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Laser welding with and without filler wire of aluminum sheets produced by rolling and additive manufacturing for e-mobility applications

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Abstract. One of the most critical factors to be taken into consideration in laser welding of aluminum alloys is the formation of pores in the fused zone, which depends strictly on the semi-finishing format of the parent sheets. According to these considerations the present paper deals with welding of AA6082 sheets with additively manufactured AlSi10 ones in a configuration that is typical for the production of casings for batteries for the e-mobility field. In order to understand the role of process strategies on weld bead quality, both autogenous welding and welding with filler wire are investigated and the eventual benefits of applying a wobbling beam shaping is also considered. For any of the above-mentioned strategies, the role of process parameters, such as laser power, welding speed, filler wire speed and wobbling, is underlined, with particular reference to the formation of pores and defects.

Introduction

Laser welding with filler wire has been studied for several years as a method for overcoming some of the most common autogenous welding drawbacks, such as difficult gab-bridging and impossibility to promote metallurgical modifications in the weld pool. The applications of filler wire in laser welding has always gone hand in hand with the development of the different beam generation technologies: starting from CO_2 lasers in late 90s and early 2000s [1,2], the attention moved to fiber delivered Nd:YAG and Disk ones [3-5], while the recent years have been characterized by a massive exploitation of modern fiber sources. In laser welding with filler wire applications, aluminum alloys play a very important role thanks to their specific applications especially in automotive and aerospace fields. In that direction Grunenwald et al. [3] pointed out the benefits of filler wire in gap bridging of AA5083 alloy. Vollertsen et al. [5] investigated the role of filler wire on crack formation in laser welding of AA6082 and AA6056 alloys. Pinto et al. [4] pointed out the importance of selecting the proper filler wire composition in laser welding of AA6xxx and AA5xxx alloys, both in similar and dissimilar configurations, with the aim of reducing both crack susceptibility and pores formation. Yu et al. [6] investigated the importance of wire-laser beam mutual position and distance for promoting a stable melt pool and a smooth wire melting. Schultz et al. [7] proposed the oscillation of a high brilliance laser beam as a mean for evenly distributing the energy on the tip of the filler wire instead of defocusing or using a low brilliance beam with a large spot. They also demonstrated that this technique can also have beneficial effects in gap bridging. Enz et al. [8] investigated the benefits of adding a filler wire in laser welding of AA7075 alloy for the production of tailored blanks. In a similar direction Adisa et al. [9] stressed on the possibility to apply pulsed laser sources in welding AA7020 alloy. In order to understand potential process productivity, Xu et al. [10] investigated high speed laser welding with filler wire of AA6xxx alloys. Li et al. [11] proposed the possibility to exploit hot wire laser welding of AA7075 alloy. Examilioti et al. [12] investigated the role of filler wire on AA2198 alloy for aerospace applications and pointed out that it greatly reduces crack formation. Huang et al. [13] gave a comprehensive explanation of the role of filler wire positioning in laser welding of AA5xxx alloys: by selecting the proper angle and stand-off distance, melting of filler wire can be greatly optimized. Concerning welding of additively manufactured component, several studies demonstrated that laser techniques allow to achieve good results on steel [14] and stainless steel [15]. The above mentioned literature shows that, in aluminum alloy laser welding, the adoption of a filler wire implies three main benefits:

- Possibility to deal with gaps, misalignments, differences in thickness, etc.
- Reduction of pores formation.
- Reduction of cracks formation.

In the automotive field, the application of laser welded aluminum alloys has become very popular in the last years, both in structural (car-body) and electric applications (batteries) [16,17] and the search for optimized processes that guarantee good versatility and high weld quality is of utmost importance. In those fields the application of filler wire has proven to be very beneficial [18], since different alloys, thicknesses and joint configurations are involved. In the light of what has been underlined so far, the present paper reports an investigation concerning laser welding of rolled AA6082 sheets on Selective Laser Melting (SLM) printed AlSi10 sheets. The idea is to evaluate the possibility of welding different aluminum alloys in different semi-finishing conditions, guaranteeing the proper joint geometry and overall quality. According to this, laser welding with and without filler wire is proposed herein and wobbling application is also involved as a mean for achieving the proper joint characteristics.

