HIGH POWER DIODE LASER WELDING OF HIGHLY REINFORCED SIC / AL COMPOSITES

Joaquin Rams, Manuel Ferrer, Claudio J. Múnez, Alejandro Ureña

Dept. de of Materials Science and Engineering
Rey Juan Carlos University
ES-28933 Madrid, Spain
joaquin.rams@urjc.es

ABSTRACT

Weldability of a metal matrix composite made of aluminum reinforced with 70% of SiC in the form of particles (AlSiC) has been tested. The welding source used has been a High Power Diode Laser (HPDL) and different tests have been carried out. On the one hand we have made some bead on plate tests under different conditions of laser power, laser speed and atmospheres. On the other hand, we have brazed two pieces of AlSiC using an aluminum alloy and different welding conditions have been tested. The effect of the laser welding conditions and atmospheres, and the effect of applying sol-gel silica coatings to the specimen in both type of test has been analysed.

1. INTRODUCTION

The application of metal matrix composites with high contents of ceramic reinforcement in electronics packaging is being investigated since late 80s. The most important candidates within this family are the Al matrix composites reinforced with a high proportion of SiC particles (AlSiC). AlSiC combine the most fitted CTEs, with high thermal conductivity, reduced density and outstanding values of specific strength and stiffness [1, 2].

Current technologies allow to fabricate flat samples made of AlSiC, but to obtain more complex shapes different processing technologies are needed. Among them, welding or brazing are cost effective technologies to obtain complex and even hermetic structures made of AlSiC. Welding of aluminium matrix composites is still under development and a number of techniques are being considered: diffusion welding [3], transient liquid phase [4] or friction-stir welding [5] are being studied, as well as techniques in which the material is molten such as TIG, MIG, plasma, laser, electronic beam welding [6 – 9] or heterogeneous welding technique (i.e. brazing in vacuum) with different success [10].

There is a double problem in the joining of AlSiC with conventional fusion techniques: on the one hand it is the high reactivity that takes place between SiC and molten aluminium which produces aluminium carbide, a brittle and hygroscopic compound that strongly reduces the material properties. On the other hand, the reduced wettability of SiC by molten aluminium causes a tendency to generate porosity, heterogeneous distribution of reinforcement and even fusion lacks. Although there are different procedures that are feasible to join SiCp/Al composites with up to 20 % reinforcement rates, none can be used to materials with reinforcement proportions above 60 %, compositions needed for electronic packaging.

In the last years, laser has revealed as a helpful tool in materials processing, showing itself as a very versatile device that can be used in cutting, welding and surface treatment of all type of materials. Ceramics, metals, polymers and composites can be easily joined with this tool. The main problem that traditionally laser technologies have found is the difficulties found to keep it operative at its full capability. However, the new laser equipments such as Nd:YAG, CO_2 and high power laser diode do not need as many maintaining as that needed a couple of years ago. Nd:YAG are nowadays being pumped with diodes instead of flash lamps, meanwhile CO_2 lasers are now made with sealed cavity to minimize maintenance costs. But, independently of the great development of these lasers in the last years, these equipments show other limitations. Most used Nd:YAG lasers are pulsed ones because of the intrinsic nature of neodimium ions. In order to get continuous wave lasers, as those required for metal welding with a high fabrication rates, highly priced equipments are needed and, in the case of using flash lamps pumping, their operative live and energetic efficiency is very small. In the case of the CO_2 lasers, they can operate with high power even in the continuous wave mode, but they have the intrinsic inconvenient of the wavelength of the laser emission. These lasers operate at 10.6 µm, a wavelength at which the absorption of energy in most metals and ceramics is very small. Due to this, much higher powers are needed than those needed with other laser sources. Finally, very few materials, and highly priced ones, are transparent to this radiation. Therefore, the use of windows gets complicated, as well as the use of protective and reactive gases.

High power laser diodes are nowadays available; up to 6 kW diode lasers can be purchased with duty lives longer than with any other lasers, with the advantage of working in continuous wave mode. In fact, CW is the natural working mode of laser diodes. One of the main advantages of these lasers resides in their high energetic efficiency, about 10 times higher that in Nd:YAG lasers. This characteristic has two different implications: on the one hand, the power consumption of these equipments is smaller that other alternative technologies, on the other hand the size, cost and consumption of auxiliary equipments such as coolers or power sources are much smaller [11 – 17].

