

Comparison of two different nozzles for laser beam welding of AA5083 aluminium alloy

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Abstract

AA5083 aluminium–magnesium alloy is increasingly used by shipbuilding industry due to its high strength to weight ratio. Laser welding is a crucial technology enabling reduction of thermal distortion of the weld assemblies and enhancing productivity, but its application to these alloys is far from being a reliable technology. In this work a comparative study has been carried out on the influence of two different shielding gas delivery systems on the autogenous laser welding process of AA5083. Bead-on-plate tests have been performed by using a 2.5 kW CO₂ laser source and helium as shielding gas, supplied respectively by a coaxial conical nozzle and a two-pipe nozzle. The effects of the variation of the main process parameters, i.e., travel speed, beam focus position, gas flow rate and nozzle standoff distance on the bead profiles (width, penetration depth, melted area), were investigated. Useful information has been obtained on the role of the welding nozzle geometry on the laser–matter interaction. Several sets of process parameters able to produce acceptable welds were selected. Some preliminary results have been presented on the laser butt welding of AA5083 3-mm-thick plates. Weld results are very competitive if compared with the state-of-the-art. © 2005 Elsevier B.V. All rights reserved.

Keywords: Laser welding; Nozzle; Aluminium alloys; Design of experiment

1. Introduction

The requirement for larger and faster vessels has resulted in an increasing use of new construction materials with a high strength to weight ratio like aluminium alloys of 5xxx and 6xxx series because of their small specific weight, high corrosion resistance, relatively good mechanical properties and high recycle potential. Conventional processes for welding aluminium alloys in the industry are arc welding and resistance welding [3]. Recent progresses in laser welding make this technology particularly advantageous because of its high speed, flexibility and low heat input that induces smaller distortions of welded assemblies. However, the application of laser welding to aluminium alloys is far from being a mature technology and fundamental questions remain open, much of them depending on the kind of alloy. In

case of 5xxx aluminium–magnesium alloys, the laser coupling to the material is critical due to its high reflectivity at the laser wavelength. Current issues in the laser welding research of this alloy are the vaporisation of alloying elements at the weld pool surface and the fluid flow or heat transfer in the melt pool, deeply influencing the chemistry and physical metallurgy of the resulting joints [1,4,6–8,10]. Indeed the incidence of porosity and hot cracking is very high in these kinds of laser-welded joints [6].

A common approach for welding aluminium alloys is to use high power lasers with incident powers higher than 5 kW, even for thin sheets, in order to overcome the initial radiation loss due to the high reflectivity of the material [7,11]. However in deep penetration keyhole welding, too high an incident power causes a large vaporization rate that may induce a loss of alloying elements and instabilities both in the plasma plume and in the molten pool, leading to the generation of weld defects like porosity and blowholes [4,6,8,11].

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The role of the shielding gas in laser welding of aluminium alloys is very important. Not only it prevents the weld from oxidation but also it may affect the magnitude of defocusing and absorption of laser beam in the plasma plume directly above the laser-generated keyhole. Whenever the plasma plume exceeds a characteristic size or moves against the direction of the oncoming laser beam and detaches from the sample surface, welding is interrupted or at least disturbed [2,5,9]. Chemical composition of the shielding gas and the flow geometry are key-factors in limiting the size of the plasma plume. Several experimental investigations and numerical simulations have been devoted to describe the effect of the plasma plume on the propagating laser beam, using ray tracing methods [9]. Other works deal with the effects of different shielding gases and mixtures for effective process optimization [2,5]. The number of publications studying the influence of the gas flow geometry on the weld quality is still small, even if the shielding of the laser–matter interaction zone from the surrounding atmosphere is crucial, especially for aluminium alloys. Many active gases composing air, like oxygen and nitrogen, react very easily with the alloying elements creating a variety of oxides and nitrides that compromise the metallurgical properties of the weld. Hydrogen, on the other hand, dissolves in the melt pool to a significant extent, thus creating numerous bubbles which can lead to porosity as well as cracks [5,6].