Materials and Methods

The equipment exploited in the present investigation was composed by a IPG YLS-6000 fiber source equipped with a IPG D50 two axes scanning optics (see Table 1) for complete characteristics. The wire feed system was based on a Fronius KD7000 push-pull equipment with a maximum wire feeding speed of 10 m/min. The welding optics was mounted on a Yaskawa-Motoman HP-20 6 axes anthropomorphic robot (see Figure 1).

Figure 1: Welding system

The filler wire was a AA5356 one, with a diameter of 1.2 mm and a mixture of 15% He and 85% Ar was used as shielding gas with a flow rate of 30 l/min. The filler wire guiding nozzle was placed at an inclination of 30° with respect to the horizontal plane ant the welding process was

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carried out in the wire leading configuration (see Figure 2a). The sheet metals involved in this investigation were 50x50x1.5 mm rolled AA6082 and 50x50x5 mm SLM printed AlSi10. The welding configuration was a lap-joint one with AlSi10 at the bottom and AA6082 on top and the weld bead was realized with an inclination of the welding head of 45° (see Figure 2b).

Table 1: Laser source and optics characteristics

Maximum power	6 kW
BPP	4 mm·mrad
Collimation focal length	200 mm
Focalization focal length	300 mm
Magnification factor	1.5
Fiber core diameter	100 µm
Spot diameter	150 µm
Maximum scanning field	8x8 mm
Maximum wobbling frequency	350 Hz

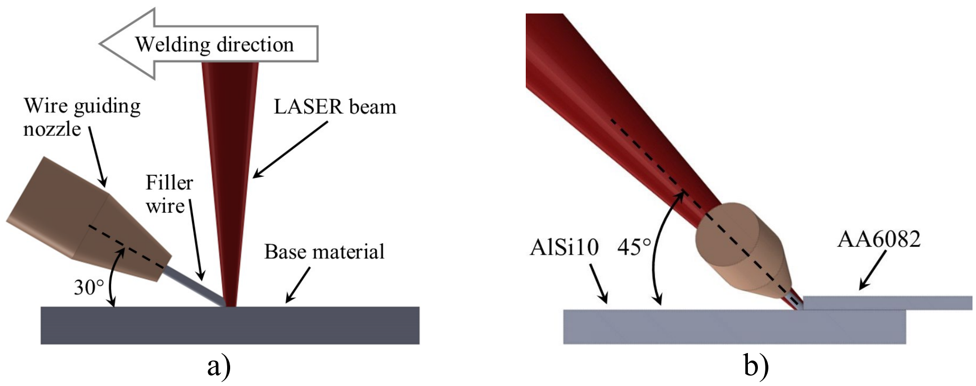

Figure 2: welding setup

The experimental campaign was carried out in three different configurations:

- Welding with filler wire, no wobbling. In this case the process parameters were selected as follows:
  - wire feed speed and welding speed 25 mm/s, Laser power 2.2, 2.4, 2.6, 2.8, 3.0 kW.
  - wire feed speed and welding speed 30 mm/s, Laser power 2.2, 2.4, 2.6, 2.8, 3.0 kW.
  - wire feed speed and welding speed 35 mm/s, Laser power 2.2, 2.4, 2.6, 2.8, 3.0 kW.
- Welding with filler wire and wobbling. In this case the process parameters were selected as follows:
  - wire feed speed and welding speed 25 mm/s, wobbling frequency 200 Hz, wobbling amplitude 1.2 mm, Laser power 2.2, 2.4, 2.6 2.8, 3.0 kW.
  - wire feed speed and welding speed 30 mm/s, wobbling frequency 200 Hz, wobbling amplitude 1.2 mm, Laser power 2.2, 2.4, 2.6 2.8, 3.0 kW.
  - wire feed speed and welding speed 35 mm/s, wobbling frequency 200 Hz, wobbling amplitude 1.2 mm, Laser power 2.2, 2.4, 2.6 2.8, 3.0 kW.
- Welding without filler wire and without wobbling. In this case the process parameters were selected as follows:
  - wire feed speed and welding speed 25 mm/s, Laser power 2.2, 2.4, 2.6 kW.
  - wire feed speed and welding speed 30 mm/s, Laser power 2.2, 2.4, 2.6 kW.
  - wire feed speed and welding speed 35 mm/s, Laser power 2.2, 2.4, 2.6 kW.