Among other advantages, high power laser diodes do not have mobile parts or open cavities, therefore alignments are not required and external works are less complicated than with other lasers. Moreover, they are sealed, and their sensitivity to dust or gases from the welding is smaller that in other technologies. Moreover, the cost of these equipments has reduced in the last years and, nowadays, their price is about a fourth part of that of an equivalent Nd:YAG.

In this work we use HPDL to make bead on plate tests as well as brazing on AlSiC samples to obtain continuous seams in the materials. The effect that laser power, laser speed and atmospheres have on the quality of welds is studied.

2. EXPERIMENTS

Laser welds have been made on commercial AlSiC substrates from Electrovac that consist of a composite with 75 % SiC in form of particles and the aluminium alloy used as matrix is an AlSi7Mg alloy (A356). It is a cast alloy that contains 7% Si to improve the infiltration of SiC performs. To get such high reinforcement degree, a bimodal distribution of ceramic particles has been used with average sizes of 46.7 and 5.9 µm for the big particles and for the smaller ones, respectively. The reinforcement distribution is affected by the presence of big spherical zones constituted only by the aluminium alloy that have up to 200 µm diameters.

The as – received dimensions of AlSiC specimens used are 102 × 24 × 2 mm, and they were directly used to make bead on plate tests to determine the weldability of the material. For real welding tests, the substrates were cut down with a diamond toot to make 24 × 30 × 2 mm samples, producing autogenous butt joints between them.

The welding equipment consists of a high power laser diode from Rofin, model DL 13S. It is a laser that emits up to 1400 W of light with a 940 nm wavelength. The minimum focused laser spot can be of only 0.75 mm^2, so up to 187 kW/cm^2 power density are reachable. The laser is placed on an anthropomorphic robot arm of 6 independent axes from ABB (RT2000/16) that allows moving it over the sample surface with controlled position, speed and relative orientation. Moreover, fumes extraction and gas protection can be also automatically controlled. A hermetic chamber with a fused silica window allows making laser welding under the complete protection of vacuum or inert gases.

Different parameters have been controlled in the welding procedure. In particular, powers between 950 and 1250 W have been used; power densities between 1.9 and 2.5 kW/cm^2; and the relative speeds between laser and sample in the 5 to 10 mm/s range have been used. In all cases, laser has been used with nearly perpendicular orientation avoiding that light reflected on the sample surface to get into the own laser.

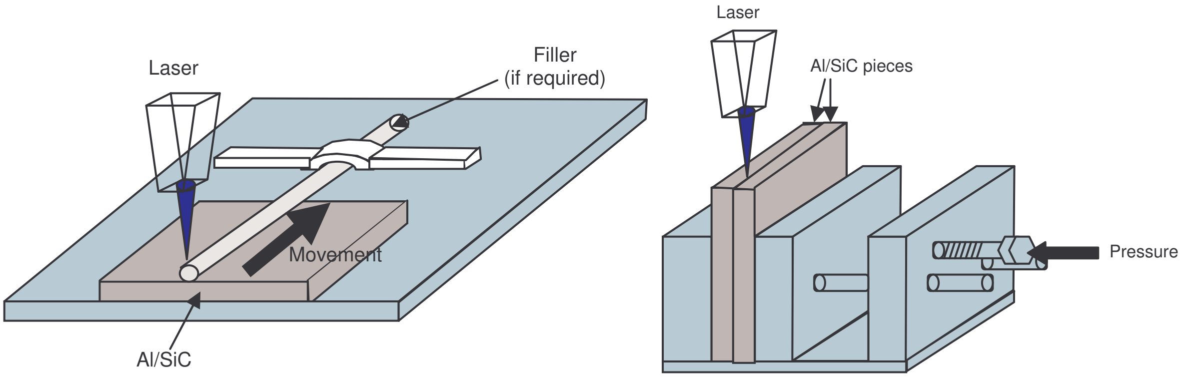

Figure 1. Experimental set-up used.

Two different types of tests were carried out. Bead on plate tests were used to determine the weldability of the samples under different conditions of laser power, laser speed and atmospheres (figure 1 a). Brazing of samples was carried out with a 5356 alloy on specimens fabricated with prepared joint edges using the geometry shown in figure 1b.

