Fabrication and Welding of Aluminum Matrix Composite Reinforced with WC and B_4C Particles

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Abstract

High content of B_4C (B-10) and WC hybrid reinforced Al matrix composite plate with combined shielding of neutron and γ radiation was fabricated using powder metallurgy (PM) method. The composite had high strength and exhibited good hot workability for being forged and rolled. In addition, the composite was successfully friction stir welded (FSW). The tensile strength of the as-welded joint was more than 80% of T6-treated base material and increased to over 95% after T6 temper.

1. Introduction

Over the past 60 years, nuclear power has been widely used all over the world. Accompanied with energy production, more and more spent fuels which still maintain high level radiation of neutron and other rays have also been produced in nuclear reactors. Therefore, issues of disposition of spent fuels including storage and transportation have been raised. In this case, neutron absorber materials are widely used for spent fuel dense storage racks and transportation casks to shield radiation and maintain a subcritical condition of spent fuels and there by prevent a criticality incident [1].

As main neutron absorber materials, cadmium has an excellent neutron absorber cross-section but shows toxicity to livings and low melt point [2]. Boron/stainless steel exhibits lower absorber effect due to low content of boron in steel as brittleness concerned (lower than 2.25 wt% [1]). And for boron containing polymer, short aging life makes it unreliable in wet storage circumstance [1, 3].

In the past decades, B_4C reinforced aluminium alloy (B_4C/Al) composites have been proved to be effective neutron absorber materials, especially for wet storage applications [1]. A number of attempts have been conducted for mass production of the composites. While interface reaction between B_4C and Al in the composites fabricated by liquid method seriously deteriorates its mechanical, corrosion and other properties [4], PM method is more suitable for fabricating B_4C/Al composites. At present, studies on B_4C/Al composites for spent fuels are mainly focused on evaluating their neutron absorbing, the shielding to other radiation, such as γ radiation from spent fuels has been ignored.

Considering light and compact design for storage container, it is interesting to develop a composite with combined shielding capabilities of neutron and γ radiation and supeirior mechanical properties. In this study, we incorpotated WC and B_4C particles into 2009Al to fabricate a 2009Al-20vol%B_4C-12vol%WC composite. Furthermore, the composite was subjected to FSW. Interface, microstructure and mechanical properties of the composite and the FSW joint were investigated.

2. Experimental

The 2009Al-20vol%B_4C-12vol%WC composite used in this study was fabricated using PM method. The 2009Al powders (Al-3.5 wt%Cu-1.5 wt%Mg), with an nominal diameter of 13 μm were blended with 20vol% B_4C particles and 12vol% WC particles with respective nominal sizes of 7 μm and 2 μm for 8 h.

The blended powder was cold compacted and then consolidated by hot-pressing at 600 ℃ and at a pressure of 100 MPa for 2 h in vacuum, followed by hot forging at 480 ℃. The forged billet was then hot rolled into a sheet 1.5 mm in thickness, with a thickness reduction ratio of 15:1. Two sheets after T6 treatment (solutionized at 515 ℃ for 2 h, water quenched, and then artificial aged at 175 ℃ for 4 h) were butt-welded along the rolling direction using a FSW machine at a welding speed of 100 mm/min and a tool rotation rate of 800 rpm. A FSW tool with a cylindrical pin 5 mm in diameter and 1.2 mm in length and a shoulder 12 mm in diameter was used.

The microstructures and interface of the as-pressed, as-rolled and as-welded composites were observed using SEM, OM and XRD. Tensile specimens were cut from the as-rolled sheet and the joints with a gauge thickness of 1.5 mm and a gauge length of 25 mm. The axis of the specimens was parallel to the rolled direction and vertical to the welding direction, respectively. The as-rolled and part of the as-welded specimens were subjected to T6 treatment.

3. Results and discussion

3.1 Interface reaction

Fig. 1 shows the XRD patterns of the as-pressed billet and the nugget of the as-welded sample. It is evident that there exists WAl_{12} in the composite besides Al, WC and B_4C in different samples. This indicates that an interface reaction between Al and WC particles occurred during the fabrication process due to the high hot-consolidated temperature [5, 6]. Besides WAl_{12}, no other interface reaction product was observed in both samples.

