Influence of CO_2 Laser Beam Welding on Microstructure of Aluminum Metal Matrix Composites Reinforced With Al_2O_3 Particles.

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ABSTRACT

The continuous CO_2 laser beam welding of two aluminum metal matrix composites (6061 and 2618 reinforced with 20% of Al_2O_3) has been investigated with special attention to the influence of the base alloys, the filler material and the process parameters on the microstructure of the welding bead. In this work square butt welding has been obtained with different CO_2 laser power, feed rate and shielding gases. The microstructure of the welding beads has been examined by optical and electronic microscopy. A migration of the Al_2O_3 reinforcement particles from the fusion zone (FZ) towards the heat affected zone (HAZ) has been detected and the particles agglomerate near the interface FZ-HAZ. An increase in both porosity and agglomerate sizes inside the welding bead has been observed as the feed rate has been reduced. The hardness of welding beads has been higher than the unaffected composites. A reduction of both the beads hardness and the Al_2O_3 migration and agglomeration has been obtained by the use of magnesium-rich filler material in the welding process, probably because magnesium is able to increase the reinforcement wettability, and to reduce the rate of formation of spinel phase $MgAl_2O_4$. The use of Ar as shielding gas was the most effective, both in order to avoid the development of porosity and to reduce the Al_2O_3 agglomeration.

INTRODUCTION

Aluminum metal matrix composites (MMCs) have established mechanical properties that are sufficiently useful to stimulate continuing developments. The use of MMCs for structural applications has been restricted by the difficulties of fabricating and joining these composites, especially when conventional fusion welding techniques are used. If fusion welding is attempted, the liquidus temperature of the base alloys is exceeded and a remarkable worsening of mechanical characteristics occurs at the joint due to behaviors as the precipitation of brittle phases, the formation of cracks and porosity. So, for useful structural components to be made in MMCs it is necessary to develop welding systems to preserve the mechanical properties of the materials.

Several conventional fusion welding methods of aluminum MMCs have been studied in the past, such as: Tungsten Inert Gas Welding, Metal Inert Gas Welding, Electron Beam Welding /1-2/, Plasma Spray Joining /3/, Capacitor Discharge Welding /4/, Laser Beam Welding /5-8/. Other techniques, such as diffusion bonding, have been useful for producing joints with good high-temperature properties. Since these methods frequently require vacuum or hot pressing equipment, their practicality is limited. The laser beam welding has developed rapidly and has obtained a remarkable importance in industry owing to its flexibility and its high shape ratio. In fact, with the laser welding process is possible in theory to produce joints with a very low impact on the microstructure of the materials, because the laser welding process has high energy density provided, both the heat affected zone and the deformations caused in the materials can be reduced. This makes the technique suitable when high production rates and high precision joining are required. The operational setting of a laser beam welding process of metal matrix composites is rather complicated by the high reflectivity, conductivity and the low ionization energy of the aluminum matrix. Aluminum is undoubtedly one of the most difficult materials for laser processing because of its low emissivity compared to most other metals. The addition of reinforcement particles to the aluminum alloys should improve the energy absorption and the overall effectiveness of the laser joining. However, the high viscosity of the melt, the development of porosity, the possibility of a reaction between the reinforcement with the matrix, and the risk of reinforcement segregation, make the laser beam welding of aluminum MMCs difficult.

Most of the work reported on laser welding has involved the Al/SiC MMCs system. Unfortunately, CO_2 laser welding has shown limited success in the welding of certain types of Al-Si/SiC MMCs /5/.

In this work the continuous CO_2 laser beam welding of aluminum metal matrix composites has been investigated with special attention to the influence of the base alloys, the filler material and the process parameters on the microstructure of the welding bead.

EXPERIMENTAL

Bars 30 x 6 mm in section and 80 mm in length, of two aluminum metal matrix composites reinforced with 0.20 volume fraction of Al_2O_3 particles were used. The chemical compositions of the alloys are summarized in Table 1 and mechanical characteristics in Table 2. A 1.2 mm diameter wire of a rich magnesium aluminum alloy was used as filler material. The chemical composition of the filler material is reported in Table 1.

Square butt welding was carried out with a CO_2

Table I

Chemical composition of matrix alloys and filler material

Alloys	Si %	Cu %	Mg %	Cr %	Mn %	Fe %	Ni %	Ti %
6061	0.60	0.28	1.00	0.20	-	-	-	-
2618	0.18	2.30	1.60	-	-	1.10	1.00	0.07
ER5356	-	-	5.00	0.12	0.12	-	-	0.13

Table 2

Mechanical characteristics of materials.