To modify further the experimental conditions, some substrates were coated with silica following a sol-gel route. The procedure uses was the following. Silica layers were fabricated from a pre – hydrolyzed solution of the silica precursor. A homogeneous, clear transparent solution was prepared by dissolving tetraethoxysilane in ethanol. The molar ratio was TEOS/C_2H_5OH = 1:11. This solution was only partially hydrolyzed by adding 0.1 M HCl acidulated water (TEOS/H_2O = 1). This mixture stirred for 2 h at room temperature and aged at room temperature for 30 minutes more. This procedure is the one that provides optimal coatings, avoiding the appearance of cracks on the surface of the samples. Coatings were obtained with a withdrawal speed from the sol of 10 cm/min and 35 cm/min. Then, the coatings were dried in an oven at 100 ºC for 1 hour, and afterwards at 500 ºC for 1 hour more, being cooled inside the oven. To determine the nature of the coating, an identical process has been followed in a Cu grating and the results have been compared with coatings made on the aluminium composite.

The welds made have been analysed with the microscope on transversal sections to determine the molten zone and the heat affected zone shapes.

3. RESULTS

During bead on plate tests, the input heat melts the aluminium that constitutes the matrix, which tends to escape from the composite. This phenomenon is caused by the low wettability of SiC and to the high proportion of ceramic phase of the composite. This causes that high capillarity forces may force molten aluminium to find its way out from the composite. During its escaping, aluminium drags small SiC particles and also reacts with SiC forming aluminium carbide, a compound that degrades in humid atmospheres and that is hard and brittle, lowering the toughness of the composite.