This work deals with an experimental comparative study on the influence of two different shielding gas delivery systems on the laser welding process of AA5083 plates. A coaxial conical nozzle and a two-pipe nozzle (flowing the gas sideways the incident laser beam) were investigated by varying the nozzle standoff distance and the gas flow rate. A cw CO₂ laser source was used with a moderate power of 2.5 kW, in order to prevent keyhole instabilities because of a too high incident power. The effects of the process parameters variations on the bead profiles have been investigated and some useful information on the laser–matter physical interaction has been argued.

2. Experimental procedure

Bead-on-plate welds were produced on 4-mm thick plates of 5083 aluminium alloy, using a continuous wave CO₂ laser operating at its maximum output power of 2.5 kW (Rofin DC025). The laser source generated a 25 mm diameter exit beam with a high quality TEM₀₀ Gaussian transverse mode and a divergence of 0.5 mrad. The two welding heads employed for this experimentation were different either for the focusing system of the laser beam or for the geometry of the nozzles that supplied the shielding gas onto the workpiece.

The first welding head, shown in Fig. 1, focused the laser beam by means of a 130 mm focal length ZnSe lens. The shielding gas was delivered by a coaxial conical nozzle with 3 mm exit diameter. The second welding head, illustrated in Fig. 2, consisted of a bending mirror directing the laser

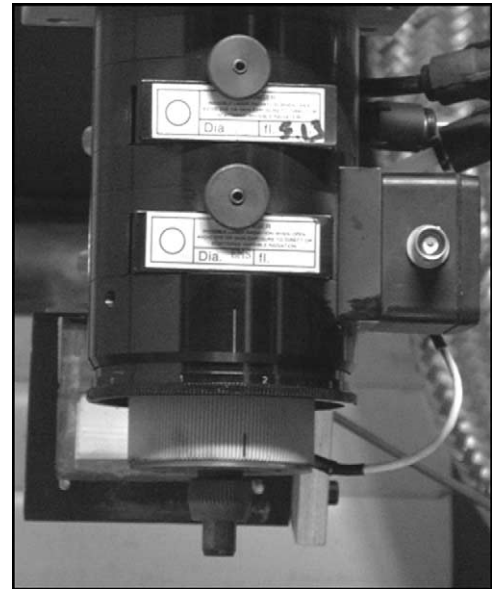


Fig. 1. Coaxial focusing head with a conical nozzle.

beam horizontally towards a water-cooled parabolic mirror of 200 mm focal length. This last mirror focused the laser radiation onto the material. The gas delivery system was composed of two L-shaped copper pipes placed sideways the incident beam, orthogonally the welding direction. Additionally, focusing optics was protected from hot vapours or weld spatters by a high velocity cross-jet. Both setups allowed adjusting the nozzle standoff distance independently from the beam focus position referred to the workpiece surface.

It is worth noting that even if the focal lengths of the two systems were slightly different, it was experimentally veri-

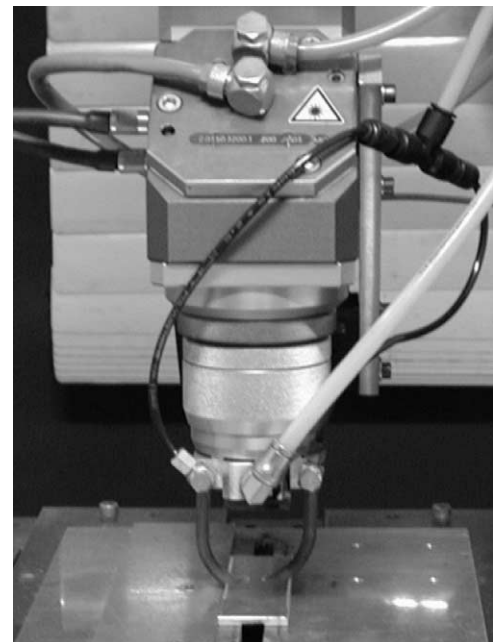


Fig. 2. Welding head with a parabolic focusing mirror and a two-pipe nozzle.

Table 1
Investigated ranges of the process parameters

	V (mm/s)	BFP (mm)	Q (Nl/min)	NSD (mm)
Coaxial nozzle	45–120	−2/+2	40–100	3–9
Two-pipe nozzle	80–120	−2/+2	60–100	3–9

fied that the depth-of-focus produced were very similar and that the resulting minimum spot size was 0.3–0.4 mm in both cases [1]. Helium was used as shielding gas. Welding samples were fixed to a three-axis fully automated translation stage.

