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Role of Gd addition on machinability of Al-15%Mg_2Si in-situ composite during dry turning

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Abstract

Recently, Al-Mg_2Si in-situ composites have achieved considerable attention due to their excellent physical and mechanical properties. In fact, there are some limitations of knowledge regarding the machinability characteristics of these composites - particularly when being inoculated with rare earth additions. This study in turn aimed to investigate the influence of machining parameters as well as Gd addition on the machinability of Al-15%Mg_2Si composite. To examine the effect of modifier (1.0 wt. % Gd) and machining parameters (feed rate, cutting speed), microstructural evolution, surface roughness (Ra) and cutting force (Fc) were evaluated during dry turning. The results revealed that Gd addition as modifier element led to better surface roughness and higher cutting force owning to the modification of Mg_2Si particle structure as well as the formation of Gd intermetallic compounds.

Keywords: Al-Mg_2Si composite; Rare earth; Modification; Cutting Force; Surface Roughness

1. Introduction

In-situ fabrication of the particulate metal matrix composites (PMMCs) during casting has some advantages such as simple production during solidification, good reinforcement particles distribution, excellent particle wetting and thermodynamic stability of particles compared to ex-situ technique [1,2].

In-situ MMCs have gained considerable attention due to the convenient technical process and strong interface between reinforcement and matrix [3]. Recently, Al-Mg_2Si in-situ composite as a new group of PMMCs has been introduced in automotive and aerospace industries owning to its proper physical and tribological features [4,5].

The tensile properties and machinability of hypereutectic Al-Mg_2Si in-situ composite are determined by the morphology and size of Mg_2Si particles; therefore, controlling the structure of Mg_2Si particles is deemed crucial to achieve the superb mechanical and machinability properties [6-8]. In this respect, several approaches such as rapid solidification [9], hot extrusion [10] and superheat treatment [11] and the addition of modifying elements such as Gd [12], Bi [13], Ba [14] and Sb [15] have been applied to control the microstructure of Al-Mg_2Si composite.

Gadolinium (Gd) has a number of useful properties in alloys. 1.0 wt. % Gd can improve the workability of iron and chromium alloys, and resistance to high temperature and oxidation. It is also used in alloys for making magnets, electronic components and data storage disks. Its compounds are useful in magnetic resonance imaging (MRI). In addition, Gd has no known biological role, and has low toxicity [16]. Gd addition is also utilized to modify the structure of primary Mg_2Si in Al-Mg_2Si composite as well as Mg-Si alloys [4,12].

Due to the existence of hard Mg_2Si particles in the soft Al matrix, the machinability of this sort of composites is expected to be difficult especially during finishing process. The addition of alloying elements such as Bi is determined to be positive in solving this problem by introducing fragile chips during machining [17]. The study carried out by Yosuf et al. [18], found that the morphology of Mg_2Si particles was considerably modified with the addition of 0.4 wt. % Bi, 0.8 wt. % Sb, and 0.01 wt. % Sr to Al-Mg_2Si composite, in which the machinability of the composite was affected by increasing in cutting force and lessening the surface roughness. Similarly, Razavykia [14] claimed that the treatment of the Al-20%Mg_2Si-2Cu composite with Ba addition caused the modification of Mg_2Si particles as well as the formation of Ba compound, which caused the lower cutting temperature and better surface roughness.

Similarly, it has been reported that the addition of Gd element to Al-15%Mg_2Si composite results in the considerable refinement/modification of composite structure and corresponding enhancement of mechanical properties of the composite compared to other RE elements [12]. For this, it is predicted that the addition of Gd element to Al-15%Mg_2Si composite could improve the machinability characteristics.

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The current study is targeted to examine the impact of Gd modifier as well as surface roughness and cutting force as machining parameters during dry turning on the machinability of Al-15%Mg_2Si in-situ composite.