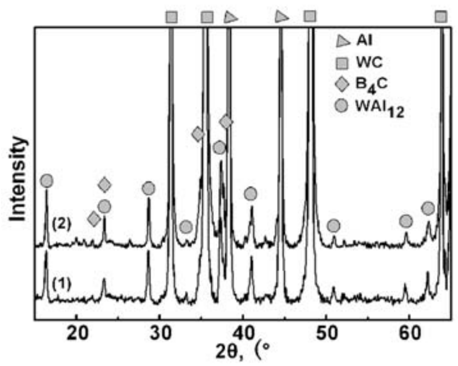

Fig. 1 XRD patterns of 2009Al-B_4C-WC composite: (1) as-pressed (2) nugget

The XRD patterns did not show noticeable difference between the as-pressed sample and the nugget of the FSW sample. This indicated that FSW process did not promote the reaction between WC and Al significantly, even though FSW was reported to facilitate chemical reaction among different phases by severe deformation and mixture [7].

3.2 Microstructure characterization

Fig. 2 shows micrograph of the as-pressed billet, as-rolled sheet, the weld joint and the weld nugget zone (NZ) of the 2009Al-B_4C-WC composite. The white, gray and black regions correspond to WC particles, Al matrix and B_4C particles, respectively.

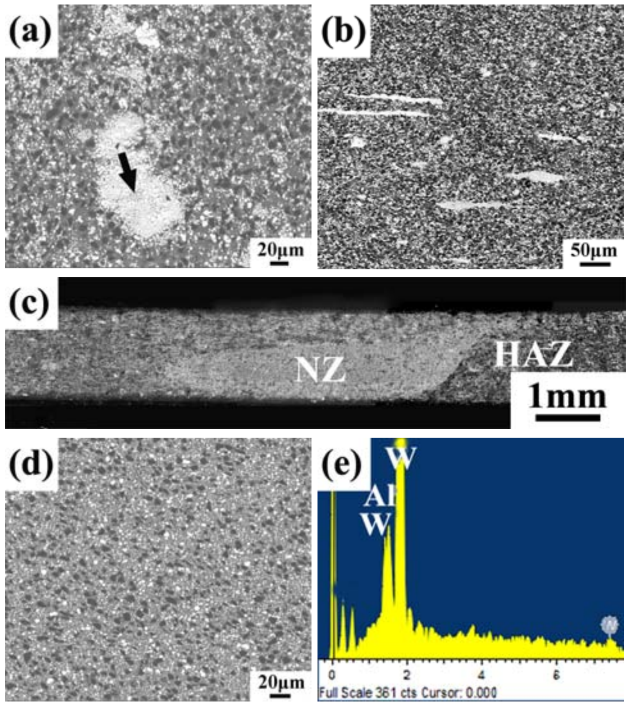

Fig. 2. SEM and OM images of 2009Al-B_4C-WC composite: (a) as-pressed (SEM), (b) as-rolled (SEM), (c) as-welded (OM), (d) nugget zone (SEM), (e) EDS of the spot marked by the black arrow in image (a).

The SEM images show that there were no discernible voids in all the samples. Although high content stiff reinforcement existed in matrix, the workability of the present composite for forging and rolling was good. While B_4C particles exhibited a uniform distribution in the matrix, the distribution of WC particles was not very uniform in the as-pressed and as-rolled samples. Some huge WC clusters more than 50 μm in diameter and strips more than 100 μm in length can be seen in the as-pressed billet and as-rolled sheet, respectively (Fig.2(a), (b)). Some aluminum infiltrated into the WC clusters as identified by EDS analysis (Fig. 2(e)). Because of the tiny size of the interface reaction product, WAl_{12}

could not be detected under SEM. After FSW, the distribution of WC particles was significantly improved in the nugget zone.

The difference in distribution of B_4C and WC particles in the 2009Al matrix resulted from the close density of B_4C particles (2.52 g/cm^3) compared with Al powder (2.7g/cm^3), and the big density difference between Al and WC particles (15.6g/cm^3). Furthermore, the big difference in size between WC particles and Al powder also produced a negative effect on the uniform distribution. Because the uniform distribution of the particles is a basic requirement for supplying adequate shielding of neutron and other radiation, the WC clusters indicated that the traditional mechanical blending methods should be optimized to obtain a more homogenous distribution of WC and B_4C particles in the matrix.

