Remote Laser Welding on the hybrid materials

Alessio Pasquale Mirarchi
Department of Innovation Engineering and Information
Guglielmo Marconi University
Via Plinio, 44 - 00193 Rome - Italy
ap.mirarchi@unimarconi.it

Andrea Girgenti
Department of Innovation Engineering and Information
Guglielmo Marconi University
Via Plinio, 44 - 00193 Rome - Italy
a.girgenti@unimarconi.it

Abstract

This paper focuses on Remote Laser Welding (RLW) technology applied on hybrid materials. RLW is an innovative technology that can find applications in different industrial sectors, due to the different types of junctions that can be prepared, the accuracy in junctions and the many materials that can be joined. If compared to the other already established welding technologies such as MIG, TIG, and MAG welding, the RLW shows the advantages in terms of welding speed, aesthetic quality and process flexibility. For these characteristics the RLW could be defined a lean process that is taking a wide use in production in the automotive field. In fact, using appropriate laser heads, it is possible to make the entire production process repeatable, fast and versatile. This research reports a preliminary experimental study to investigate the potential of this technologies for the application on two different aluminum alloys.

Keywords
Remote Laser Welding, RLW, aluminum alloy, welding of edge, pulsed laser cycle

1. Introduction

Since 2005, the Kyoto Protocol has set the mandatory reduction of harmful emissions greater than 8% of carbon dioxide, methane, nitrous oxide, hydro fluorocarbons, perfluorocarbons, and sulfur hexafluoride. Such reduction is set on the levels recorded in 1990, considered as a base year. Such dictate has been recently confirmed in the twenty-first Conference of the Parties (United Nations Framework Convention on Climate Change) held in Paris from 30th November to 12th December 2015.
The automotive industry is necessarily oriented to solve conflicts arising from fulfilling environmental standards and from customer requirements in terms of performance, i.e. lightness, efficiency and automobile aesthetics. A significant step in this direction is the introduction in the automotive sector of the concept of vehicle lightening. A lighter car would ensure better fuel economy and lower emissions of harmful NO_x. This issue has led to an extensive research of lighter materials, the mechanical properties of which are nonetheless very close to those of commonly used steels. In this scenario many research project have been made [Hagebeuker et al., 2016] to develop viable and sustainable solutions for electric vehicles mid-range destined to reach the market in the next 8-12 years. In recent decades, with each new generation, cars have become bigger and heavier. The weight of vehicles has seen an average increase of about 16 kg per year.
Today, mid-size vehicles are almost twice as heavy, if compared to those of 20 years ago; in fact, for example, a Volkswagen Golf GTI in 1976 weighed 820 kg, in 2006, the equivalent model weighs 1340 kg. This is where the need

for lighter future vehicle arises, both as of the regulations established by the above-mentioned Kyoto Protocol, i.e. to see a lowering of the thresholds of pollutants NO_x, and to reduce production costs.
This objective can be achieved by introducing, in the automotive field, innovative materials and new technologies that aim to lightening the car chassis. The lightening of the car starting from its frame is pursued through the choice of high resistant alloys able to provide greater stiffness with a minor amount of material, i.e. a minor weight. On the other hand technologies to make the use of these alloys more sustainable from an economical standpoint is an increasingly important issue. In this context the RLW is able to provide a flexible innovative solution to make welded joints of lighter alloys like the aluminum and zinc ones [Haboudou et al., 2003].