All samples were carefully cleaned with acetone prior to the laser treatment, in order to prevent weld defects caused by surface contamination and moisture. Then specimens were fixed to the translation table with adhesive paper, so avoiding that mechanical clamping systems could induce residual stresses on the welding beads.

Two series of bead-on-plate tests were carried out, one for each welding head, varying the main process parameters: travel speed (V), nozzle standoff distance (NSD), beam focus position (BFP) and gas flow rate (Q). Experimental tests were planned using a full factorial design (FFD) approach in order to reduce the number of bead-on-plate runs while obtaining reliable results in the process parameter window of interest.

Two levels for each of the four process parameters were investigated, the ranges of which are reported in Table 1.

Two different lower values of speed and gas flow rate were chosen for each focusing head, since preliminary bead-on-plate tests showed that, using the welding head equipped with the two-pipe nozzle, full penetration was achieved on the 4 mm thick specimens for travel speeds lower than 70 mm/s. Moreover, in case of 40 Nl/min of helium flow rate, gas shielding was completely ineffective in containing the plasma plume volume thus producing bad welds. This is probably due to the lower gas pressure produced by this particular nozzle on the metal surface, due to the splitting of the gas flow into the two pipes. For this reason it was chosen to set the lower level of Q at 60 Nl/min for the second head.

The response variables of the 2^4 FFD were the bead width (BW), penetration depth (PD) and melted area (MA) of the resulting beads. In order to measure the bead profiles, samples were sectioned, mounted, polished and finally macroscopically etched with a solution of HCl 40%.

Based on FFD results, several combinations of process parameters were selected for each welding head, in order to perform preliminary butt welds on 3 mm thick plates.

3. Results and discussion

3.1. Bead-on-plate tests

The analysis of the bead-on-plate cross-sections allowed studying the influence of the main process parameters on the selected response variables. Fig. 3 reports the main effects plots of all parameters at first order, without interactions. For

both heads results pointed out that the travel speed was the most important variable of the laser welding process, since it determined the linear energy input released onto the material. The increasing of the welding speed caused the decrease of BW, PD and MA.

The main effects plots on the bead widths, using respectively the coaxial conical nozzle and the two-pipe nozzle are represented in Fig. 3a and b. The helium flow rate Q has a significant influence on the BW for both experimental setups whereas the effects of the NSD and of the BFP can be neglected. An increase of the BWs was found as Q was reduced. This behaviour could be explained taking into account the perturbation introduced by the plasma plume in the coupling of the laser beam to the keyhole. Several works have demonstrated that the focused laser beam can be affected by refraction or diffusion phenomena in its way through the plasma plume [2,5]. If the covering gas is not able to contain adequately the volume of the plasma plume, e.g. because of a low flow rate, an enlargement of the transverse dimensions of the laser beam impinging on the metal occurs, thus determining an increase of the BW.

Furthermore, a noticeable difference, in the same operating range of process parameters, was observed between the BWs produced by the two welding heads. The two-pipe nozzle produced BW even 30% lower than the coaxial nozzle at $v = 80$ mm/s and $Q = 60$ Nl/min, as shown in Fig. 4. This result seems to indicate that the two-pipe gas delivery system contained more efficiently the plasma plume volume, limiting in this way the refraction effects on the laser beam. This hypothesis was confirmed by the slight decrease of this difference as far as the gas flow rate or the travel speed was increased. For lower linear energy inputs the creation of plasma vapours was reduced, while for higher helium flows the pressure of the shielding gas itself confined the plasma plume. Hence under these conditions a minor effect of the gas stream geometry was expected. The influence of the NSD and of the BFP on the BWs was not significant.

The two-pipe nozzle generally yielded deeper penetration depths than coaxial nozzle. PDs obtained with the two heads, in the same range of V and BFP, are sketched in Fig. 5. A steady difference of 0.7–0.8 mm was found, corresponding to an increase of about 25% of the welding performances using the two-pipe nozzle with respect to the coaxial one.