2. Materials and Methods

Pure aluminum, magnesium in bulk form and pure silicon in the form of small blocks were utilized to fabricate Al-15%Mg_2Si composite ingot, supplied by Stanford Advanced Materials (CA 92630, USA). Table 1 depicts the composition of the elements in the fabricated composite ingot. Having been cut into small sections, the ingot of the composite was melted into a SiC crucible with the capacity of 5kg with the help of a resistance furnace at a temperature of 760± 5ºC. When the molten metal was degassed using C_2Cl_6 tablets, 1.0 wt. % Gd was introduced to the melted composite using Al-10Gd rod master alloy supplied by the same supplier. The melted composite was allowed for homogenization and dissolution for approximately 5 min and the molten metal was agitated and casted at the temperature at 740 ± 5ºC into a mild steel mold to produce work-piece with a cylindrical shape.

Table 1. Composition of the elements in ingot of Al–15%Mg_2Si (wt. %)

Element	Weight %
Mg	9.5
Si	5.5
Fe	0.02
V	0.02
Cr	0.01
Ni	0.01
Ti	0.01
Cu	0.01
Mn	0.01
Al	Bal.

The composite work-piece without Gd addition was fabricated using the aforementioned process. The machinability experiments were carried out on Al–15%Mg_2Si (unmodified) and Al–15%Mg_2Si–1.0%Gd (Modified). To achieve a uniform specimen with the diameter of 45 mm and length of 450 mm, the specimens were rough turned and placed onto CNC lathe machine (Alpha 1350S, Harrison, UK, 8.3 kW power drive and maximum 6000 rpm spindle speed).A standard tool holder was used to hold the inserts machining. Dry turning was carried out for all tests at various feed rates (0.1, 0.2, 0.3 mm/rev), cutting speeds (100, 200, 300 m/min) and fix depth of cut of 0.5 mm. The chosen machining parameters were aligned with the range of the machining parameters used in the previous studies during machining of the MMCs, in which proper machining outcome has been achieved through their application [14,18].

Machinability experiment was targeted to measure the surface roughness and cutting force. Several preventive measures were taken to minimize the influence of vibration. At first, to decrease the cutting forces, the selected cutting tool owned a considerable features which reported elsewhere [14]. Then, to reduce the contact and friction between rake face and chip, the insert was selected with a chip breaker. Thus, to accomplish the turning experiments, Kennametal coated carbide insert was utilized. Metallography procedure was applied on the specimens to reveal the microstructure in which after cutting the specimens from the work-piece they were prepared by standard grinding and polishing using SiC sand paper and colloidal silica (5µm) respectively. Microstructure examination was conducted using optical microscope (MIDROPHOT-FXL) and SEM microscope (Philips XL40) equipped with EDS facility. Surface roughness tester (CS5000, Mitutoyo, Japan) was used to measure the surface roughness. In addition, Fc (main cutting force) was recorded during dry machining using a three-component dynamometer. Fig. 1 depicts the flowchart of the research.