Materials	E (Gpa)	Rm (Mpa)	Strain %	Density (g/cm^3)
Alloy 2618	74	440	10.0	2.71
Alloy 6061	69	316	17.0	2.73
Reinforcement Al_2O_3	380-450	2	/	3.96
Composite 2618/20% Al_2O_3	100	500	1.0	2.75
Composite 6061/20% Al_2O_3	98	379	2.1	2.78

ROFIN–SINAR laser (ROFIN-SINAR Inc., Plymouth, MI, U.S.A.) up to a maximum average output power of 6 kW. The operating parameters of the laser were: wavelength of 10.6 μm, spot diameter of 0.5 mm, beam polarization of 45° and focal spot on the samples surfaces. Square butt welding was obtained with powers of 6 and 4 kW and feed rate of 8, 6 and 4 m/min without filler material and feed rate 4, 3.5, 3 and 2.5 m/min with filler material. Nitrogen, helium and argon, with purity of 99.99 %, were employed as shielding gas with a 5 dm^3/min flow rate.

Sample microstructures were examined by optical microscopy and scanning electron microscopy (SEM) equipped with energy dispersion spectroscopy (EDS). The microhardness profiles were obtained with a Leitz-Werlag microhardness tester (Leitz-Werlag, Germany) with 100 g weight at 0.1 mm from the sample's edge (upper zone) and in the middle of the welded zone (lower zone). Agglomerate size evaluation was made on several cross sections of the reinforced samples, using Image Pro-Plus (Media Cybernetics, Silver Spring, MD, U.S.A.) image analysis software.

RESULTS AND DISCUSSION

Butt welds performed at 6 kW exhibit the maximum laser beam penetration inside the samples. The welding beads obtained show the migration of Al_2O_3 particles from the fusion zone towards the heat affected zone to make large agglomerates of Al_2O_3 particles at the interface fusion zone-heat affected zone (Fig.1). This behavior is stronger at lower feed rate and leads to depletion of reinforcement in the center of the weld joint, inside the fusion zone. The migration of Al_2O_3 particles can be attributed both to the effect of the strong interaction between Al_2O_3 with the laser wavelength, and to the high laser power.

The evaluation of the agglomerates size, made on several cross sections of the welding beads (Fig. 2), shows that the Al_2O_3 particles assemble in larger size agglomerates in the fusion zone near the interface fusion-heat affected zone, as the feed rate decreases. The migration and agglomeration produce a particle free zone in the fusion zone, which reduces the mechanical properties of the joint.

Fig. 1: Welding bead side of 6061 composite reinforced with 20% Al_2O_3. The arrow indicates a large reinforcement agglomerate on the welding bead.

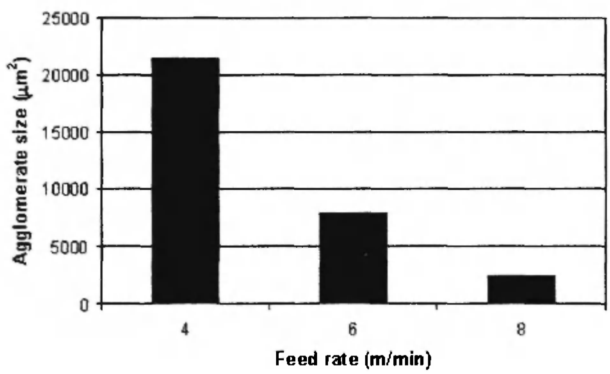


Fig. 2: Average agglomerate size vs. feed rate of a 2618/20% Al_2O_3 composite, welded with laser beam power of 6 kW.

Moreover, an increase in porosity is observed in the center of the cross sections of the welding beads, at lower feed rates (Fig. 3). The porosity problem appears more severe in 6061 composites than in 2618 composites, as reported in Fig. 4. However, a reduction in both the number and the size of pores in the welding beads is obtained when a magnesium-rich filler material as ER5356 is used in the welding process. Magnesium, besides preventing the reinforcement dewetting /1/, also seems to stabilize the plasma formation /8/. Plasma is formed when vaporized material in the keyhole absorbs the laser beam and dissociates in ions /9/. Kawall and

