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Subject review

Liquid Metallurgy Synthesis of Gr or MoS_2-Reinforced Aluminum Composites: a Short Review

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Abstract: This review briefs the vortex casting and hardness of mono aluminium matrix composites (AMCs) and hybrid AMCs (HAMCs) containing lamellar solids (Gr (graphite) or MoS_2 particles). The vortex addition process and the associated process parameters to fabricate the mono and hybrid AMCs are discussed. The Gr particles are coated with Ni or Cu where they alloyed with the melt to enhance the wettability. Furthermore, the addition of alloying elements and the particle preheating improve the wetting of the uncoated lamellar solids with the melt. The Gr-reinforced or MoS_2 reinforced mono AMCs exhibited a decrease in hardness with the addition of lamellar solids. In HAMCs, the ceramic particles resist the indentation, leading to their better hardness than the lamellar solid reinforced mono AMCs.

Keywords: Gr-reinforced composites; hardness studies; MoS_2 reinforced composites; stir casting

1 INTRODUCTION

Metal matrix composites (MMCs) are methodical combinations of different materials (one of them is a metal) synthesized to attain customized properties [1, 2]. Thus, MMCs possess two or more duly dispersed phases (physically and chemically unique) whose combined properties (mechanical, tribological, or physical) are better than the individual phases [1]. The hybrid MMCs (HMMCs) possess two or more reinforcement phases to exhibit various properties and sustain different operating conditions [3-5]. The hybrid aluminum matrix composites (HAMCs) and mono aluminum matrix composites (AMCs) are proposed as candidate materials to replace aluminum alloys used to fabricate elements of automotive power train, chassis, and body [5, 6]. The intention behind synthesizing HAMCs containing lamellar solids and ceramic particles is to impart better tribological and mechanical properties [7-9]. The mono AMCs are also synthesized with lamellar solids. The composites containing MoS_2 or Gr (graphite) particles have shown the most potential for different commercial applications [3]. Gr particles (lubricity enhances with condensable vapors [10]) and MoS_2 particles (lubricity degrades with moisture in the air [10]) exhibit contrasting lubrication characteristics, based on which the suitable operating environments are selected. Gr possesses a sheet-like crystal structure [10] wherein all of the carbon atoms in its basal planes (atomic layers) are bonded together by strong covalent bonds, while weak van der Waals forces bond the basal planes themselves [11]. A carbon atom in the basal plane of Gr joins three adjacent carbon atoms at a distance of 0.1415 nm and an angle of 120°. At room temperature, the distance between the atomic layers of Gr is 0.335 nm [10]. The hardness of Gr in a direction parallel to the basal plane is 8.5 Mohs or reasonably greater than 1500 Vickers Pyramid Number (VPN) [12]. MoS_2 is one of the transition-metal dichalcogenides and forms a large molecule with a layer lattice [13]. Each layer of MoS_2 is stacked, and strong covalent bonds exist within the layers [14], and a layer is bonded to the layer above and below by weak van der Waals forces [10]. MoS_2 is highly anisotropic, and even though the mean hardness is only about 1 to 1.5 Mohs, its crystallite edges can be 8 Mohs (roughly equivalent to 1000 VPN) [15]. Unlike Gr, MoS_2 possesses intrinsic lubrication property [16].

