(SiCp) in the aluminium alloy metal matrix was 17%. The effect of SiCp on both microstructural development and resultant mechanical properties of the as-synthesized composite was carefully examined. In this independent study, the spray-deposited AA7055/SiCp metal matrix composite was composed of alpha-aluminium, silicon carbide particulates (SiCp), and the precipitates Al2CuMg, Al2Cu and MgZn2. Size of the liquid particles of aluminium are noticeably different, and the phenomenon of large particles consuming the small particles was common in areas containing a high volume fraction of the reinforcing SiC particles. This is essentially because of a synchronization of the nucleation kinetics caused by noticeable differences in cooling rates of the hard and brittle reinforcing SiC particles and the soft and ductile aluminium alloy metal matrix. The gradient region of silicon and carbon was gradually dissolved from surface of the reinforcing SiC particle (SiCp). This can be seen from the EDS midline scanning that is shown in Figure 3.

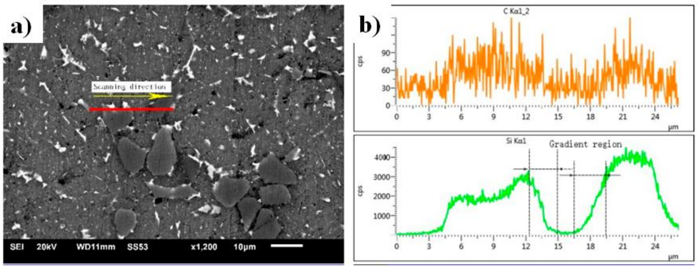

Figure 3. (a) The line scanning image, and (b) Distribution of the elements carbon (C) and silicon (S) along the scan line in (a) of spray-deposited AA7055/SiCp metal matrix composites.

Mechanical properties of the aluminium alloy metal-matrix composites in the radial direction were found to be better than those in the longitudinal direction. The tensile strength and elongation following fracture was 17.4% and 8% higher in the radial direction when compared to the longitudinal direction. Fracture morphology of the chosen aluminium alloy based metal matrix composite essentially revealed a combination of cleavage and pockets of dimples, with few features reminiscent of “locally” brittle fracture

Esmaily and co-workers [22] fabricated SiC particle-reinforced AM50 matrix composite and AZ91D matrix composite using the technique of RheoMetal process by investigating the newly developed and emerging technique of rheocasting (RC). The microstructure and hardness of the as-synthesized magnesium-based metal matrix composites [MMCs] was examined and compared one-on-one with the unreinforced counterpart

The X-ray diffraction patterns for the rheocast AZ91 MMC and rheocast AM50-based MMC are shown in Figure 4. With specific reference to α-Mg, the β-phase (Mg17Al12) had a comparatively low intensity peak for the two chosen composites. These peaks could be easily detected for the AZ91D alloy while it was difficult to detect for the AM50 alloy. The β-SiC had strong peaks for the two chosen magnesium alloys. When compared to magnesium alloy AZ91D, the peaks related to the intermetallic particles MgO and Mg2Si had better, clear and sharp intensity. For both the magnesium alloy-based metal matrix composites [MMCs], a few of the peaks had properties that was similar to magnesium Hydride (MgH2).

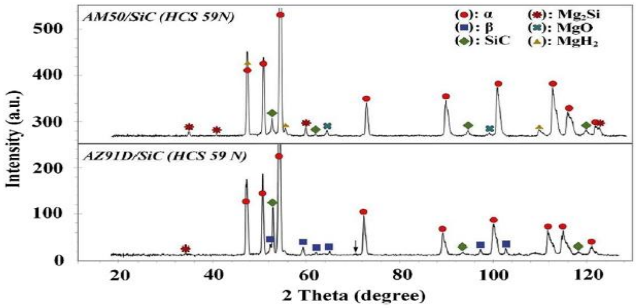

Figure 4.X-ray diffraction (XRD) diffractograms of RC AM50-and AZ91D reinforced with silicon carbide (SiC) particles