The different values of process parameters selected were defined by means of previous preliminary tests aimed at defining plausible process windows suitable for comparing the three working conditions defined above. The welded samples were cross sectioned, resin mounted, polished and chemically etched, so that the main geometrical characteristics, such as weld bead width and penetration depth could be measured (see Figure 4). By means of the ImageJ image analysis software, average porosity was also measured.

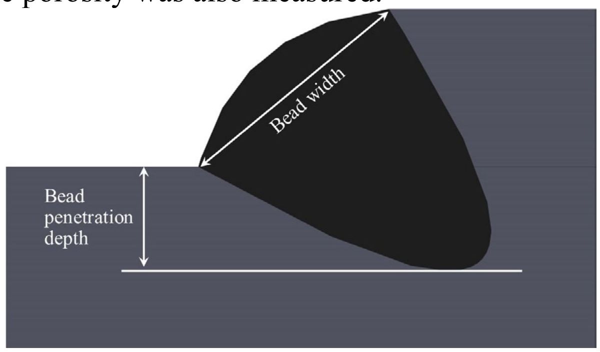

Figure 4: Weald bead measurement

Results and Discussion

Concerning welding with filler wire, the graphs in Figure 5 shows some results in terms of weld bead width, penetration depth and porosity.

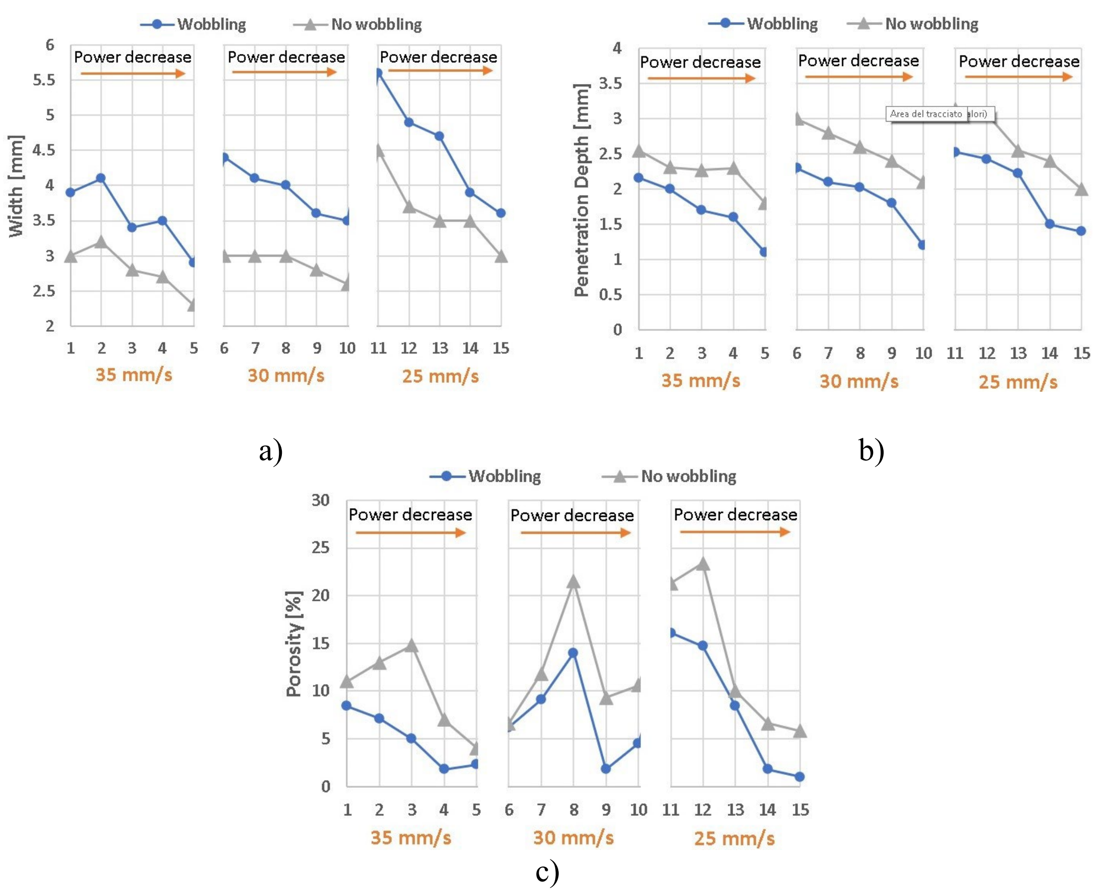

Figure 5: Welding with filler wire

Concerning weld bead width, the trend is exactly the same both with and without wobbling: this parameter tends to decrease if laser power decreases and if welding speed increases, as expected. The main difference between the two modes is that, when wobbling is enabled, bead width is larger, due to the "stirring" effect of beam oscillation, that tends to distribute the molten pool on a larger area. The trend characterizing bead penetration depth is very similar to the one analyzed above: an increase of welding speed leads to a decrease of penetration depth, while an increase of laser power leads to an increase of penetration depth.