BFP significantly affected the PDs obtained using the coaxial nozzle whilst it did not show any noticeable effect on the second head performances, as it is clearly shown in Fig. 3c and d and more in detail in Fig. 6.

This result could be ascribed to the different focal lengths of the two welding heads, although it was verified that the two focusing systems had a similar depth-of-focus. The lower focal length of the coaxial head might have caused the BFP to have some influence on the laser beam energy distribution inside the workpiece thickness. When using the coaxial nozzle, as far as the BFP was shifted towards negative values, an increase of PD was found, maybe due to a deeper distribution of the laser energy (Fig. 6a).

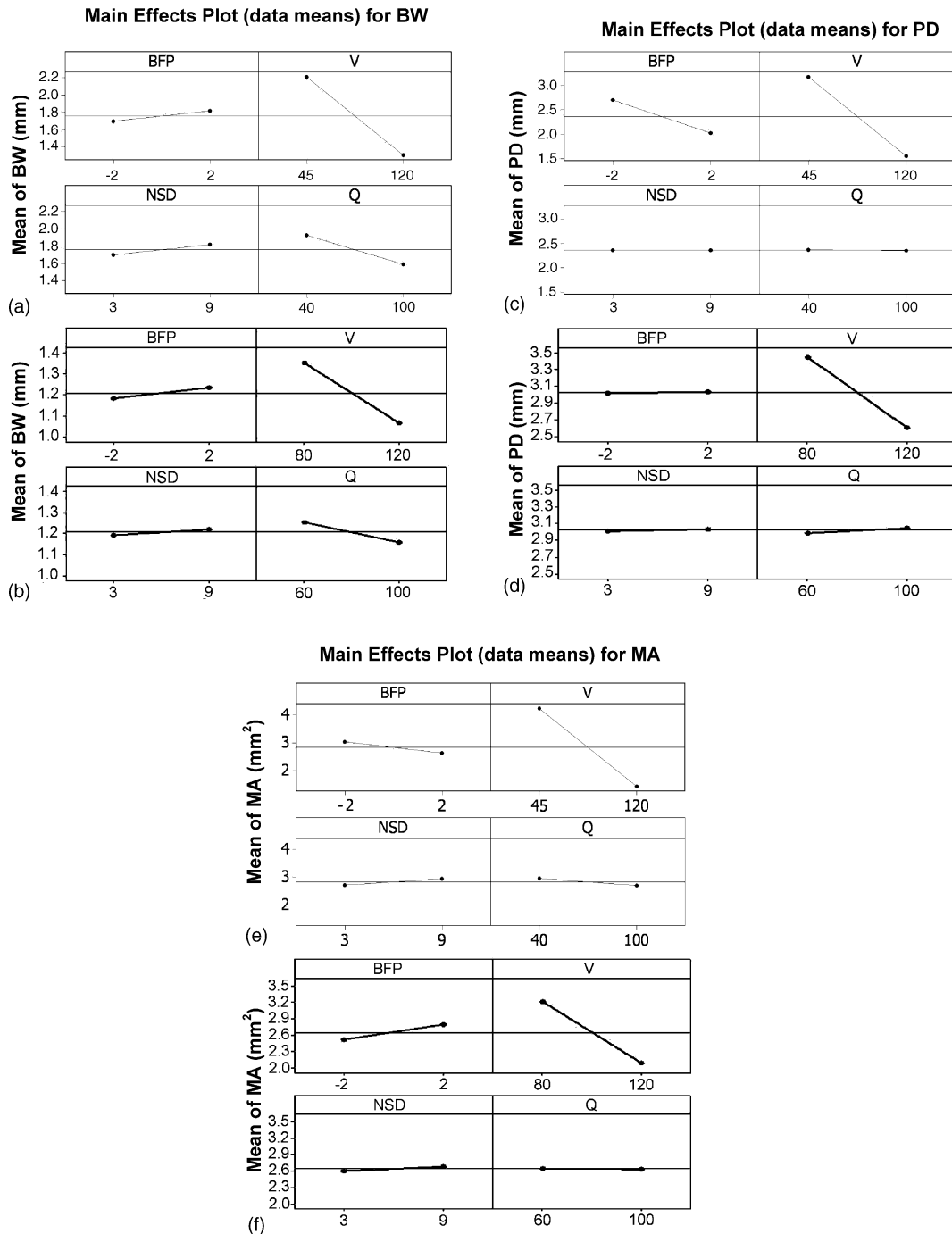


Fig. 3. Main effects plots of the welding process parameters: BFP (mm), V (mm/s), NSD (mm) and Q (Nl/min) obtained with the coaxial nozzle and the two-pipe nozzle, respectively. The measured bead-on-plate features are: bead width (a) and (b), penetration depth (c) and (d), and melted area (e) and (f).