A few noticeable changes in the grain structure was observed for the SiC particle reinforced AM50-based metal matrix composite [MMC]. For the AM50 alloy-based composite, an observable decrease in the grain size of α-Mg, by as much as 28-mm, was observed. Furthermore, an increase in aspect ratio of ~0.8 was observed for the α-Mg grains that was made possible by the addition of the reinforcing SiC particles. This clearly demonstrates a noticeable enhancement in the spherical morphology of the primary α-Mg grains. In the interdendritic regions traces of the β-phase particles were observed. Similar observations were recorded for the AZ91D alloy-based MMC

The intrinsic difference in hardness of the alloys AM50, AZ91D, and the composite counterparts is shown in Figure 5. It is observed that the engineered MMCs were noticeably harder than the host alloy. Due to the presence of clusters of the reinforcing SiC particulate (SiCp) in the as-synthesized MMCs an observable difference in the hardness values was noted. The hardness value of alloy AM50 and alloy AZ91D were increased to a maximum value in the range of ~50 to 73 and ~64 to 76 with the use of HCS 59N particulate reinforcement. The HCS 400 particulate reinforcement revealed lower hardness than HCN 59N, which incidentally is noticeably harder than the unreinforced rheocast alloys AM50 and AZ91D.

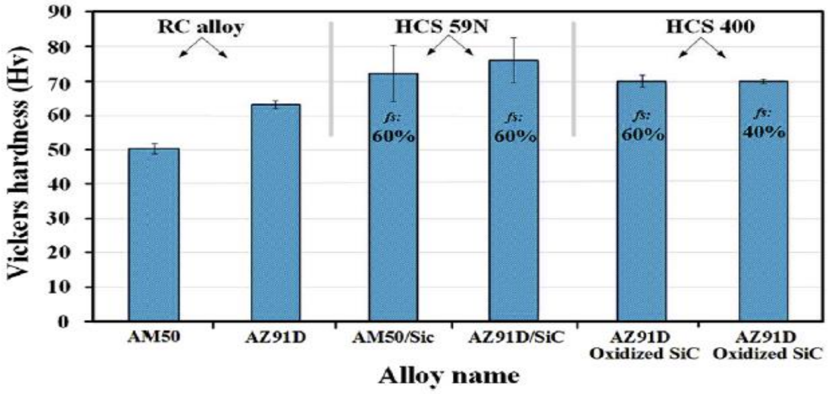

Figure 5. Hardness of Rheocast alloys and the resultant metal matrix composites [MMCs].

Poddar and co-workers [23] studied the mechanical properties and microstructure characteristics of SiC particle- reinforced magnesium-based composite synthesized using the technique of rheocasting. A temperature of 596o C and 468o C was applied to both the liquidus and solidus states in this independent research study. During stirring, the preheated SiC particles (SiCp) were gradually added to the alloy slurry. Using a rotational speed of 450 rpm and maintaining a temperature of 584±2oC, the melt was gradually stirred with the help of a mechanical stirrer for full 20 minutes during the rheocasting process. Subsequently, the slurry was filled into rectangular molds that measured 20 mm *100 mm*300 mm. The resultant ingots of both the rheocast alloy and the composite counterpart were heat treated at a temperature of 415 C for 18 hours in an environment of carbon dioxide gas.

These researchers also reported the SiC particles (SiCp) to be uniformly distributed in the matrix of the rheocast AZ91D alloy. The fine size of the reinforcing SiC particles did result in their agglomeration in the as-synthesized AZ91D/15 SiCp composite. The growth of primary α-Mg grains forced the reinforcing particles to the grain boundary regions and their small size was conducive for both clustering and agglomeration. The clustering and agglomeration of the reinforcing SiC particles at the boundary regions was essentially because of the high surface tension force due to the high volume ratio at the region of the interface.

The values of hardness of the as-cast composites are summarized in Table 1. When compared to the unreinforced counterpart, the composite samples did possess noticeably higher hardness. The hard and brittle reinforcing SiC particles (SiCp) tend to suppress matrix deformation by constraining the movement of dislocations. The load bearing capacity of the resultant composite material was enhanced by the presence of the reinforcing silicon carbide particles (SiCp)s in the microstructure of the engineered composite material. At the particle-matrix interfaces, the micro-hardness value revealed an observable decrease following the T4 heat treatment.