FSW process improved the distribution of reinforcing particles significantly due to intense stirring effect of threaded rotating pin [7, 8]. There were no evident changes of the particle size and shape after FSW which indicated the damage to the particles caused by FSW was not significant.

3.3 Mechanical properties

Tensile properties of the 2009Al matrix, the T6-treated plate, the as-welded joint and the T6-treated joint are shown in Table 1. It is noted that the as-rolled composite exhibited a significant increase in ultimate tensile strength from 465 MPa to 553 MPa compared with the unreinforced 2009Al with T6 temper, but the elongation decreased drastically from 8% to 0.5%. The low ductility was attributed to high content of stiff reinforcing particles. And the clusters of WC also decrease the elongation [9, 11].

Table 1 also shows that the FSW successfully joined 2009Al-20vol%B_4C-12vol%WC composite, producing a joint efficiency of more than 80%. After T6 temper, this efficiency increased to 95%, different from the results from Refs. [4, 10] which was attributed to abnormal grain growth. However, the abnormal grain growth did not happen in the present composite because of the high content of reinforcement and the tiny WC particles. The fracture locations of the T6-treated joints were random. It demonstrates that the nugget, the heat affect zone (HAZ) (Fig. 2(c)), and the base material have similar mechanical properties after the T6 process.

Table 1 Tensile properties of 2009 Al matrix, T6-treated plate and weld joint of the composite with and without T6 temper.

Samples	Yield strength, MPa	Tensile strength, MPa	Elongation, %
AA2009	420	465	8
Composite	450	553	0.5
Joint	-	450	-
Joint/T6	475	531	0.8

The failed locations of the as-welded samples were distributed in HAZ. And the WC strips with some microcracks were found in all of the failed locations of these samples (Fig. 3(a, b)). That indicated that some WC strips in the HAZ facilitate fracture. This implies that the WC strips in this composite, as a kind of particle clustering, deteriorating the strength of the weld joints and the composite [11].

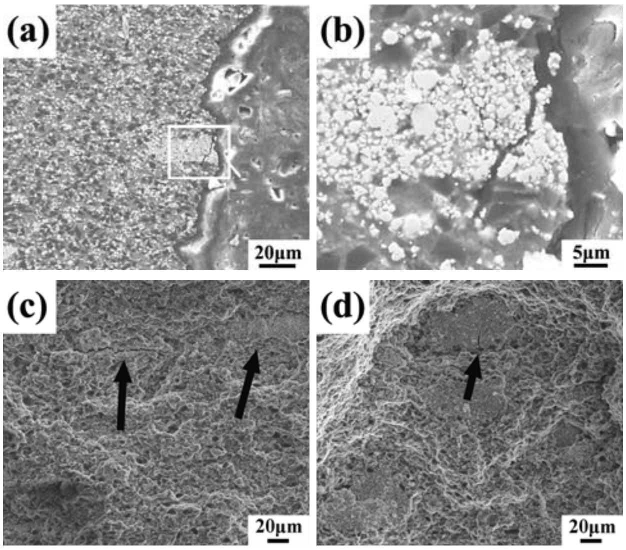

Fig. 3 SEM images of failed location and fracture surface of the composites: (a) failed location, (b) detail with large scale of the white square zone in image (a), (c) as-rolled, (d) as-welded.

The fractographs of both the as-rolled and as-welded composites showed some microcracks (marked by black arrow in Fig. 3 (c, d)) in the WC cluster. Because of the cluster of WC particles, the infiltration of the aluminum powder with a larger size became very hard. This resulted in a weak cohesion between WC and Al in the WC clusters, which could also lead to the weakness of the clusters of WC.

4. Conclusion

The microstructure, interface reaction and weldability of the 2009Al-20vol%B_4C-12vol%WC composite produced through PM method were investigated in this study and the main results are summarized as following:

1. Traditional PM method can obtain dense billet. But mechanical blend method can not obtain the uniform distribution of WC particles in the Al matrix.
2. There was distinct interface reaction between Al and WC particles.
3. The composite exhibited enhanced tensile strength with a significantly reduced ductility.
4. Joining of the composite was successfully achieved by means of friction stir welding. The joint efficiency was more than 80% and increased to 95% after T6 temper.

5. References

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