As it is shown in Fig. 3c and d and more in detail in Fig. 7, for both heads it was found a small influence of the gas flow rate Q on the PD, while this process parameter significantly affected the BW.

The two-pipe nozzle generally produced larger volumes of melted metal with respect to the coaxial nozzle (Fig. 3e and f). As far as the travel speed was increased, this difference was more evident. It was found that the weld cross-sections of the bead-on-plates performed at the fastest speed

of 120 mm/s (BFP = 0, NSD = 6 mm and Q = 80 Nl/min) with the coaxial nozzle, had a melted area of 1.7 mm² while the corresponding samples produced with the two-pipe nozzle had a MA of 2.4 mm² with an increment of 40%. Therefore for short laser–matter interaction times the second gas delivery system allowed higher energy transfer efficiencies from the laser beam to the metal. Since the reflectivity and the thermal conduction of the welding metal did not change, this could be ascribed to a smaller perturbation introduced by the

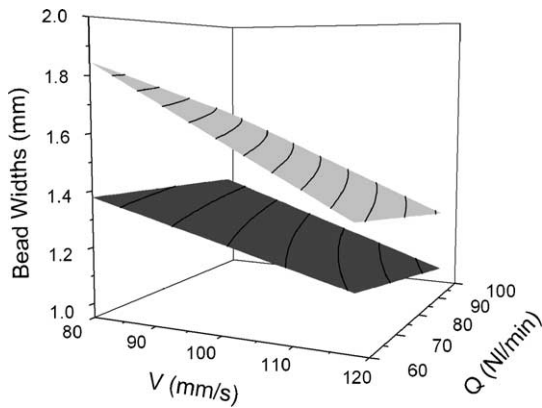


Fig. 4. Bead widths as a function of travel speed and gas flow rate using the coaxial nozzle (light grey) and the two-pipe nozzle (dark grey) at NSD = 6 mm and BFP on the surface.

plasma plume. Main effects plots of the MA confirmed this hypothesis; in fact a slight influence of NSD and Q (process parameters playing the most significant role in the plasma confinement) was noted only when using the coaxial nozzle (Fig. 3e). Rising the NSD and reducing the gas stream Q , a larger MA was produced mainly due to the concurrent increase of the BW. NSD and Q effects on the MA were negligible in case of two-pipe nozzle (Fig. 3f).

The effect of the BFP on the MA is shown in Fig. 8. Variations of the BFP with the coaxial nozzle produced small changes of the MA at constant speed (Fig. 8a), while an increase of MA for positive defocusing was found when using the two-pipe nozzle (Fig. 8b).

Results of Fig. 8 are consistent with the corresponding ones of Fig. 6 concerning the influence of the BFP on the PD:

- (i) The coaxial nozzle yielded MA almost independent from the BFP but a sudden decrease of PD was observed when rising the BFP. As a result the aspect ratio of the bead profile, defined as the ratio of the PD over the BW, in-

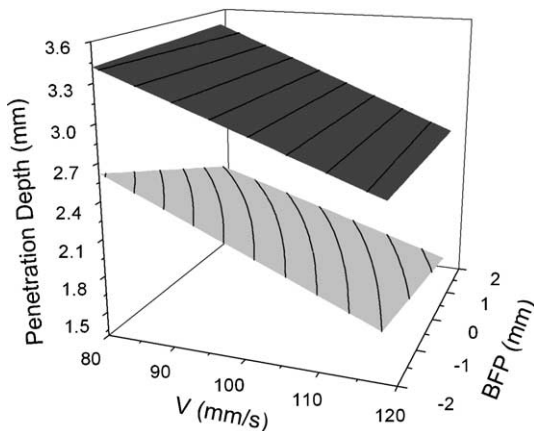


Fig. 5. Penetration depths as a function of travel speed and beam focus position using the coaxial nozzle (light grey) and the two-pipe nozzle (dark grey) at NSD = 6 mm and $Q = 80$ Nl/min.