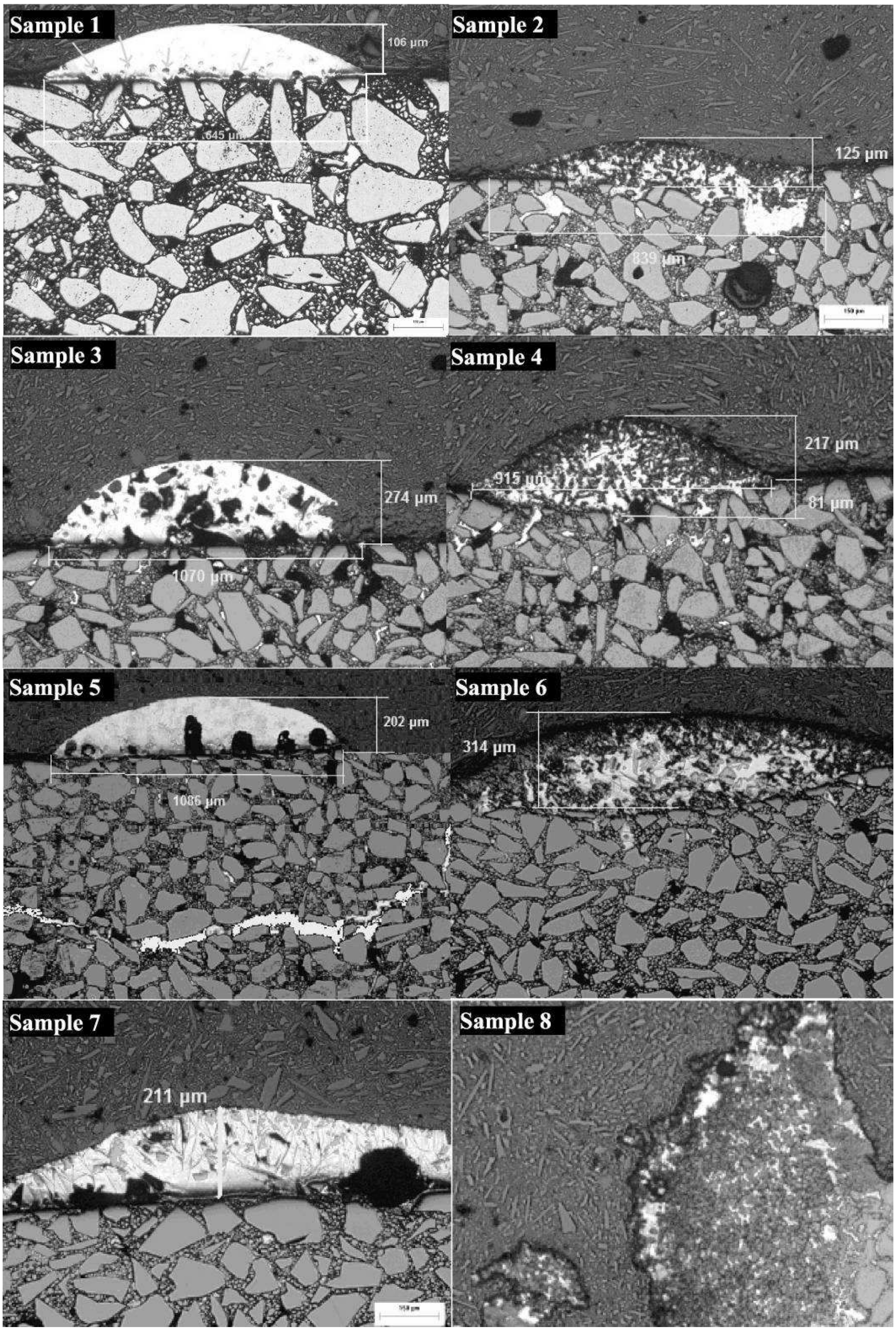

Figure 2. Expulsion of aluminium from the matrix during bead on tests.

The extracted material forms a seam on the top of the composite whose height and width depends on the laser conditions used. Figure 2 shows the transversal sections measured for the different test conditions used: laser power of 950 W (fig. 2a and e) and 1250 W (fig 2b and f); focal areas of 0.5 (fig. 2a, b, e and f), 0.75 (fig. 2c and g) and 0.25 (fig. 2d and h). In the first four cases the laser speed was kept at 10 mm/s and it was reduced to 5 mm/s in the latter four ones.

The main effect of the presence of an aluminium seam over the specimens is that an equivalent volume to that of displaced aluminium appears as porosity inside the samples (figure 3). Because of the low amount of metallic phase, the presence of porosity has an important effect in the mechanical properties of the composites.

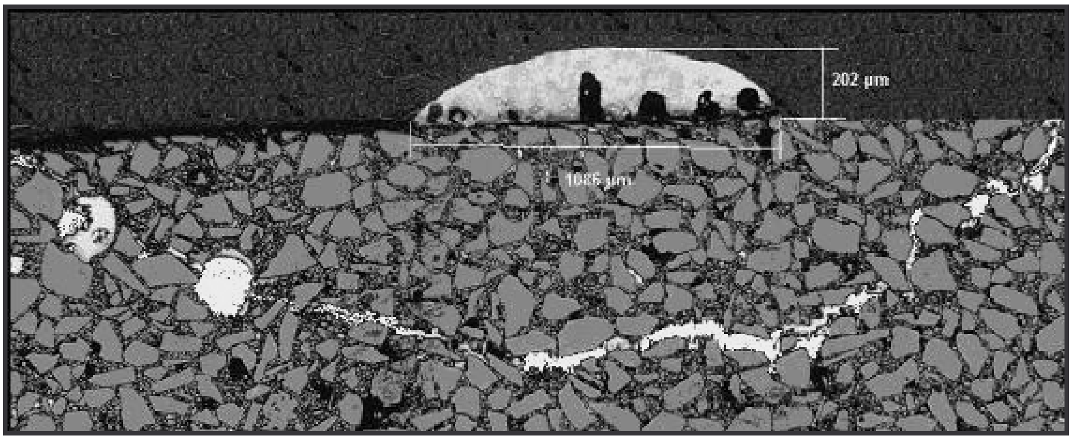

Figure 3. Porosity caused in the composite by means of the aluminium escaping from the matrix.

Apart from surface tension, the main reason why aluminium flows to the surface of the samples is that there is no equilibrating force applied in the opposite direction to that followed by aluminium. To avoid this problem, we have followed to different routes: we have used an increased atmospheric pressure system and we have also placed a physical barrier.

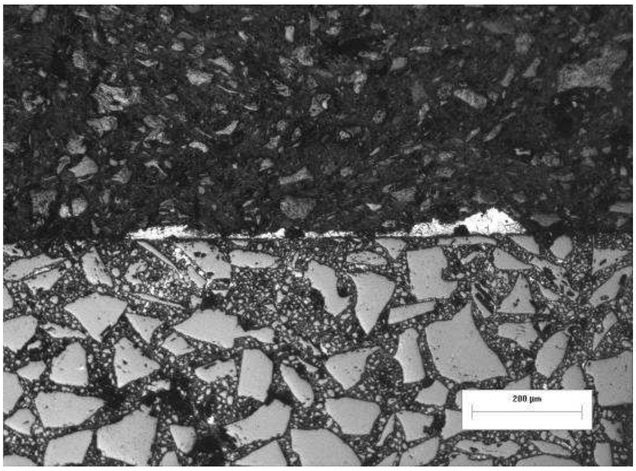

Figure 4. Transversal section observed applying an external gas pressure of 1 bar.