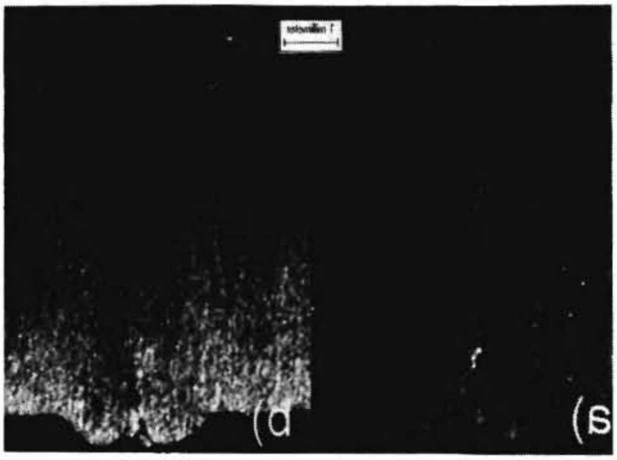


Fig. 3: Welding bead cross section of a 6061/20% Al_2O_3 composite, welded with laser bema power of 6 kW at a) 4 m/min and b) 8 m/min feed rates.

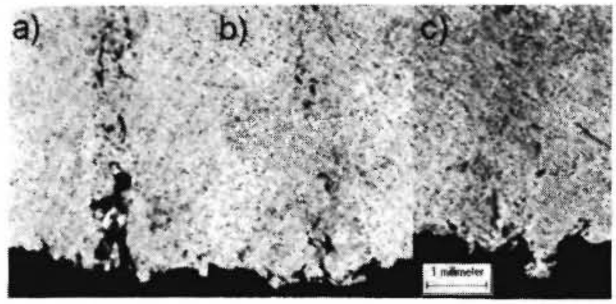


Fig. 4: Welding bead cross sections of a) 6061/20% Al_2O_3 composite, b) 2618/20% Al_2O_3 composite, c) 2618/20% Al_2O_3 composite with filler material. The laser beam power was 4 kW and the feed rate was 6 m/min for the samples a) and b), while it was 4 m/min for the sample c).

co-workers found that the explosive expansion of plasma was the main cause of generation of pores /8/. Then, the high magnesium content in ER5356 filler material avoids the explosive expansion of plasma during the laser beam welding process, inducing a depletion of porosity. Moreover, probably the lower magnesium content in 6061 alloy is responsible for the difference in porosity inside the joint.

An increase in hardness is recorded inside the welding beads obtained without filler material. As reported in Figure 5, the microhardness profiles, obtained for the 6061 welding bead at 0.1 mm from the surface of the sample (upper zone) and at about 3 mm from the surface (lower zone) show higher values in the welded zones than in the unaffected material. This increase in hardness appears higher especially in the lower zone.

This behavior may be due to chemical reactions between the reinforcement and the magnesium in the alloy. The chemical reactions are likely to be:

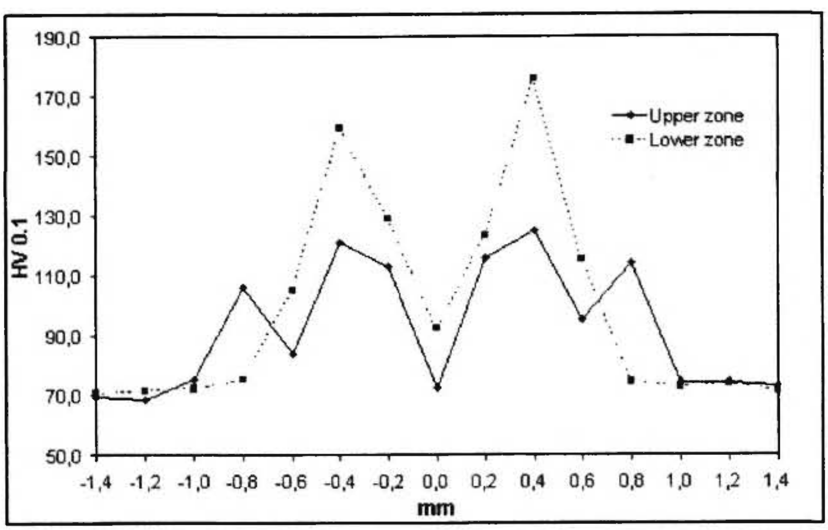


Fig. 5: 6061 joint microhardness profiles (Power = 4 kW, Rate = 6 m/min).