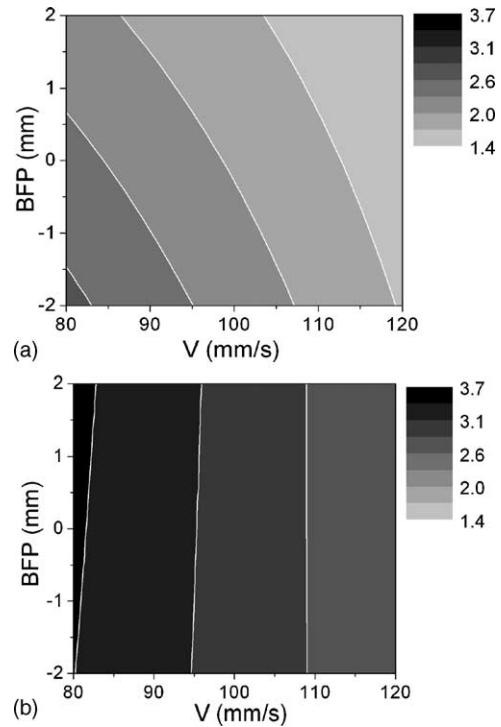


Fig. 6. Contour maps of the penetration depth (mm) as a function of travel speed and beam focus position obtained with the coaxial nozzle (a) and the two-pipe nozzle (b) at NSD = 6 mm and $Q = 80$ Nl/min.

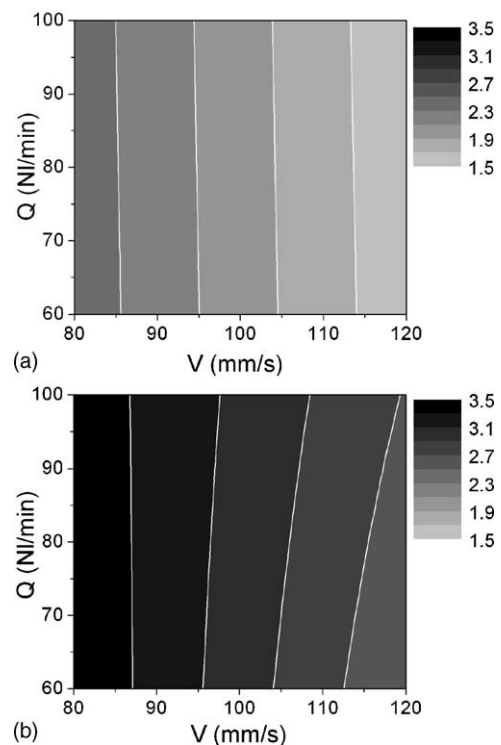


Fig. 7. Contour maps of the penetration depth (mm) as a function of travel speed and gas flow rate obtained with the coaxial nozzle (a) and the two-pipe nozzle (b) at NSD = 6 mm and BFP on the surface.

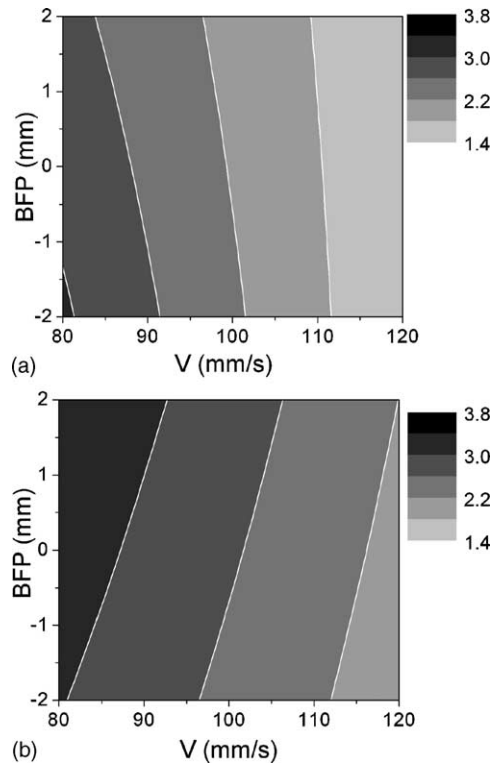


Fig. 8. Contour maps of the melted area (mm^2) as a function of travel speed and beam focus position with the coaxial nozzle (a) and the two-pipe nozzle (b) at $NSD = 6 \text{ mm}$ and $Q = 80 \text{ N l/min}$.

creased for negative defocusing thus indicating that the beam energy was distributed deeper inside the sample thickness.