Figure 4 shows the results obtained when the atmospheric pressure was increased to 1.9 bar, i.e. an overpressure of 0.9 bar above the standard atmospheric one, inside the chamber designed. The results can be favourably compared with any of the cases shown in figure 2 because very little aluminium has flown from the composite. The effect of the different condition tested can be observed in figure 5 where it is represented the thickness and height of the seam of the material that was expulsed from the matrix during the bead on plate tests. The higher the use of standard atmospheric pressure reduces the amount of material extracted and the use of overpressure reduces it further.

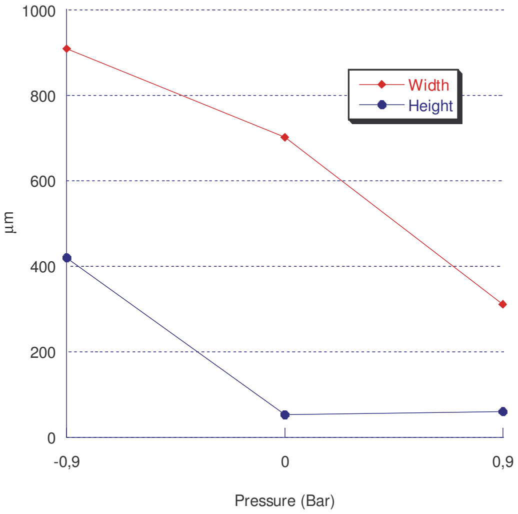

Figure 5. Size of the seam under different argon pressure conditions (laser power: 760 W; energy input 1 900 J/cm)

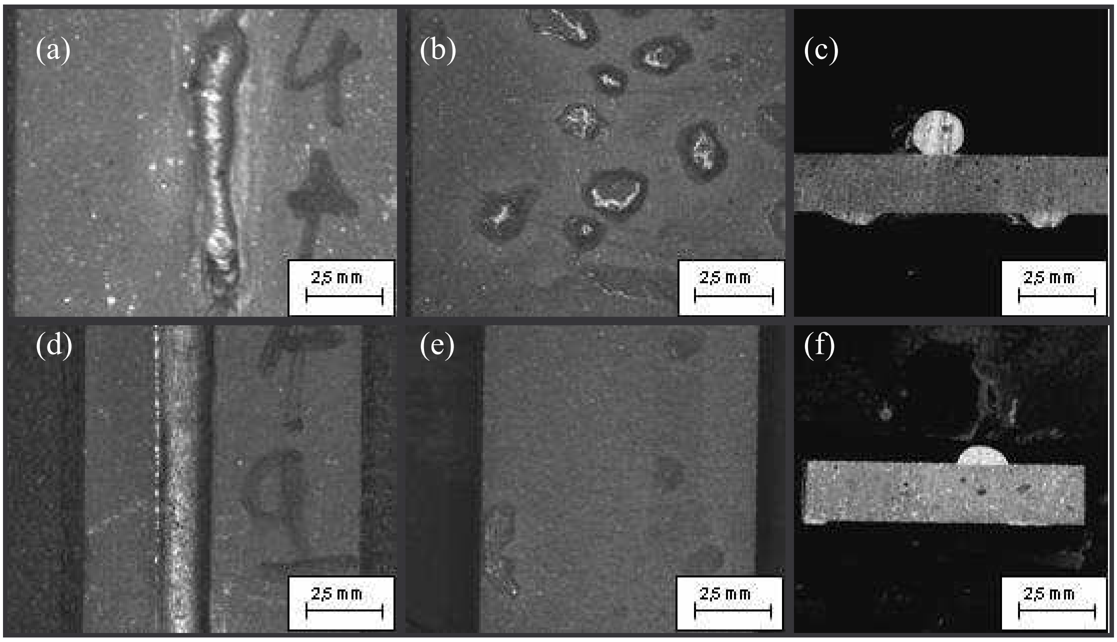

Figure 6. Top, bottom and transversal views of bead-on-plate tests under vacuum (a, b and c) and under an external gas pressure of 0.9 bar (d, e and f).