The hardness of Gr-reinforced mono AMCs decreases with the increase in the addition of Gr particles, and the same phenomenon is also observed for the MoS_2 reinforced mono AMCs [7, 17]. On the contrary, the increase in the addition of ceramic particles increases the hardness of mono AMCs having ceramic reinforcements [18]. The HAMCs contain both lamellar solids and ceramic particles, providing interesting premises to discuss their hardness. In the past few decades, self-lubricating HAMCs and mono AMCs (containing Gr or MoS_2 particles) fabricated through solid and liquid-state processing methods have frequently been reported [19]. However, particles-reinforced composites produced through liquid metallurgy are observed to be the least expensive [20]. Foundry processing enables the synthesis of intricately shaped components at high production rates and sizeable numbers - the requirement of the manufacturing industries [20]. The vortex-based casting process (stir casting) has been widely used to synthesize AMCs owing to the flexible, simple, and commercially viable execution of the process [20, 21]. The above discussion revealed the scope to discuss the hardness of mono AMCs and HAMCs reinforced with Gr or MoS_2 particles. Furthermore, it is understood that the vortex-addition technique is a convenient method to synthesize the commercially viable, particles-reinforced composites. By taking these factors into account, the synthesis of self-lubricating mono AMCs and HAMCs (containing Gr or MoS_2 particles) through stir casting is discussed in this short review. Furthermore, the hardness of these composites is also reviewed with an emphasis on the combined influence of lamellar solid and ceramic particle addition on hardness.

2 GRAPHITE-REINFORCED MONO AND HYBRID ALUMINUM COMPOSITES

The synthesis of Gr-reinforced mono and hybrid AMCs through vortex casting is discussed; the hardness of these composites is also reviewed in this section.

2.1 Fabrication

For the first time, in 1969, Badia and Rohatgi [22] fabricated Al/Gr composites by injecting Ni coated Gr particles into the Al melt using a stream of nitrogen gas. The composite melt was mixed to eliminate the segregation anomalies and ensure the homogeneous distribution of Gr particles. In 1971, for the first time, Badia et al. [23] introduced the Ni coated Gr particles into the Al melt through the vortex formed by an impeller mixer (stirrer). Low-speed stirring kept the Gr particles dispersed, leading to their uniform distribution. The Al melt wetted the Ni coated Gr particles as Ni was alloyed with the aluminum. The investigators stated that the impeller mixing technique (stirring) is superior to the gas stream injection method for synthesizing composites. It is reported that three parameters related to stirring are critical-stirring speed and stirrer position and diameter [24]. Stir casting of Al/Gr composites with uncoated Gr particles is also reported. Krishnan et al. [25] fabricated Al/Gr composites using uncoated Gr particles as reinforcements. The Gr particles are preheated to 400 ºC for 1 h in the air to aid their dispersion in Al alloy melt. Besides preheating, 0.5% Mg or 5% Si (approx.) was added to the melt that substantially improved the distribution of Gr particles. Preheating enhances the wettability between the Gr particles and the alloy melt, and the Gr particles get free of adsorbed gases and volatile substances, confirmed by thermogravimetric analysis. The real-time operability of Gr-reinforced AMCs depends on the strong bonding of the Gr particles to the Al matrix. The weak interfacial bonding causes partial or complete debonding of Gr from the matrix [26]. The weak interfacial bonding is the efficacy of poor wettability between the Gr and liquid Al. The contact angle (157°) between the Gr and liquid Al alluded to poor wettability [27]. Considerable improvement in the wettability is obtained by reducing the surface energy of the Gr particles. The following methods reduce the surface energy of Gr particles: (i) the addition of alloying elements to the Al melt (magnesium, titanium, chromium, zirconium, vanadium, cobalt, or niobium [27, 28]), (ii) preheating of Gr particles [25, 29], and (iii) coating of Gr particles with Cu or Ni [30]. The coating process is time-consuming and increases the production cost. Moreover, the uniform coating thickness is difficult to attain, and there is a likelihood of partial or complete dissolution of the coating while Gr particles establish contact with the melt [26]. In synthesizing HAMCs, the reinforcement particles (ceramic particles and lamellar solids) are mixed either manually or using automat before the vortex addition. Tab. 1 shows the vortex casting parameters and particle sizes of the reinforcement particles of different studies [31-40]. The stir casting procedure (Fig. 1) of a typical HAMC begins with the coating of the equipment components-specifically, those that come into contact with the melt [9]. Then, the components were heated to remove the coating moisture. The Al matrix is melted in the argon environment, followed by adding alloying elements and degassing tablets. The preheated reinforcement particle mixture was added into the vortex of the melt. The composite melt is then poured into the preheated permanent mold.