- (ii) The two-pipe nozzle produced larger MA as far as the BFP was lifted above the sample surface while the PD was unaffected by the BFP variations. Even in this case the resulting effect was an increase of the aspect ratio of the weld as far as the BFP was moved inside the material.

Therefore the concurring effects of the BFP on the PD and on the MA with two different nozzles, gave results that are in agreement with a physical interpretation of the laser energy distribution inside the welding metal. Anyway MA measurements confirmed that the two-pipe nozzle was able to achieve higher welding performances, especially at highest speeds.

3.2. Butt welds

Based on the analysis of bead-on-plate tests, several sets of working parameters, for each welding head, were selected in order to perform butt welds on AA5083 specimens. The criterion adopted for choosing the sets of process parameters was to obtain fully penetrated joints with the highest aspect ratio on 3 mm thick samples, and operating at the fastest speed. Table 2 reports two sets of values of process parameters, one for each welding nozzle, producing acceptable welds.

Table 2

Sets of process parameters employed for preliminary butt welds

	V (mm/s)	BFP (mm)	Q (N l/min)	NSD (mm)
Coaxial nozzle	100	−2	80	6
Two-pipe nozzle	120	0	80	6

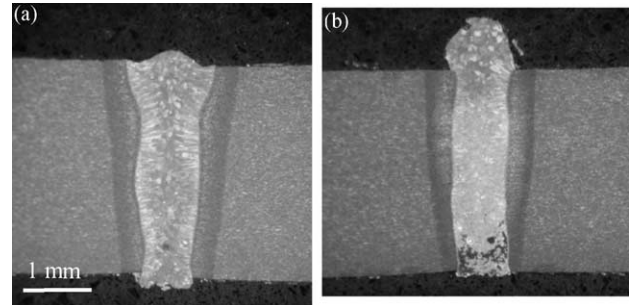


Fig. 9. Macrographs of the sections of the butt welds of Table 2 using: (a) the coaxial nozzle and (b) the two-pipe nozzle.

Since the bead-on-plate tests did not show any dependence of PD on Q and NSD, intermediate values were chosen for these parameters. Negative defocusing was employed when using the coaxial nozzle and beam focus on the surface in case of two-pipe nozzle, for analogous considerations on the PD and MA results. The resulting welded joint cross-sections are shown in Fig. 9. It is important to note that the second head achieved fully penetrated joints at a higher speed.

These butt welds were just the results of some preliminary tests. The optimization of the process parameters for autogenous laser butt welding of AA5083 was beyond the scope of this work and it will be the next step.

Nonetheless it was found that the microhardness profiles across the widths of the performed welds did not show a significant increase in hardness of the fused zone in comparison to the adjacent base metal. Furthermore some preliminary evaluation of the porosity content was carried out through the analysis of the longitudinal sections of the welds. It was found that the porosity content of all the examined joints turned out to be below the limit of the highest welds quality level stated by the EN 30042 standard. Therefore the obtained welds seemed to be of acceptable quality. Obviously, it should be preferred the second welding nozzle since it is capable of producing acceptable butt joints at a higher welding speed.

For a quantitative evaluation of the weld quality, further microhardness and tensile tests are needed. Both optimization of the process parameters and characterization tests will be the objective of future investigations.