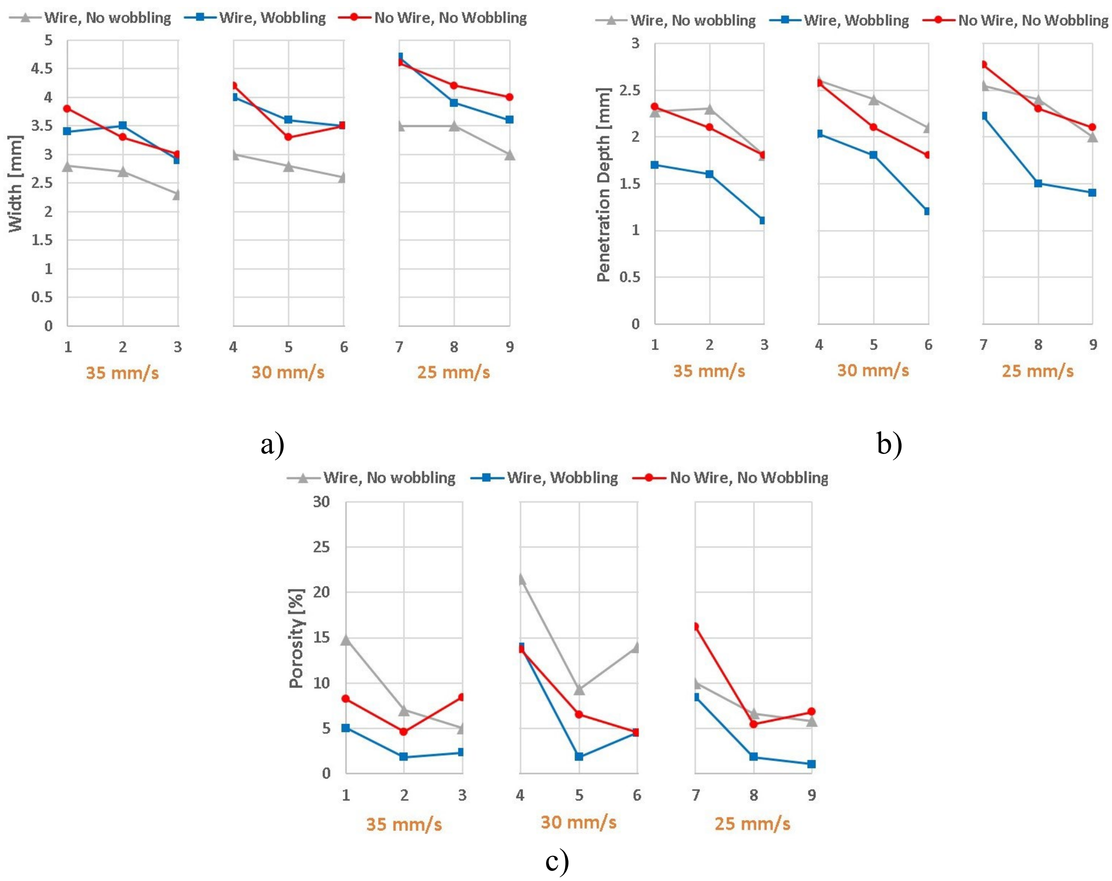

Figure 6: Overall comparison

The adoption of wobbling leads to a general decrease of penetration depth: this is due to the fact that oscillation of the beam enlarges the interaction zone between laser radiation and base material, determining a general decrease of energy density during the process and, thus, the formation of a larger molten pool. The effect of beam wobbling, in fact, is to determine a large apparent spot that leads to a general increase of melt pool dimension, while keeping the actual "instantaneous" spot small and promoting a good beam-material coupling especially in case of highly reflective materials. Concerning porosity, the trend is much different and the role of the main process parameters is not so clear. Analyzing laser power, it looks like there is not a definite trend: these results could be very much affected by the fact that porosity percentage was evaluated only in one specific section of every specimen and, thus, it is really far from being an average value of the whole bead. The investigation at the base of the present paper is, in fact, to give a preliminary idea of what to expect in the different welding modes analyzed: further investigations in this direction could involve tomographies, so that a more generalized porosity could be detected, and also a more comprehensive experimental campaign with repetitions, design of experiment and statistical analyses. Concerning welding speed, it looks like there is a more definite trend, since porosity increases as this parameter decreases: this is due to the fact that low welding speed determines a relatively high specific heat input and a high interaction time, that promote the formation of a large quantity of pores that fail to evolve from the melt pool. The most interesting result concerning porosity is related to which welding mode is applied: in case of wobbling mode, in fact, the average porosity always tends to be lower: the "stirring" effect of wobbling promotes a de-gassing of the molten pool given a certain set of process parameters. These results are also in accordance with the studies carried out by Ramiarison et al. [19]: the authors put in evidence that wobbling mode helps to mitigate several defects such as cracks and pores. Concerning welding without filler wire, the graphs in Figure 6 show a comprehensive comparison of the three welding modes investigated herein. The