Table 1.Results of hardness measurement on both the As-cast and T4 heat-treated specimens

Material	Condition	Particle size (µm)	Microhardness (HV, 0.5 N)	
			Matrix (±1)	SiC/matrix interface (±3)
AZ91D	As cast	---	62	---
AZ91D	T4	---	75	118
AZ91D/15 SiCp	As cast	150	78	106
AZ91D/15 SiCp	T4	150	65	---
AZ91D/15 SiCp	As cast	15	77	93
AZ91D/15 SiCp	T4	15	81	89

The total elongation for the AZ91D/15 SiCp (grain size of 150µm) composite was 1.6 percent and for the AZ91D/15 SiCp composite (grain size of 15µm) it was 1.8 percent, which is noticeably less than that for the unreinforced alloy (8 percent). The gradual transfer of load from the soft, ductile and plastically deforming metal matrix to the hard, brittle and essentially elastically deforming particulate reinforcement was the basic mechanism governing deformation of the chosen composite at the fine microscopic level. Enhanced mechanical properties coupled with good load carrying capability could be easily achieved by the good bonding between the reinforcing silicon carbide particles (SiCp) and the chosen metal matrix.

The Osprey process was developed to prepare both aluminium-based and aluminium alloy based metal matrix composites [24]. In this technique, the reinforcement particle was introduced into a stream of the molten alloy. The molten metal is subsequently atomized using a jet of inert gas. The sprayed mixture was allowed to solidify on a substrate resulting in the formation of fine pellets.

A method for manufacturing hypereutetic Al-Si alloys was developed by Osprey Metals Ltd, which was termed as the Osprey deposition process and was based essentially on the technique of spray deposition. The need for both a simple technique and low processing cost was essential since the processing parameters were often complex and the resultant manufacturing cost was noticeably high. An important aspect was the critical need to maintain flow rate of the melt along with the required characteristics for both atomization and deposition [25].

IV. CONCLUSIONS

This review provides an adequate insight into the two-phase fabrication process coupled with a brief overview of both microstructure and mechanical characteristics of the as-synthesized metal matrix composites [MMCs]. The advantages and limitations of each of the processes are presented and briefly discussed. spray deposition has now gained the recognition of being the most promising technique for the purpose of development of metal-matrix composites [MMCs] due to a healthy synergism of a technically viable and an economically affordable cost-effective process. Test samples of the rheocast Mg-SiC composites revealed noticeable improvement in elastic modulus, hardness and yield strength, with a marginal decrease in ductility and ultimate tensile strength. Aluminium alloy 7075, which is a preferred candidate for selection and use in structural applications in combination with silicon carbide (SiC) reinforcement finds for itself selection and use in industries spanning the automobile sector and performance-related products.

References

[1] Sanjay K. Mazumdar, “Composites manufacturing”, RC Press, 2010.

[2] Tamer Ozben, Erol Kilickap, Orhan Çakır, Investigation of mechanical and machinability properties of SiC particle reinforced Al-MMC, Journal of Materials Processing Technology, 198 (2) (2008) 220–225.

[3] Rajan Verma, Saurabh Sharma, Dinesh Kumar, Analysis of mechanical properties of aluminium based metal matrix composites reinforced with alumina and sic, International Journal of Engineering Research and Technology, 6 (03) (2017) 454–459.

[4] P. Sri Ram Murthy, Y. Seetha Rama Rao, Evaluation of mechanical properties of aluminium alloy-alumina-boron carbide metal matrix composites, World Journal of Mechanical Engineering, 4 (1) (2019) 027–034.

[5] Miracle DB. Metal matrix composites – From science to technological significance. Composites Science and Technology, 2005; 65:2526–2540.

[6] Gurusamy P, Prabu SB, Paskaramoorthy R. Influence of processing temperatures on mechanical properties and microstructure of squeeze cast aluminium alloy composites. Materials and Manufacturing Processes, 2015;30:367–73.

[7] Hassan SF, Gupta M. Development of high strength magnesium based composites using elemental nickel particulates as reinforcement. Journal of Materials Science, 2007;37:2467-2474.

[8] Kala H, Mer KKS, Kumar S. A review on mechanical and tribological behaviours of stir cast aluminium matrix composites. Procedia Materials Science., 2014;6:1951–60.