$$3\,Mg + Al_2O_3 \longrightarrow 3\,MgO + 2Al \qquad (1)$$

$$3\,Mg + 4\,Al_2O_3 \longrightarrow 3\,MgAl_2O_4 + 2\,Al \qquad (2)$$

Martinelli and co-workers /10/ found that the chemical reaction (2) gives rise to the precipitation of a hard $MgAl_2O_4$ spinel phase that grows on the surface of the Al_2O_3 particles, depleting the magnesium content of the surrounding alloy. The thin spinel crystals act as notches at the reinforcement ·surfaces, which become more prone to fail under load. From the literature, the rate of reaction (2) is considerably reduced by alloys with high magnesium content /5/. Our experimental results confirm that the formation of $MgAl_2O_4$ is promoted by low magnesium content in aluminum alloys. In fact, the increase in hardness in the weld beads of 2618 matrix composites appears lower than in the 6061 matrix composites welding beads (Fig 6). Moreover, the use of a magnesium-rich filler material such as ER5356 alloy, in the laser welding process, besides reducing the Al_2O_3 migration and segregation, also depletes the hardness of the welding beads (Figs. 7-8),

The formation of spinel phases is observed by SEM investigation on the surface of Al_2O_3 particles inside the welding beads obtained without filler material. As reported in Figure 9, after laser welding, two phases are generated on the surface of the reinforcement particles. The small octahedral phase is identified by EDS analysis as a spinel phase $MgOAl_2O_3$, while the larger amorphous phase appears to be a non-stoichiometric magnesium silico-aluminate. Moreover, the absence of the intermetallic precipitates containing Fe, Ni, and Cu is observed. This is because the high cooling rates obtained in the laser welding process do not allow the precipitation of intermetallics from melt.

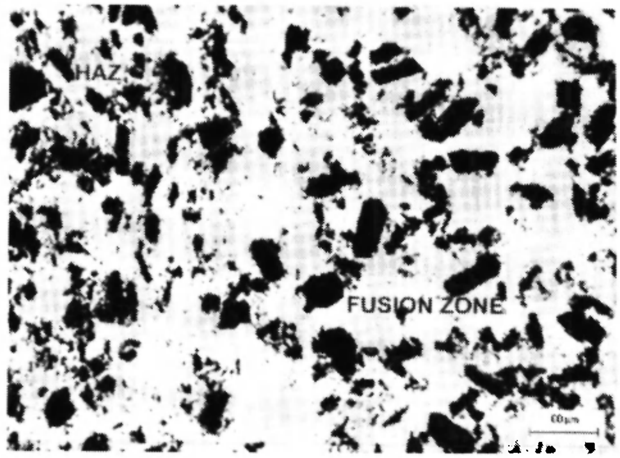


Fig. 7: Weld bead of 6061/20% Al_2O_3 composite material joined with ER5356 filler material (Power = 4 kW, Feed Rate =4 m/min).

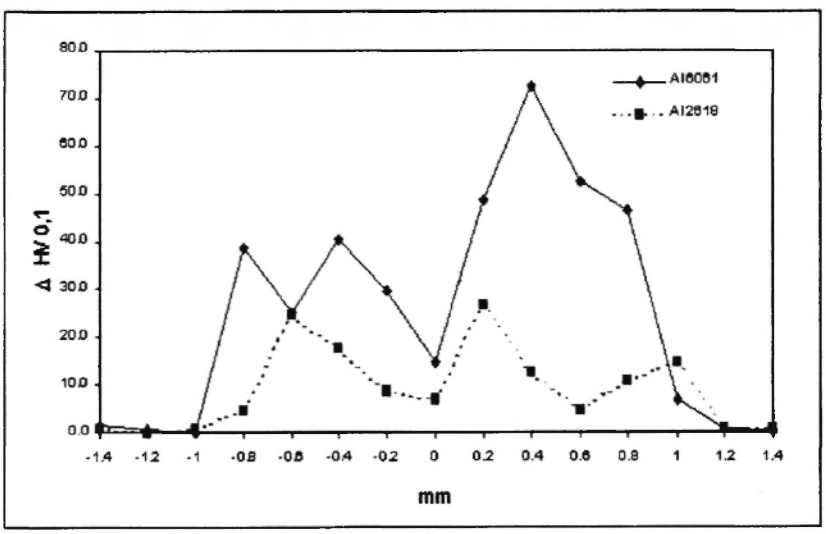


Fig. 6: Differences in microhardness profiles of laser welded 6061 and 2618 composite materials (Power = 4 kW, Feed Rate = 4 m/min).