Table 1 Details of vortex casting and the particle sizes of reinforcement particles

Parameters of stir casting and particle sizes of reinforcement particles	Mohanavel et al. [31]	Kosaraju et al. [32]	Sharma et al. [33]	Prabagaran et al. [34]	Radhika et al. [35]	Vencl et al. [36]	Kumar and Dhiman [37]	Thirumalai et al. [38]	Pai et al. [39]	Gajakosh et al. [40]
Composite	AA6351/ Al_2O_3/Gr	Al/SiC/Gr	AA6082/Si_3N_4/Gr	AA6061/B_4C/Gr	AlSi10Mg/ Al_2O_3/Gr	A356/SiC/Gr	AA7075/SiC/Gr	A356/B_4C/Gr	AA6061/ Granite/Gr	AA7075/ TiO_2/Gr
Melt temperature / ºC	850	825	900	650	- -	600 (semi-solid melt)	700	750	780	800
Stirring speed / rpm	400	- -	200	300	350	500^{+} $1000^{\wedge}$ $1500^{\#}$	600	400	- -	100
Stirring time / min	30	- -	10	3	3	7^{+} $2^{\wedge}$ $5^{\#}$	- -	$2\text{-}3^{\$}$	780	- -
Particle sizes	Al_2O_3-60 to 70 µm and Gr-60 to 70 µm	SiC-30 to 40 µm and Gr-40 to 50 µm	Si_3N_4-50 µm and Gr-50 µm	650	700	500	- -	- -	Granite-≤100 µm and Gr- ≤ 100 µm	TiO_2-25 µm and Gr-25 µm
Preheat temperature / ºC	Al_2O_3-400 and Gr-300	200	500	B_4C-20 to 50 µm and Gr-50 µm	Al_2O_3-15 to 20 µm and Gr-50 to 70 µm	SiC-39 µm and Gr-35 µm	SiC-27 to 33 µm and Gr-20 to 25 µm	B_4C-5 to 25 µm and Gr-25 to 75 µm	500	- -
Degassing gas	- -	Argon	- -	300	- -	500	- -	200	Room	Room
Particles feed rate / g/s	0.9 to 1.4	- -	- -	- -	1.5 wt. %	- -	1 wt. %	3 wt. %	Nitrogen	C_2Cl_6
Mixing of reinforcement particles	- -	- -	Ball milling	- -	C_2Cl_6 (Hexachloroethane)	Room	Nitrogen	Room		
				- -	Room	- -	- -	C_2Cl_6		

$^{+}$Stirring speed and time during particles addition

$^{\wedge}$ First combination of stirring speed and stirring time after particles addition

$^{\#}$Second combination of stirring speed and stirring time after particles addition

$^{\$}$Afterparticles additio

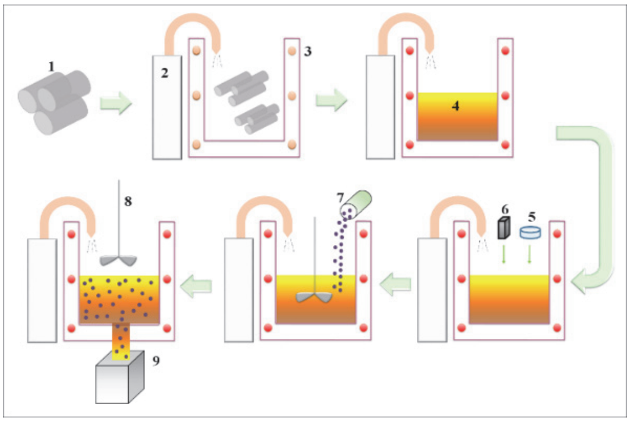

Figure 1 The Schematic illustration of vortex casting (1 – Al matrix, 2 - Argon, 3 - Coated crucible, 4 - Matrix melt, 5 - Degassing tablet, 6 - Wettability enhancers, 7 - Particles, 8 - Impeller (Stirrer), 9 - Permanent mold) [9]