The behaviour of aluminium from the matrix tending to escape form the composite reproduces when bead-on-plate tests were carried out using a filling metal. Figure 6a, b, c show the shape of the samples essayed in vacuum and figure 6 d, e and f show the results of the sample essayed in over pressure of 0.9 bar. It can be observed that in vacuum conditions the filler metal did not have a homogeneous shape (fig. 6a), moreover the back of the specimen used was severely damaged because the input heat facilitated the pushing of the aluminium flowing away from the matrix (fig. 6b). In addition, the filler metal did not wet the specimen as it kept its cylindrical shape (fig. 6c).

The application of an overpressure to the samples has totally avoided the outwards flow of molten aluminium and the damage of the composite (fig. 6d and e). This also permits using higher laser input energies, obtaining higher temperatures in the filler metal and favouring the wettability of the composite without degrading the specimens used (figure 6f).

The second strategy used consisted on depositing a sol-gel silica coating on the AlSiC samples. Figure 7a for shows a transversal section of the composites where the substrates were extracted at 35 cm/min from the gel. The thickness of the coatings measured is of approximately 15 micron, and it can be modified changing the extraction speed from the gel. To determine if the silica coating deposited can act as a physical barrier that inhibits the progression of aluminium outwards the composites, a coated samples has been submitted to a treatment of 650 ºC for 1 h inside an over. At this temperature all the matrix is molten and, in the absence of any coating, aluminium easily flows outwards. The results obtained (figure 7b) evidence that the barrier has been effective as no aluminium has been expulsed in any part of the specimen..

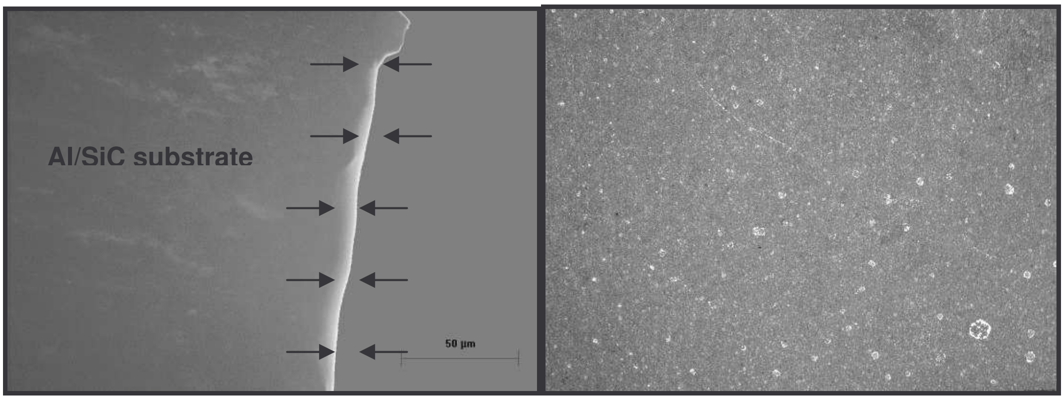

Figure 7. a) Sol-gel silica coating on AlSiC and b) coated AlSiC treated in oven at 650 ºC 1h.

Applying bead-on-plate tests to the coated substrates evidences the improvement obtained by applying this layer. Figure 8 shows the area of the seam formed during the test for the same conditions using sol-gel silica coated and uncoated specimens. The area of the seam obtained for the different input heats applied is always smaller in the case of coated substrates and in some cases it is only a 10 % of the area measured in uncoated substrates.

Some initial tests carried out using a filler metal indicate that the sol-gel coating also favours the wetting of the specimens with the molten filler material, validating the use of these coatings for brazing procedures.