result that surely deserves more attention, in this case, is that the lowest porosity still remains a beneficial characteristic of welding with wobbling and filler wire, while welding without filler wire shows, generally, worse results. The number of trials in this case was lower because 3.0 kW and 2.8 kW without filler wire caused an excessive penetration in the lower sheet and, thus, they were excluded from the campaign. Figure 7 shows representative micrographs of the three investigated modes (Laser Power 2.2 kW, Welding speed 25 mm/s). The pictures confirm that welding with wobbling and filler wire gives the best results in terms of porosity.

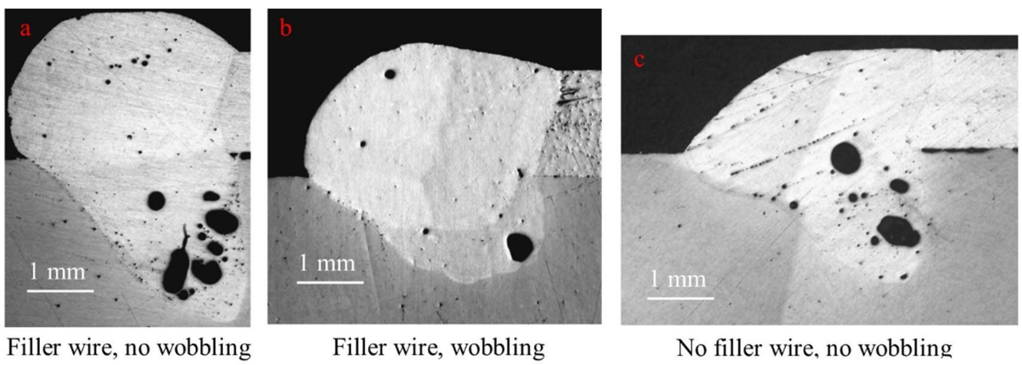

Figure 7: Micrographs of representative weld beads

The presence of filler wire generates a higher reinforcement on the weld bead, that can be beneficial when gap bridging is needed. In particular, concerning weld bead reinforcement, the presence of wobbling and filler wire determines a shape of the top part of the weld bead that is more evenly distributed on the corner between the sheets. If no wobbling is adopted, the reinforcement is generally very prominent, and the transition between the sheets and the weld bead is abrupt: this situation very likely promotes a severe stress concentration in correspondence of the heat affected zone, causing a general decrease of mechanical performance of the joint. These results are also supported by the studies underlined by Zhao et al. [20], where it was put in evidence that the presence of wobbling has a beneficial effect in evenly distributing the molten pool during the process.

Summary

The present paper investigates welding with and without filler wire of different aluminum alloys in different semi-finished conditions. In particular a rolled sheet is welded on an additively manufactured one. The activity is a preliminary one and future developments will involve more thorough investigations of porosities and micro-structures and also tensile tests to assess the actual mechanical performance of the joints. The main outcomes resulting from the investigation are the following:

- Welding with filler wire and wobbling is the best solution for achieving a low porosity in the weld bead.
- The presence of filler wire determines a higher reinforcement in the weld bead and wobbling helps to distribute it more evenly.

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