[9] Jayalakshmi, S.; Gupta, S.; Sankaranarayanan, S.; Sahu, S.; Gupta, M. Structural and mechanical properties of Ni60Nb40 amorphous alloy particle reinforced Al-based composites produced by microwave-assisted rapid sintering. Materials Science and Engineering A 2013, 581, 119–127.

[10] S. Li, Y. Su, Q. Ouyang, D. Zhang, In-situ carbon nanotube-covered silicon carbide particle reinforced aluminium matrix composites fabricated by powder metallurgy, Materials Letters, 167 (2016) 118–121.

[11] A. Azarniya, H.R.M. Hosseini, M. Jafari, N. Bagheri, Thermal decomposition of nanostructured Aluminium Titanate in an active Al matrix: a novel approach to fabrication of in situ Al/Al2O3-Al3Ti composites, Materials Design, 88 (2015) 932–941.

[12] Ye HZ, Liu XY. Review of recent studies in magnesium. Journal of Materials Science, 2004;9:6153–71.

[13] Olszówka-Myalska A, Szala J, Cwajna J. Characterization of reinforcement distribution in $Al/(Al_2O_3)_p$ composites obtained from composite powder. Materials characterization 2001;46(2–3):189–95.

[14] Bhaskar Chandra Kandpal, Jatinder Kumar, Hari Singh. Production Technologies of Metal Matrix Composite: A Review. International Journal of Research in Mechanical Engineering & Technology, vol. 4, no. 2, pp. 27-32, 2014.

[15] Ramanathan Arunachalam, Pradeep Kumar Krishnan, Rajaraman Muraliraja. A review on the production of metal matrix composites through stir casting –Furnace design, properties, challenges, and research opportunities. Journal of Manufacturing Processes 42 (2019) 213–245.

[16] Elsharkawi EA, Pucella G, Côte P, Chen X. Rheocasting of semi-solid Al359/20% SiC metal matrix composite using SEED process. Canadian Journal of Metallurgy and Materials Science, 2014;53:160–8.

[17] Leatham, A.G., Brooks, R.G., Coombs, J.S., and Ogilvy, A.J., The past, present, and future development of the Osprey preform process,’ 1st International Conference on Spray Forming, Osprey Metals, Swansea, Sept., 1990.

[18] White, J., T. C. Willis, I. R. Hughes, I. G. Palmer and R. M. Jordan, in "Dispersion Strengthened Aluminium Alloys", edited by Y. W. Kim (Metallurgical Society of AIME, Warrendale, PA, 1988)

[19] Chaorun Si, Xingling Tang, Xianjie Zhang, Junbiao Wang, Weichao Wu. Microstructure and mechanical properties of particle reinforced metal matrix composites prepared by gas-solid two-phase atomization and deposition technology. Materials Letters 201 (2017) 78–81.

[20] B. Liu, Q. Lei, L. Xie, M. Wang, Z. Li, Microstructure and mechanical properties of high product of strength and elongation Al-Zn-Mg-Cu-Zr alloys fabricated by spray deposition, Materials Design., 96 (2016) 217–223.

[21] Yang, H.; She, X.-W.; Tang, B.-B.; Li, C.-M.; Jiang, X.-Q. Study of the Microstructure and Ring

Element Segregation Zone of Spray Deposited SiCp/7055Al. Materials 2019, 12, 1299.

[22] M. Esmaily, N. Mortazavi, J.E. Svensson, M. Halvarsson, M. Wessen, L.G. Johansson a, A.E.W. Jarfors. A new semi-solid casting technique for fabricating SiC-reinforced Mg alloys matrix composites". Composites Part B 94 (2016) 176-189.

[23] P. Poddar, S. Mukherjee, and K.L. Saho, The Microstructure and Mechanical Properties of SiC Reinforced Magnesium Based Composites by Rheocasting Process. Journal of Materials Engineering and Performance Volume 18(7) (2009) 849-855.

[24] A. Leatham, A. Ogilvy, P. Chesney, J.V. Wood, Osprey process – production flexibility in materials manufacture, Metallurgy and. Materials, 5 (1989) 140–143.

[25] Z. Cai, C. Zhang, R. Wang, C. Peng, K. Qiu, Y. Feng, Preparation of Al-Si alloys by a rapid solidification and powder metallurgy route, Materials Design., 87 (2015) 996–1002.