Effect of Mg on Microstructure and Mechanical Properties of the Novel Al-Based Composite for Thermal Neutron Shielding

Yigeng Ding[1], Zhiwei Liu[1,*]
1. State Key Laboratory for Mechanical Behavior of Materials, School of Materials Science and Engineering, Xi'an Jiaotong University, No. 28, Xianning West Road, Xi'an, Shaanxi Province 710049, P.R. China
2. *Corresponding address: e-mail: liuzhiwei@xjtu.edu.cn

Abstract: The structural materials used for neutron shielding are typically fabricated as thin-walled grillage structures, which require a combination of superior neutron shielding capacity and acceptable mechanical properties. A novel (5 wt.% B_4C_p+4.5 wt.% Gd)/Al-5Cu neutron shielding composite which exhibited promising commercial potential was designed based on equivalent B areal density (EBAD) calculations. Additionally, the influence of Mg on microstructure and mechanical properties was investigated. The primary phase of the composite was τ-Al_8Cu_4Gd, which altered from a lamellar to a massive structure along with the addition of Mg, and the Mg was completely dissolved in the Al matrix and Al_3Gd. After hot rolling, the large-size τ-Al_8Cu_4Gd phase was broken into smaller particles, resulting in a more homogeneous dispersion within the matrix. This fragmentation process proved advantageous for enhancing both the strength and ductility of the composites. The addition of Mg significantly increased both the yield strength (61.7%↑) and ultimate tensile strength (42.9%↑) after hot rolling, which was due to a synergistic effect of refinement of second phase and solution strengthening. The study presents a high-performance Al-based composite with outstanding casting ability containing biphasic neutron-absorbing elements.

Keywords: Aluminum alloy; Mechanical properties; Casting; Neutron shielding materials

1 Introduction

High abundance of B^{10} makes B_4C_p/Al composite suitable for the ideal neutron radiation shielding materials [1]. However, B_4C_p is a brittle phase, which introduced excessively led to the decline of the deformability and plastic toughness of the material [2]. Therefore, there are many researchers have introduced the Gd element, which has a higher neutron absorption cross-section (48,800 b), to partially replace B_4C_p. Chen et al. [3] developed $6TiB_2$/Al-6Mg-1Gd composite wich the UTS and El were 464 MPa and 15.6%, respectively. The composite had outstanding mechanical properties, but its absolute neutron shielding property was below the standard. Chen et al. [4] fabricated ($10B_4C_p$+3.6Gd)/6061Al by ultrasound-assisted casting, the UTS and El of as-cast composite were only 117.8 MPa and 0.8%, respectively, which was still lack of ductility.

In consideration of the trade-off between shielding phase content and properties, adding elements for alloying is an undeniably effective method. Mg has a notable solution-strengthening effect in Al, because of high solid solubility in Al and 13% larger than Al at atomic radius, which introduced lattice distortion [5]. This work designed and fabricated high Gd content (4.5 wt.%) composites and investigated the influence of Mg element on the microstructure and corresponding mechanical properties of as-cast and rolled $5B_4C_p$/Al-5Cu-4.5Gd composites.

2 Experimental procedure

According to the formula of B_{Eq} [6] ,when the B_4C content was determined to be 5%, the Gd content can be calculated to be 4.5%. The B_4C_p/Al-5Cu-4.5Gd-xMg (x=0, 2) composites were fabricated by using pure Al (99.7%), Cu (99.9%), Mg (99.9%), Al-30Gd master alloys and Al-$10B_4C_p$ (Al-K_2TiF_6 system [7]) master composites as raw materials. Al-30Gd master alloys, Al-$10B_4C_p$ master composites, pure Al, and pure Cu were initially melted at 750 ℃ for 20 min within a graphite crucible in a high-frequency induction furnace. After that, Mg was added to the melt, and mechanical stirring was introduced into the melt with a rotating speed of 380 r/s for 5 min. Finally, the composite melt was poured into a graphite mold to obtain an ingot. For simplicity, the B_4C_p/Al-5Cu-4.5Gd composite and the B_4C_p/Al-5Cu-4.5Gd-2Mg composite were referred to as the 0Mg composite and the 2Mg composite, respectively.

The phases and microstructure of samples were examined by X-ray diffractometer (XRD, Bruker D8 ADVANCE) and scanning electron microscopy (SEM, Sigma300). Flat specimens (gauge length×width×thickness: 20×4×3.5 mm) were tensile tested by using a testing machine (CMT5305, MTS, USA) equipped with an extensometer at a constant cross-head speed of 0.5 mm/min.