2.2 Hardness

In Gr-reinforced mono AMCs, the decrease in hardness with the increase in the Gr addition is attributed to the softness, brittleness, and crystal structure of the Gr particles [17]. Furthermore, the increase in Gr particles addition increases the propensity for crack initiation and propagation at the matrix Gr interface due to the clustering, segregation, and agglomeration anomalies of Gr particles in the matrix [41]. These anomalies are induced during the synthesis of the composites, adversely influencing the hardness [41]. Hassan et al. [42] studied the hardness of AlMg/SiC/Gr hybrid composites. The hardness of the hybrid composites increased with the increase in the addition of 1, 2, and 4 vol. % SiC particles. On the contrary, the hardness decreased with the increase in adding 1, 2, and 4 vol. % Gr particles. Fig. 2 shows the variation of hardness with Gr and SiC particles addition. The investigators stated that the hard ceramic particles (SiC) offer resistance against indentation, while the soft lamellar solid (Gr) sheared easily under the compression action of the indenter. The hardness of the 4 vol. % Gr hybrid composite is 11 % lower than that of the 1 vol.% Gr hybrid composite. It is to be noted that both the 1 and 4 vol. % Gr hybrid composites are reinforced with 4 vol. % SiC particles. Suresha and Sridhara [43] compared the hardness of Al/SiC/Gr composites and Al/Gr composites.

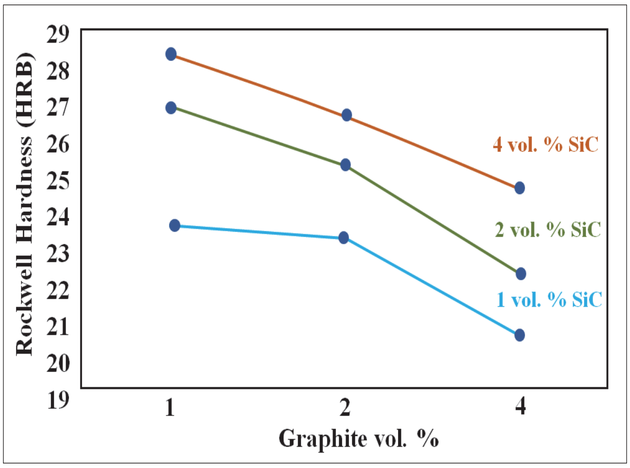

Figure 2 The effect of SiC and Gr particles addition on the hardness of AlMg/SiC/Gr hybrid composites [42]

The hardness decreased with an increase in the Gr addition due to an increase in porosity. Furthermore, the investigators observed that the hardness of the hybrid composite is higher than that of the mono composite due to the presence of SiC particles. Pugazhenthi et al. [44] studied the influence of solidification on the hardness of the Al/TiC/Gr hybrid composites. The hardness increased with an increase in the cooling rate, attributed to the TiC particles impeding the dislocation in the Al-matrix.

3 MoS_2 REINFORCED MONO AND HYBRID ALUMINUM COMPOSITES

The synthesis of MoS_2 reinforced mono and hybrid AMCs through vortex casting is discussed; the hardness of these composites is also reviewed in this section.

Table 2 Details of vortex casting and the particle sizes of reinforcement particles