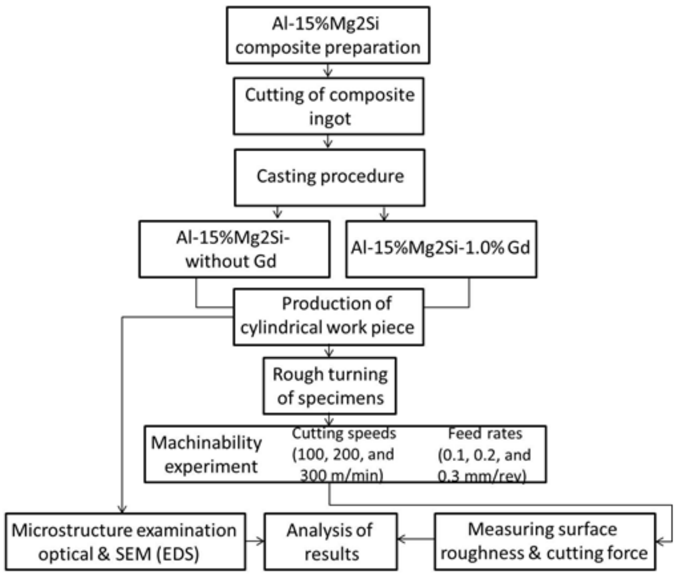


Fig. 1. Experimental procedures flow chart

3. Results and Discussion

3.1. Microstructure Examination

Fig.2 (a-d) depicts the OM/SEM images of Al–15%Mg_2Si work-piece with and without gadolinium addition. As seen in Fig. 2 (a,c), primary Mg_2Si has a polyhedral morphology with hollow in its center as the indicative of unmodified primary Mg_2Si morphology. Fig.2 (b,d) illustrates Al-15%Mg_2Si composite work-piece modified with 1.0 wt. % Gd. Microstructural observation revealed that the microstructural features of primary Mg_2Si crystals altered when the composite was treated with Gd addition, in which the particles refined the their morphology transformed to the truncated octahedral morphology in comparison to the unmodified composite. Furthermore, i- Solution image analyzer was utilized to assess the Mg_2Si crystal features including density, size and aspect ratio. The features of Mg_2Si particles altered considerably after the addition of Gd. The results demonstrated that the size, aspect ratio and density in the unmodified composite were 40µm, 1.34 and 495 particle/mm^2 respectively.

Nevertheless, composite modification using Gd addition led to the increase in density to 1167 particle/mm^2 and reduction in aspect ratio and size to 1.25 and 20µm respectively. This designated that the density increased by 33% and aspect ratio and size reduced by 8% and 25%. These features implied the modification effect of Gd element on primary Mg_2Si crystals in the composite.

Fig.3 (a,c) presents the BSE micrograph of the Gd modified work-piece, in which there were some white particles in the composite matrix near the Mg_2Si particles. The resultant EDS analysis presented that these particles included Gd intermetallic compounds composing Al, Si and Gd. According to the atomic percentage as shown in Fig. 3b, the composition of intermetallic compound with irregular morphology is $GdAl_2Si_2$. In addition, the composition of needle-like particle is AlSiGd (Fig.3d). The modification mechanism of Gd addition on primary Mg_2Si in Al-15%Mg_2Si composite can be attributed to the non-homogeneous nucleation, mechanism of growth restriction of Mg_2Si particles by Gd IMCs and poisoning influence by altering the growth manner of primary Mg_2Si particles by absorbing the Gd atoms on {100} facets of primary Mg_2Si, hindering the growth [12]. It is worth mentioning that the ultimate tensile strength (UTS) value for the composite without Gd was 204.79 MPa, which increased to 224.62 MPa with the addition of 1.0 wt. % Gd. Furthermore, work-piece without Gd showed El% of 2.65, which was lower than that of with 1.0 wt. % Gd (3.75).

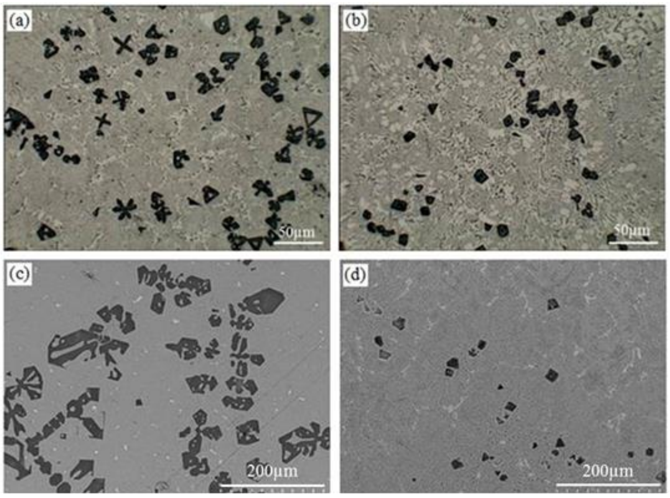
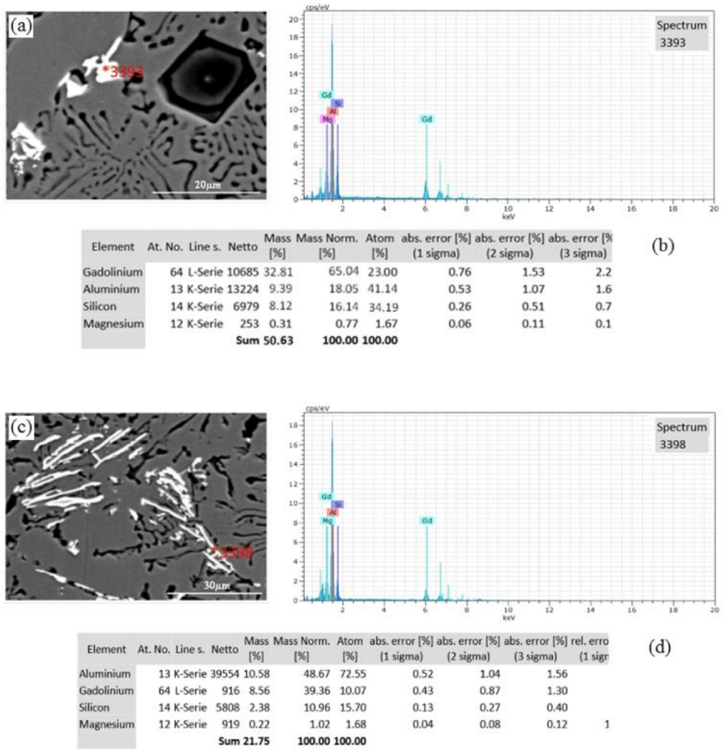