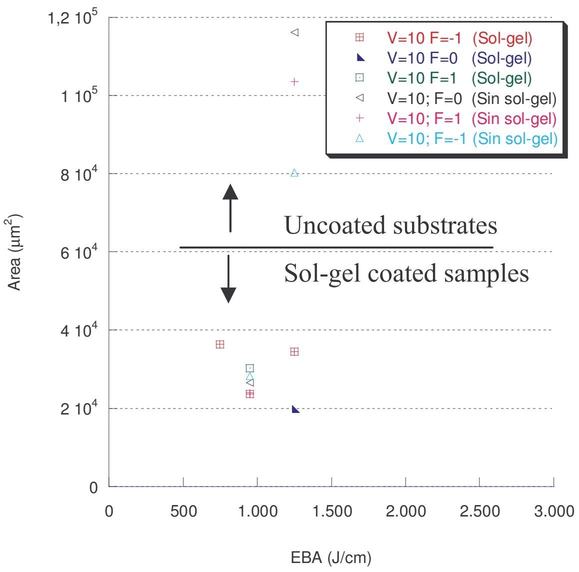

Figure 8. Height of the seam in bead-on-plate tests for different input heat values and for uncoated and silica coated specimens.

The different processes developed have allowed obtaining welds in AlSiC without damaging the specimens used. Figure 9 shows the results obtained applying different conditions of laser power and speed, using the A5356 filler and 0.9 bar nitrogen overpressure. The shape of the seam is homogenous all along the seam (fig. 9a), but if the welding conditions are not optimized the seam obtained presents defects and material from the matrix may escape from the composite (figure 9b). However, the use of an increased atmospheric pressure or using a physical barrier on the substrates made of silica fabricated through a sol-gel route allows using a much wider range of conditions and reduces significantly the heat effect on the specimens used.

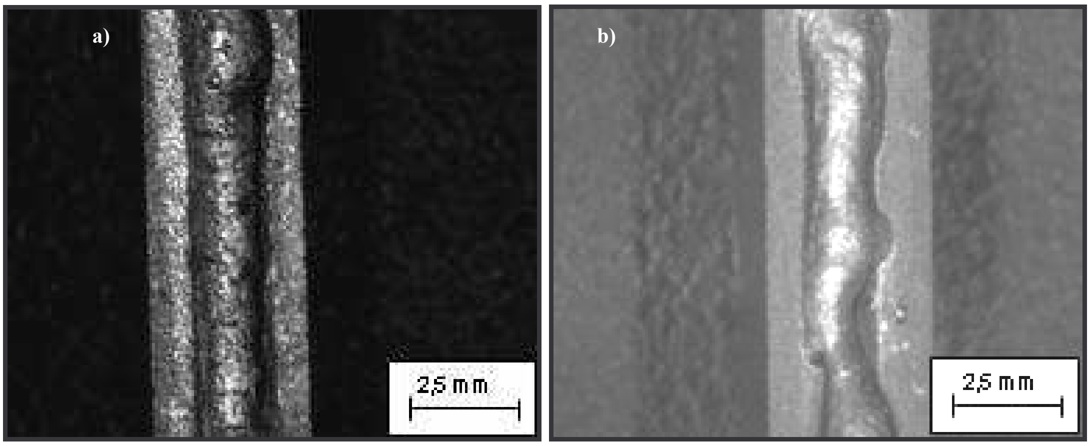

Figure 9. Welds fabricated using different conditions with a 0.9 bar N_2 overpressure.

4. CONCLUSIONS

The laser irradiation needed in laser welding and brazing of AlSiC composites causes that the material escapes from the composite, leaving pores and gaps in the material. The use of different strategies has allowed reducing the amount of material expulsed during laser application. This has allowed making joints with an AA5356 filler material using laser welding, allows obtaining continuous seams without degrading the joined AlSiC were obtained. In these processes the following conclusions have been derived:

- The amount of aluminium expulsed from the composite can be modified by controlling the laser welding conditions but cannot be avoided in any case without using other strategies.
- Applying an overpressure of about 1 bar reduces up to 90 % the amount of molten aluminium expulsed because it exerts a force that opposes to the aluminium tendency to flow outwards the composite.
- Sol-gel silica layer have been successfully placed on AlSiC composites without the formation of cracks or macroscopic defect in the surface. The thickness of the coating has been controlled by means of the extraction speed used during dip-coating procedure.
- The sol-gel coating deposited acted as a physical barrier that avoided the molten aluminium to escape from the composite at many different conditions. The amount of aluminium flown can be reduced in 90 %, as compared with uncoated systems. Moreover, this coating is easily wet by molten aluminium and is suitable for brazing with different fillers.
- Samples have been butt-end joined using aluminium filler applying the different tested strategies. Homogeneous and continuous seams have been obtained with different laser conditions and the specimens have not been damaged because of the input heat, showing that the strategies tested are feasible for the fabrication of complex shape structures made of AlSiC composite.

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