4. Conclusions

Bead-on-plate welding tests have been performed in partial penetration of 4 mm thick AA5083 plates using a 2.5 kW cw CO_2 laser and two different welding heads. A comparative study of the performances of a coaxial nozzle config-

uration with respect to a two-pipe gas delivery system was carried out by varying the main process parameters (travel speed, beam focus position, gas flow rate and nozzle standoff distance) and measuring the resulting bead profiles. The following conclusions have been drawn from the bead-on-plate analyses:

- (i) The most important process parameter was the travel speed since it determined the linear energy input released onto the material.
- (ii) When gas stream was reduced an increase of bead widths have been observed because of the enhancement of the plasma plume, modifying the transverse dimensions of the incident laser beam due to refraction.
- (iii) The gas flow rate and the nozzle standoff had a small influence on the penetration depth.
- (iv) The aspect ratio of the bead profile increased as far as the beam focus position was shifted below the metal surface maybe due to a deeper distribution of the laser energy inside the workpiece. In fact for negative defocusing the coaxial nozzle produced deeper penetrations but constant melted areas, while the two-pipe nozzle resulted in smaller melted areas but no significant variation of the penetration depth was found.
- (v) The two-pipe configuration generally produced joints with a lower width, deeper penetration and larger melted areas, with respect to the coaxial nozzle. Therefore it was argued that this gas delivery system allows a more efficient energy transfer producing joints with a higher aspect ratio.

Based on the bead-on-plate results, several sets of working parameters, for each welding head, were selected in order to perform autogenous butt welds on 3 mm thick specimens. Preliminary results showed acceptable quality of the joints being very competitive if compared to previous works where laser sources of higher power have been employed [6,7,10,11]. The two-pipe gas delivery system has been preferred with respect to the coaxial welding head since it allowed producing fully penetrated butt joints at a higher welding speed and with a higher aspect ratio.

Further studies are under development to optimize the laser butt welding process of AA5083 plates.

References

- [1] A. Ancona, G. Daurelio, L.A.C. De Filippis, A.M. Spera, CO₂ laser welding of aluminium shipbuilding industry alloys: AA5083, AA5383, AA5059, and AA6082, in: Proceedings of the XIV International Symposium of SPIE on Gas Flow and Chemical Lasers and High Power Lasers, vol. 5120, Wroclaw, Poland, 2002, pp. 577–587.
- [2] M. Beck, P. Berger, H. Hugel, The effect of plasma formation on beam focusing in deep penetration welding with CO₂ lasers, *J. Phys. D: Appl. Phys.* 28 (1995) 2430–2442.
- [3] R.C. Calcraft, M.A. Wahab, D.M. Viano, G.O. Schumann, R.H. Phillips, N.U. Ahmed, The development of the welding procedures and fatigue of butt-welded structures of aluminium-AA5383, *J. Mater. Process. Technol.* 92–93 (1999) 60–65.
- [4] L.M. Galantucci, L. Tricarico, R. Spina, A quality evaluation method for laser welding of aluminium alloys through neural networks, *Ann. CIRP* 49 (1) (2000) 131–134.
- [5] M.H. Glowacki, The effects of the use of different shielding gas mixtures in laser welding of metals, *J. Phys. D: Appl. Phys.* 28 (1995) 2051–2059.
- [6] A. Haboudou, P. Peyre, A.B. Vannes, G. Peix, Reduction of porosity content generated during Nd:YAG laser welding of A356 and AA5083 aluminium alloys, *Mater. Sci. Eng. A* 363 (2003) 40–52.
- [7] C. Mayer, F. Fouquet, M. Robin, Laser welding of aluminium–magnesium alloys sheets process optimization and welds characterization, *Mater. Sci. Forum* 217–222 (1996) 1679–1684.
- [8] E. Schubert, M. Klassen, I. Zerner, C. Walz, G. Sepold, Light-weight structures produced by laser beam joining for future applications in automobile and aerospace industry, *J. Mater. Process. Technol.* 115 (2001) 2–8.
- [9] V.V. Semak, R.J. Steele, P.W. Fuerschbach, B.K. Damkroger, Role of beam absorption in plasma during laser welding, *J. Phys. D: Appl. Phys.* 33 (2000) 1179–1185.
- [10] H. Zhao, D.R. White, T. DebRoy, Current issues and problems in laser welding of automotive aluminium alloys, *Int. Mater. Rev.* 44 (6) (1999) 238–266.
- [11] J.P. Weston, Laser welding of aluminium alloys, Ph.D. Thesis, University of Cambridge, 1999.