Fig. 2. OM/SEM images of Al–15%Mg_2Si composite (a and c) untreated and (b and d) treated with Gd

3.2. Cutting Force

Among the cutting forces, F_c is considered as the main and prime substantial cutting force in cutting speed direction, which produces the requisite power in order to cutting. Fig. 4 depicts the amount of the cutting force under various conditions of cutting including cutting speed, constant depth of cut (0.5mm) and feed rate during machining. The results indicated the increase of feed rate from 0.1 mm/rev to 0.2 mm/rev and the increase of the main cutting force in all conducted tests owning to the load increasing on tool tip as well as the existence of high friction between tool rake surface and chip in the zone of cutting. In addition, the increase of cutting speed from 100 m/min to 300 m/min led to the reduction of the main cutting force (Fig.4).



Element	At. No.	Line s.	Netto	Mass [%]	Mass Norm. [%]	Atom [%]	abs. error [%] (1 sigma)	abs. error [%] (2 sigma)	abs. error [% (3 sigma)
Gadolinium	64	L-Serie	10685	32.81	65.04	23.00	0.76	1.53	2.2
Aluminium	13	K-Serie	13224	9.39	18.05	41.14	0.53	1.07	1.6
Silicon	14	K-Serie	6979	8.12	16.14	34.19	0.26	0.51	0.7
Magnesium	12	K-Serie	253	0.31	0.77	1.67	0.06	0.11	0.1
			Sum	50.63	100.00	100.00			

Element	At. No.	Line s.	Netto	Mass [%]	Mass Norm. [%]	Atom [%]	abs. error [%] (1 sigma)	abs. error [%] (2 sigma)	abs. error [%] (3 sigma)	rel. erro (1 sigr
Aluminium	13	K-Serie	39554	10.58	48.67	72.55	0.52	1.04	1.56	
Gadolinium	64	L-Serie	916	8.56	39.36	10.07	0.43	0.87	1.30	
Silicon	14	K-Serie	5808	2.38	10.96	15.70	0.13	0.27	0.40	
Magnesium	12	K-Serie	919	0.22	1.02	1.68	0.04	0.08	0.12	1
			Sum	21.75	100.00	100.00				

Fig. 3. (a, c) BSE micrographs of Gd IMCs (white area) and related EDS analysis

High cutting speed resulted in the increase of cutting zone temperature; as a result local material softened, which promoted the lower cutting force.