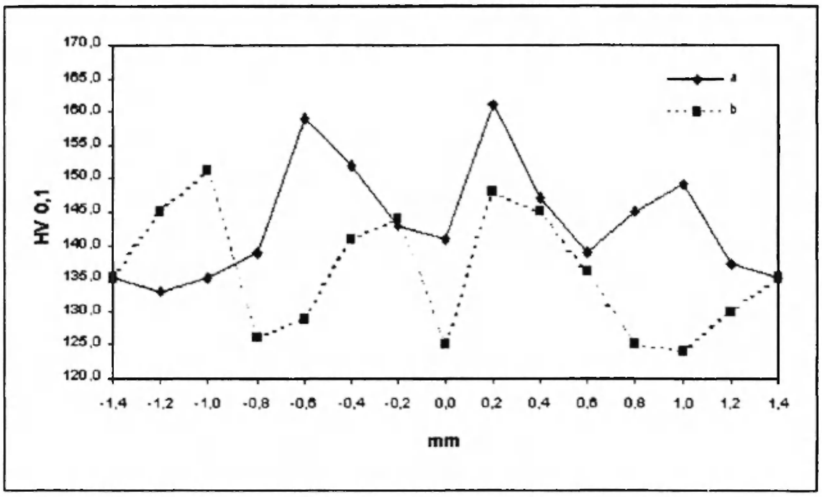


Fig. 8: Microhardness profiles in the welded upper zone of 2618 samples joined without a) and with b) filler material (Power = 4 kW, Feed rate = 4 m/min).

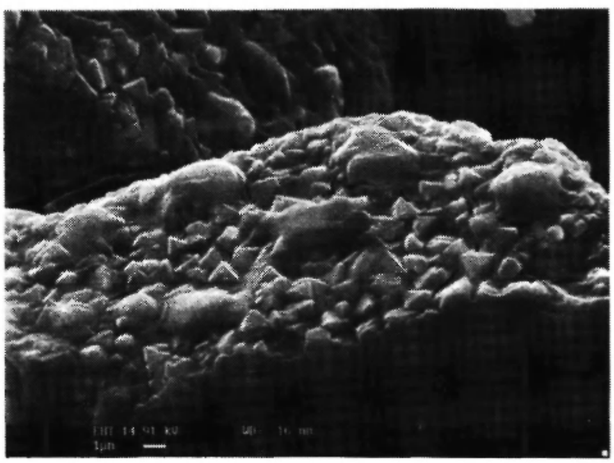


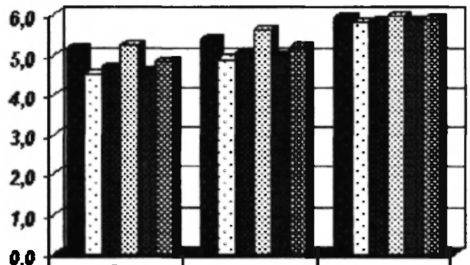
Fig. 9: SEM image of a Al_2O_3 particle in the welding bead of a 6061/20% Al_2O_3 composite joined without filler material.

Several shielding gases were tested during the welding operations. In Figure 10, the laser beam penetration in function of both the shielding gas and the feed rate of the process is reported. When nitrogen is used as the shielding gas, the obtained joints show a low laser beam penetration, a fairly good bead finishing, and a clear formation of both porosity and segregation. When helium is used, an increase in laser beam penetration is recorded but, at the same time, increased porosity and worse welding beam finishing occur. The use of Ar as shielding gas appears very effective both for avoiding the development of porosity and reducing the Al_2O_3 segregation.

CONCLUSIONS

This investigation on the weldability with CO_2 laser beam of Al MMCs, reinforced with 0.20 volume fraction of Al_2O_3 particles, has emphasized the following microstructural modifications, that deplete the mechanical properties of the joints:

- the migration of Al_2O_3 reinforcement particles from the fusion zone towards the heat affected zone. Moreover, the reinforcement particles assemble in larger size clusters, especially when low feed rate were used. This behavior is less marked as the power was reduced;
- the precipitation of a $MgAl_2O_4$ spinel phase on the surface of Al_2O_3 particles, which increases the joint hardness. This is probably promoted by low magnesium content in aluminum alloys;
- the formation of porosity inside of the welding beads. This appears more severe in the 6061 alloy than in the 2618 alloy.
- The use of Ar as shielding gas was the most



	8	6	4
6061 helium	5,2	5,4	5,9
6061 nitrogen	4,5	4,9	5,8
6061 argon	4,7	5,1	5,9
2618 helium	5,3	5,6	6,0
2618 nitrogen	4,6	5,0	5,9
2618 argon	4,8	5,2	5,9

Fig. 10: Laser beam penetration for different shielding gas.

effective both in order to avoid the development of porosity and to reduce the Al_2O_3 segregation.

The use of a magnesium-rich filler material is effective to reduce both the welding beads hardness and the Al_2O_3 agglomeration, since magnesium is able to increase the reinforcement wettability. Moreover magnesium also seems to stabilize the plasma formation, and welds obtained with a magnesium-rich filler material show a reduced porosity.

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