3 Result and discussion

Phase analysis and microstructure

The XRD patterns of as-cast 0Mg and 2Mg composites were shown in Figure 1. The primary peaks except for α-Al correspond to τ_1-Al_8Cu_4Gd (marked by orange verticals) and Al_3Gd phase. No peaks of Mg-contain were found, which indicated Mg existed as a solid solution, it was also suggested by the leftward shift of the peak of α-Al. The continuous net-like phase was proved to be α-Al+τ_1 eutectic structure by the EDS analysis, as shown in Table 1. Mg solubilized mainly in α-Al matrix and τ_1, consistent with the XRD results. Perceptibly, Mg addition altered the precipitation behavior of τ_1, due to Gd can reduce the diffusion coefficient of Cu and Mg in Al, the Mg and Cu elements were segregated on the surface of the τ_1 phase at the later period of precipitation of eutectic τ_1, resulted in overcooling of the composition, which inhibited the growth of the τ_1 phase, resulting in the transformation of the τ_1 phase from a lamellar to a massive structure (Figure 2(a-b)). The continuous net-like τ_1 phase was broken into fine particles aligned along rolling direction after hot rolling, as shown in Figure 2(c-d).

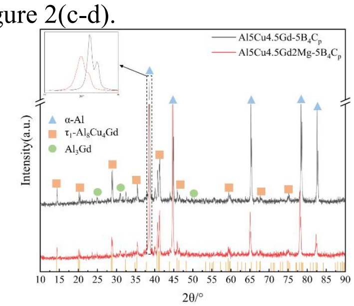

Fig.1 XRD patterns

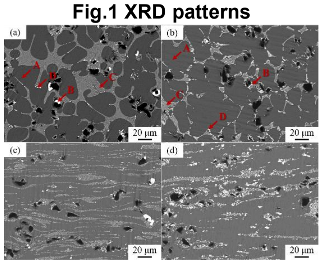

Fig.2 BSE micrographs of the 0Mg ((a)as-cast, (c)as-rolled) and 2Mg ((b)as-cast, (d)as-rolled) composites

Table1 EDS results of point in Figure 2 (a-b)

Point		Al	Cu	Gd	Mg
Fig. 2a	A	99.27	0.73	0.00	0.00
	B	71.31	0.00	28.69	0.00
	C	88.31	9.29	2.41	0.00
	D	60.45	31.65	7.90	0.00
Fig. 2b	A	98.09	0.40	0.00	1.51
	B	70.8	0.00	29.20	0.00
	C	88.89	8.92	2.19	0.89
	D	62.13	30.55	7.32	0.00

Tensile properties and fracture fractography

Figure 3 exhibited the typical strain-stress curves and corresponding tensile properties of as-cast and as-rolled B_4C_p/Al composites with and without Mg. For all curves, significant Portevin-Le Chatelier (PLC) effects were observed, indicating a high content of solute atoms. With the addition of Mg, YS and the UTS increased while the El decreased. The improvement of YS and UTS was attributed to solution strengthening and refinement of τ phase. According to the fracture fractography, large and shallow dimples with lamellar τ_1 phase inside were observed in as-cast 0Mg composite (Figure 4(a-b)), indicating a mixed ductile-brittle fracture. While the cleavage planes were observed (Figure 4(c)) and demonstrated to be a massive τ_1 phase by BSE diagrams (Fig. 4(d)), in as-cast 2Mg composite, which led to brittle fracture. The improvement of comprehensive mechanical properties of the composites with and without Mg after hot rolling was attributed to the broken of τ_1 phase (Figure 4(e-h)), which diminished stress concentration. The as-rolled 2Mg composite had excellent comprehensive tensile properties, the YS and UTS were 217 MPa and 284 MPa, respectively, which increased by ~76 MPa and ~74 MPa over as-rolled 0Mg composite.

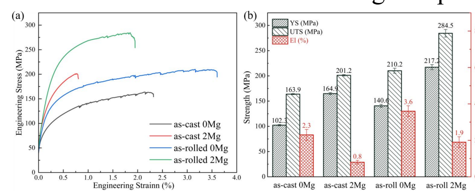

Figure 3 (a) Engineering stress-strain curves and (b) detailed mechanical properties.

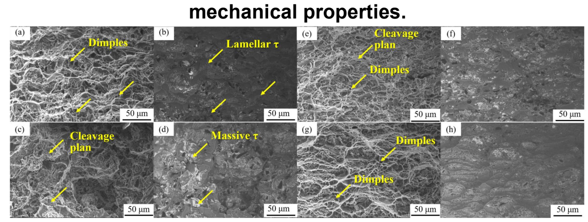

Figure 4 SE and BSE fractography of the as-cast 0Mg(a-b), 2Mg(c-d), as-rolled 0Mg(e-f), and 2Mg(g-h) composites.

4 Conclusion

In the present work, a B_4C_p/Al-5Cu-4.5Gd-xMg (x=0, 2) composite material with high neutron shielding ability and desirable mechanical properties was designed and prepared by the stir casting method, and the effect of the addition of Mg on the microstructure and properties of the composites was investigated. The addition of Mg did not form a new second phase, instead, it was dissolved in the Al matrix and the τ_1 phase. The τ_1 phase altered from reticular to massive because Mg reduced the diffusion coefficient and inhibited the growth of the τ_1 phase. The addition of Mg improves the YS and UTS due to solid solution strengthening and the refinement of the second phase, while hot rolling improves the properties as a result of the broken second phase which reduces the stress concentration.

Acknowledgments

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