Additionally, with the increasing cutting velocity, the angle increased and then decreased the friction between chip and rake face, related to the cutting force reduction [20]. Moreover, the morphology, distribution and volume fraction of the reinforcement particles in addition to the matrix properties were are all parameters bringing some effects on the cutting properties [21]. Fig.4 also depicts the dependency of the main cutting forces on the microstructure of the work-pieces in which cutting force differed based on the microstructure state. In fact, the features of Mg_2Si particles, e.g. morphology, size, density and aspect ratio were significantly affected by Gd addition, which consequently influenced the turning process (Fig.2). The Gd modified work-piece interpreted higher cutting force in comparison with the unmodified composites. During the turning of the Gd modified work-piece, high cutting force could be associated to the morphology changes of Mg_2Si crystals and its characteristics including shape, size and density, leading to the decrease of material tendency in the formation of built-up edge (BUE) on the face of tool rake. The alteration of the Mg_2Si crystals morphology from coarse shape to fine octahedral morphology led to cutting force to be increased as a result of the high energy required to pull out or fracture the refined polygonal crystals from the composite matrix. The existence of the particle with high density improved the frequency of collision between cutting tool tip and particles; thus, the cutting force and tool deflection increased [22]. On the other hand, the type and reinforcement particles content in addition to strength of interfacial bonding in the interface of the matrix and particle significantly affected the peaks of stress on the cutting tool tip. Moreover, with the increase of the particle density for the plastic deformation, more energy was required of Al. Indeed, during the turning of the Al composites, Al showed a plastic flow among the crystals served as an obstacle to the plastic deformation of Al between the crystals and push Al to deform between the directions with minus boundaries of particles, which subsequently resulted in the cutting force to be increased. Therefore, lowest cutting force and easier plastic deformation were generated when the particle interfaces were less or their density was low. Nevertheless, it is believed that the required cutting force for Al composites with small particles is less than Al composites with large crystal. In fact, particles with large size have large interfaces with the matrix and become the barrier for the Al to flow plastically between the particles. It subsequently leads to the increase of the cutting force [23].

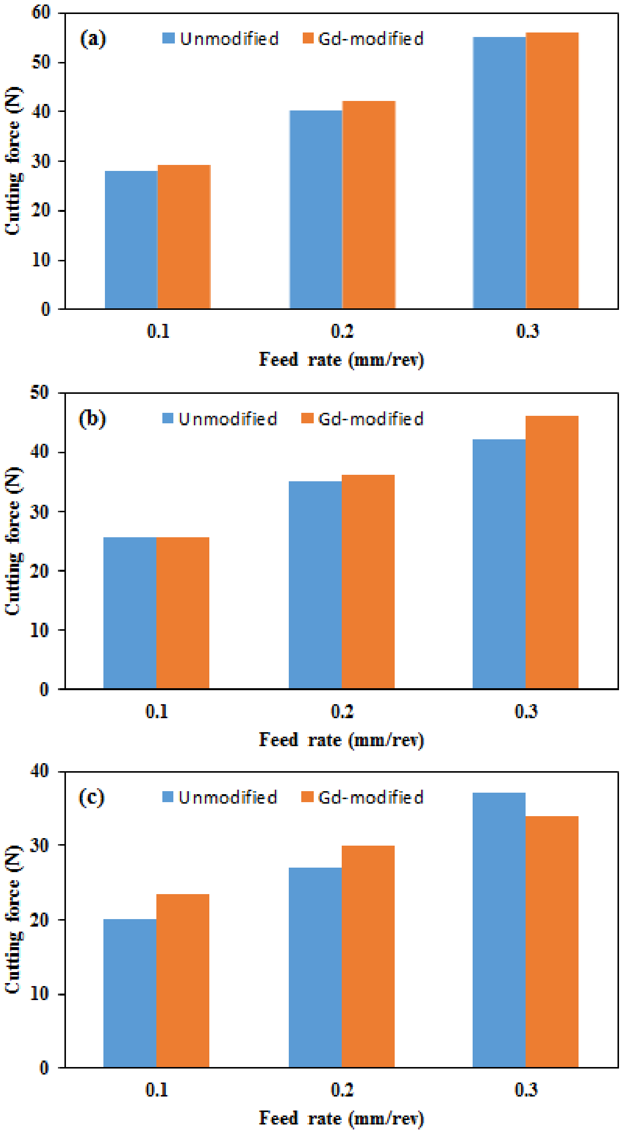


Fig. 4. Influence of feed rate and addition on cutting force (Fc) at (a) 100, (b) 200 and (c) 300 m/min cutting speeds