Parameters of stir casting and particle sizes of reinforcement particles	Kumar et al. [45]	Kumar et al. [46]	Perumal and Prakash [47]	Rebba and Ramanaiah [48]	Dharmaling-am et al. [49]	Liu et al. [50]	Daniel et al. [51]	Jojith and Radhika [52]	Wasekar and Khond [53]	Smart et al. [54]
Composite	AA2219/n - B_4C/MoS_2	AA2219/n - B_4C/MoS_2	A356/ B_4C/MoS_2	AA2024/B_4 C/MoS_2	AlSi10Mg/ Al_2O_3/MoS_2	AA7075/ B_4C/MoS_2	AA5059/ SiC/MoS_2	A332/TiO_2/ MoS_2	AA6061/ fly ash/MoS_2	AA5083/Ni/ MWCNT/MoS_2
Melt temperature / ºC	820	750	850	- -	800	680	600-700	- -	720	680
Stirring speed / rpm	200-250	150-200	350	300	- -	450-500	750-850	250	500	200
Stirring time / min	7	5	5*	10	10*	10-15	5	10	- -	5
Pouring Temperature / ºC	780	780	- -	- -	Al_2O_3-10 to 20 µm and MoS_2-1.5 µm	1100	- -	760	500	500
Particle size	n-B_4C-30 to 60 nm and MoS_2-600 to 900 nm	n-B_4C-30 to 60 nm and MoS_2-600 to 900 nm	B_4C-63 µm	500	- -	B_4C-10 µm and MoS_2-2 µm	SiC-10, 20, and 30 µm	TiO_2-100 µm MoS_2-10 µm	Mg is added	- -
Preheat temperature / ºC	250	200	200	Mg is added	- -	900	400-500	250	Nitrogen	Argon
Melting environment	Room	Room	Room	Room	Argon	- -	Mg is added	- -		
Degassing gas and Temperature / ºC	- -	C_2Cl_6	C_2Cl_6 and 800			Argon	Room	Argon		
						300	- -	- -		

*After particles addition.

3.1 Fabrication

In synthesizing the MoS_2 reinforced composites, the particles are preheated to enhance the wettability of the MoS_2 particles with the Al melt [45, 46]. Several studies reported the fabrication of HAMCs containing MoS_2 particles [45-54]. Tab. 2 shows the vortex casting parameters and particle sizes of ceramic and MoS_2 particles used in these studies. Kumar et al. [45] melted the matrix above its liquidus temperature, and in related work, Kumar et al. [46] degassed the melt using C_2Cl_6 (hexachloroethane) tablets. Furthermore, the mixed reinforcement particles (ceramic particles and MoS_2 particles) are preheated to remove the moisture and other impurities.

3.2 Hardness

In MoS_2 reinforced mono AMCs, the decrease in hardness with the increase in the addition of MoS_2 particles is attributed to the agglomeration [7] and softness of the MoS_2 particles. Kumar et al. [8] observed that the AA2219/n-B_4C/MoS_2 hybrid composites exhibit higher hardness than the AA2219/n-B_4C mono composite and the matrix alloy, leading to the better wear resistance of hybrid composites. Jojith and Radhika [52] studied the hardness of the A332 matrix and A332/TiO_2/MoS_2 hybrid composites. The hardness of the hybrid composites is 16.5% higher than that of the base matrix. The investigators observed that particle strengthening, dispersion strengthening, and grain boundary strengthening influence the hardness of the hybrid composites. The reinforcement particles inhibit the dislocation and provide significant resistance against plastic deformation. The decrease in the dislocation density due to the reinforcement particles addition strengthens the matrix, leading to better hardness of hybrid composites.

4 CONCLUSIONS

The processing of mono AMCs and HAMCs (containing Gr or MoS_2 dispersions) through the vortex addition method is discussed in this short review. Both coated or uncoated Gr particles are used as reinforcements, and the particle preheating and alloying elements enhance the wettability. In the case of MoS_2 reinforced composites, particle preheating is prevalently adopted to enhance wettability. Different processing environments, such as room conditions and nitrogen and argon-filled crucibles, are adopted to synthesize the lamellar solid reinforced composites. C_2Cl_6 tablets are used in the degassing procedure of Gr-reinforced and MoS_2 reinforced mono AMCs and HAMCs. The hardness of the Gr-reinforced HAMCs decreased with the increase in the Gr addition, owing to the Gr particles increasing the propensity for crack propagation. In contrast, in HAMCs, the increase in the addition of ceramic particles increased the hardness. The ceramic particles decrease the dislocation density; this phenomenon and the different strengthening mechanisms contribute to increasing the hardness of the hybrid composites with the increase in the addition of the ceramic particles.

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