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Study on laser welding of AA1100-16 vol.% B_4C metal–matrix composites

J. Guo [a,b,*], P. Gougeon [b], X.-G. Chen [a]

[a] University of Quebec at Chicoutimi, Chicoutimi, QC, Canada G7H 2B1

[b] Aluminium Technology Centre, National Research Council Canada, Chicoutimi, QC, Canada G7H 8C3

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ABSTRACT

Laser welding of AA1100-16 vol.% B_4C metal–matrix composites was explored in the study. It was found that most B_4C particles were decomposed and that needle-like AlB_2 and Al_3BC phases were substantially formed during the welding process without filler. Consequently, a joint efficiency of 63% (UTS) was obtained. The addition of Ti with 150 μm thick foil increased the joint efficiency to 75% due to the decrease of needle-like phase formations. On the other hand, the addition of Ti with filler wire did not show significant tensile property improvement due to the Ti segregation and microstructure inhomogeneity in the weld zone. The fracture surfaces of laser welded joints were investigated to understand the fracture mechanisms.

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1. Introduction

Aluminum-based metal–matrix Composites (MMCs) have been used in automobile, aerospace and defense industries as they provide the opportunity of combining various characteristics such as higher specific modulus and specific strength, better wear resistance and superior properties at elevated temperatures to the aluminum matrix [1–3]. However, manufacturing and processing barriers still exist for their wide application. Challenges pertaining to welding techniques for joining complex structure components must particularly be overcome to enhance the engineering usage of composite materials.

Earlier efforts for joining MMCs have been focused on conventional fusion welding techniques such as the Tungsten Inert Gas (TIG) or the Metal Inert Gas (MIG) because of their relative maturity and their equipment accessibility [4–7]. Problems such as viscous welding pool, porosity, and chemical reaction may arise during the welding process. Sound welds are only achievable with special attention to joint preparation and design, process parameters and the selection of filler metals. Following the rapid development of laser welding and because of its advantage of using a focusable high intensity heat source, it is increasingly used in many industries. In comparison with conventional arc welding techniques, the deep and narrow fusion zone in laser welding produces a much smaller heat affected zone and results in less thermal distortions and mechanical property reductions [8,9]. In addition, the laser welding presents good process flexibility as the laser heat input can be delivered through optic fibers. It can be performed in various environments and no-contact welding can be realized in locations inaccessible to other welding processes. The application of laser welding for joining MMCs reinforced with SiC and Al_2O_3 particles has been reported [10–14]. The majority of investigations have emphasized the effect of the chemical reactions between the reinforcement and the matrix on the joint quality. It was reported that welding parameters and filler materials are significant for minimizing the chemical reaction problem [12,14].

Referred to as a new advanced material, the Al–B_4C MMCs are principally used as a neutron absorber material in spent nuclear fuel storage and transport due to their good thermal conductivity and excellent neutron absorption capability [15,16]. An increasing demand for joining components has been requested for applications with complex structures. However, only a few research works on fusion welding of Al–B_4C MMCs using arc welding processes can be found [4,17]. Problems of porosity, inhomogeneous distribution of B_4C particles and chemical reaction still exist. The current applications of laser welding techniques for joining Al–B_4C MMCs have never been reported. More research works are definitely needed to understand the welding mechanism and to improve the quality of laser welded joints for Al–B_4C MMCs.

The present work is intended to evaluate the feasibility of laser welding for joining the Al–B_4C MMCs. The microstructures of the laser joints with and without Ti filler are characterized by using an optical microscope (OM), a scanning electron microscope

* Corresponding author at: Aluminium Technology Centre, National Research Council Canada, 501 de l'Université Blvd., Chicoutimi, QC, Canada G7H 8C3. Tel.: +1 418 545 5358; fax: +1 418 545 5345.

E-mail address: junfeng.guo@cnrc-nrc.gc.ca (J. Guo).

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(SEM), and an X-ray Diffraction (XRD). The tensile properties of the joints at various conditions are compared to reveal the laser welding potential for Al–B_4C MMCs.

2. Experimental procedures

2.1. Materials

As-rolled 4.3 mm thick plates of AA1100-16 vol.% B_4C MMCs were selected for the study. The nominal particle size of boron carbide in the MMCs products is approximately 17 μm and the matrix is a standard 1100 aluminum alloy. The AA1100-16 vol.% B_4C composite was fabricated by Rio Tinto Alcan via an ingot metallurgy route [3,16]. The cast ingots were hot-rolled with multi-passes of cross-rolling to the final shape. For the laser welding, commercially pure titanium in the forms of foil (150 μm thick) and wire (1 mm diameter) were used as filler metal.