3.3. Surface Roughness

Fig.5 presents the surface roughness of the subjected work-piece for all combinations of machining parameters. It shows that by the increase of feed rate from 0.1 to 0.3 mm/rev, the surface roughness became worse in all work-pieces, which might be as the result of higher load applied on the tool. Moreover, once the feed rate value increased, the feed mark was dominated and the distance between peaks and valleys increased later on resulting in the worsening surfaces [24]. The results showed a decrease in the surface roughness values as well as the increase in the cutting speed from 100 to 300 m/min as a result of production of BUE with shorter cycle time and smaller BUE size. Surface roughness deteriorated if the formation of BUE was like a cheap on the tool tip. Furthermore, Fig.5 depicts the effect of Gd on the composite surface roughness. As seen for all combinations of cutting speed and feed rate, the work-piece modified with Gd addition illustrated superior surface (lower R_a) compared to unmodified one. The coarse and irregular primary Mg_2Si particles were sensible to fragmentation during machining. As a result, the length of peaks and valleys was achieved in unmodified composite due to the large cut off particles; therefore, more fragmentation of such particles with cleavage fractured faces was expected to introduce a rather rough surface after machining. However, in Gd containing work-piece, with the presence of fine Mg_2Si particles with a lower aspect ratio, the surface roughness was expected to be less than that of Gd-free composite. Furthermore, owning to the low solubility of Gd in the aluminum solid solution and high melting point compared to aluminum, the fine Gd-rich intermetallic compounds are dispersed in the matrix (Fig.3), playing a substantial role in the composite to lessen the friction between chip and tool wear and induce a smooth surface finish (Fig.5).

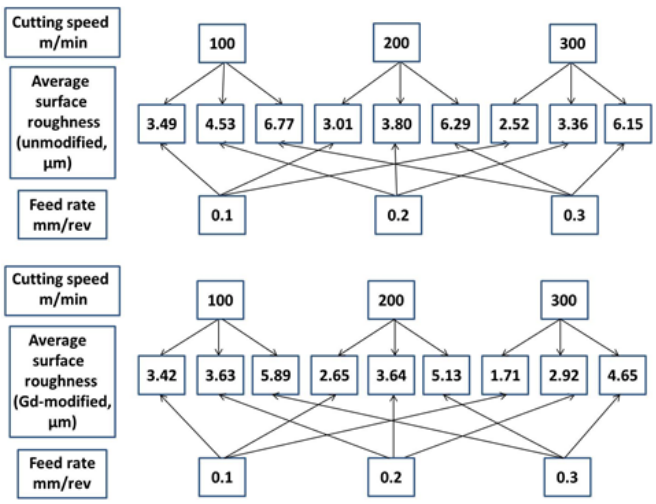


Fig. 5. Surface roughness of the untreated and Gd-treated composites

4. Conclusion

The machining of Al-Mg_2Si composite was carried out during dry turning to evaluate the effect of Gd element and machining parameters (constant depth of cut of 0.5 mm, feed rates of 0.1 to 0.3 mm/rev and cutting speeds of 100 to 300 m/min) on the machinability of in-situ composite. With the introduction of the Gd element to Al-Mg_2Si composite, Mg_2Si particles size, aspect ratio and density significantly altered, which in turn affected the machinability of the composite. For all combinations of machining conditions with the addition of Gd the Mg_2Si particles, density increased, thus leading to the increase of cutting force. The formation of BUE and work-piece material affected the surface roughness. Gd addition led to the formation of smaller Mg_2Si particles in the fabricated composite, which caused the lower surface roughness to be achieved. Moreover, in the cutting zone, surface roughness, friction and temperature decreased due to the formation of new Gd IMCs.

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