2.2. Welding tests

The plates were first cut into pieces measuring 150 mm long (rolling direction) and 50 mm wide. The welding surfaces were machined into flat. All plates were then carefully degreased with liquid acetone and air dried. A steel brush was used on the plate edges to remove residual smudges and oxide films before the actual welding. All tests were performed with a robotized Nd:YAG laser welding equipment (4 kW max power) in a continuous mode using an optical fiber to deliver the laser power inside a 600 μm laser beam spot at focal point. Welding conditions are generally divided into three groups: without any filler, with Ti foil and with Ti filler wire. No gap was left between two plates to butt weld. A schematic of laser welding with Ti filler foil is shown in Fig. 1 as an example. During laser welding with a Ti foil, an aluminum backing plate was used to keep the Ti foil layers in position. The amount of Ti added was controlled by adjusting the number of foil layers or the feeding rates of the filler wire. The detailed parameters are listed in Table 1. An argon shielding gas was used at a flow rate of 20 L/min. The laser welding head had a focal length of 200 mm and was pushed 10° away from the vertical axis to avoid possible damage to the laser optics from the beam reflection. Finally, a 20 s preheating was applied on the welding plates using an electric heat-gun.

2.3. Material characterization

Laser welded samples were transversely sectioned and metallographically polished. Microstructures of the welds and the base material were then characterized using an optical microscope (OM) and a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). Qualitative phase analysis was carried out using the SEM/EDS and XRD techniques. The Vickers microhardness profiles across the weld were measured using a load of 100 gf in the fusion zone and 10 gf in other zones. The transverse tensile tests were carried out according to the ASTM E8-04 standard at a test speed of 1 mm/min. Rectangular flat specimens of 50 mm long and 12.5 mm wide gauge in the reduced section were used. The tensile properties of each joining condition, namely the ultimate tensile strength (UTS), the yield strength (YS) and the fracture elongation (ε), are the average values of a minimum of three tensile samples.

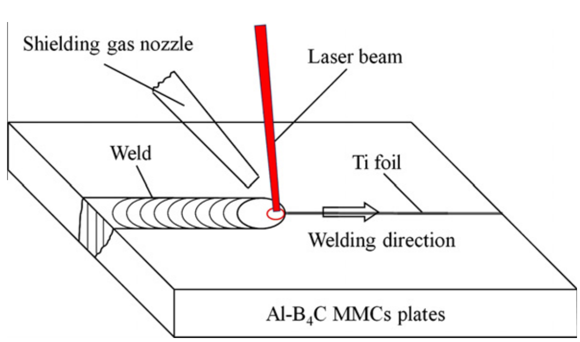

Fig. 1. Schematic of laser welding with a Ti filler foil.

3. Results and discussion

3.1. Microstructural characterization

3.1.1. Laser welds without filler

Fig. 2a shows a typical macro-view of joints without filler indicating that a sound joint can be obtained. The base material consists of aluminum matrix and B_4C particles which are uniformly distributed in the matrix (Fig. 2b), while the laser weld zone consists of a large number of needle-like phases and some B_4C residues (Fig. 2c and d). The EDS analysis under SEM reveals that these needle-like phases are Al–B–C and Al–B compounds and the XRD results confirm that both phases are Al_3BC and AlB_2 respectively (Fig. 3). In the weld pool, the following chemical reaction took place:

$$9Al(l) + 2B_4C(s) \rightarrow 3AlB_2(s) + 2Al_3BC(s) \quad (1)$$

Two intermetallic phases, AlB_2 and Al_3BC, are produced at the expense of the B_4C decomposition which is similar to the interfacial reaction occurring under conventional casting conditions [18] although the peak temperature in the laser weld pool is reported to be much higher (above 980 °C) [19,20]. The needle-like phases can promote high stress concentrations at the interface between the matrix and the needles and can be very harmful to the mechanical properties of the material. Thus, the prevention of the needle-like phases is preferable to improve the mechanical properties. During the tests, different energy inputs were then applied by varying the laser power from 2 to 4 kW and the welding speed from 1 to 2.5 m/min. However, the needle-like morphology of both intermetallic phases was not changed to a noticeable level. In the laser welding of Al–SiC MMCs, it was reported that the size and the amount of the needle-like reaction product, aluminum carbide, could be modified by varying the laser energy input [12]. Formation of the needle-like phase was constrained in both size and quantity by decreasing the laser energy input. The formation of needle-like phases in Al–B_4C MMCs does not seem sensitive to the welding process parameters in conditions tested. Therefore, an alternative method must be found to effectively limit the harmful needle-like phases.

3.1.2. Selection of filler material

A method to modify the microstructure of the weld zone is to find an effective filler material that has a higher affinity to the specific elements than that of Al. As indicated in [18], addition of Ti filler seems particularly promising to modify the microstructural compounds in the Al–B_4C system. The standard Gibbs free energy formation of possible carbides and borides in the Al–B_4C system are calculated from data [21] and the results are illustrated in Fig. 4. An approximate comparison could be made if both carbon and boron atoms could be balanced. Compared to aluminum, it is obvious that titanium has shown a much greater affinity to boron and carbon under standard conditions. It can therefore be expected that the titanium addition would change the microstructure of the Al–B_4C MMCs laser weld zone. The ideal amount of Ti addition

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