2. Literature review and research scope

Several sustainable solutions to comply with the Kyoto Protocol and with the need to optimize automotive production process have been investigated in the past decades, and also to establish guidelines to devise and prevent all potential issues ahead, or at least to establish procedures and best practices to handle them, as in [Arcidiacono et al., 2002].
In view of such holistic perspective of the production process, diverse methodologies have been experimented, such as for example Six Sigma to optimize many aspects belonging to this topic, as in [Arcidiacono et al., 2015] and [Arcidiacono et al., 2006]. Other studies, based on Axiomatic Design, have tried to drive the design to avoid criticalities, as in [Girgenti et al., 2015] and [Monti et al., 2015]. Further attempts have been performed to reduce wastes and scraps through LCA and Design for X techniques [Giorgetti et al., 2016] and increasing efficiency [Vezzu et al. 2015].
Lying at the core of the implementation of RLW welding too, research on ensuring and improving automotive reliability [Arcidiacono et al., 2004] has been debated extensively. Some examples are carried out also from the point of view of single assemblies through innovative approaches like the FMETA approach, as in [Arcidiacono et al., 2004] and the Fault Tree Analysis (FTA), as in [Arcidiacono, 2003].
Within the scope of this research, several previous studies have been reviewed on applied RLW methodology, in order to validate its relevance in the selected context of application.
RLW methodology has been introduced as an innovative technology that can be applied in different industrial sectors, due to its versatility, as for the different types of junctions that can be prepared, and the many materials that can be joined. Indeed, RLW is able to provide a flexible innovative solution to make welded joints of lighter alloys like aluminum and zinc ones [Haboudou et al., 2003]. Moreover, if compared to other already established welding technologies, such as MIG, TIG, and MAG, the RLW shows advantages in terms of welding speed, aesthetic quality of the welding, besides process flexibility. Its versatility in preparing different types of junctions and using many materials make this technology successful and widely employable in many industrial fields, not just the automotive one.
On the other hand, the RLW process has high costs due to the equipment as the anthropomorphic robots, the laser heads and the scanner lasers employed that it could not allow the widespread use of this technology recommended. At a first stage of implementation as a new technology within a manufacturing process, the optimal use a RLW may pass through the understanding of relations among joints features and their characteristics.
Some authors [Sanchez-Amaya et al., 2009] have highlighted the role of auxiliary treatments and process variables to optimize the result of RLW conducted on aluminum alloys like the preparation of metallic surface, as well as the dual beam welding, as adequate methods to reduce porosity formation in welded parts. The effects of RLW process parameters on the resulting welded joint have been investigated by several studies [Haboudou et al., 2003]. These efforts want to find out the best setup for parameters like the laser power and the welding speed to obtain good quality welds. The obtained results allow to define experimental conditions, which lead to welds with deep cords (3 and 2.3 mm obtained for two aluminum alloys (the 5083 and 6082, respectively).
The preparation of the metallic surface could be very important for reducing porosity in the joints obtained by RLW, indeed the surface cleaning of aluminum alloys using a pulsed cycle CO_2 laser (5 kW) has been proved that may contribute to reduce the development of porosity, especially at high speed (≥4 m/min) [El-Batahgy et al., 2013].
Moreover, [Miller et al., 2000] have stressed the role of optimizing the flow of protective argon gas after the accurate cleaning of the base metal.
Another study [Barnes et al., 2000] takes into account the techniques of solid and liquid state welding in which the automotive industry has shown the greatest interest, as potential candidates for the manufacture of reticular structures. This study points out the most successful solid state welding technique is the one based on the mechanical friction between two workpieces in relative motion, also named friction welding. This kind of welding is able to fuse materials due to heat generated by the friction. The friction leads also the advantage of crushing the stable oxide layer on the aluminum surface (alumina), and dispersing it throughout the weld zone, thus minimizing its deleterious effects.

As highlighted above, the most significant difficulties in welding aluminum are its compact oxide layer (alumina) and, in the case of liquid-state welding, its tendency to crack. Beyond this general issue, the RLW employment on aluminum alloys is even more difficult than that on steels because the aluminum alloys have a high reflectivity (more than pure aluminum), high thermal conductivity and a low viscosity [Aluminum Extruders association, 2007]. The high reflectivity allows aluminum to absorb a small fraction of the incident radiation. The high thermal conductivity causes a rapid heat transfer to prevent its concentration in the molten metal and the low viscosity of the melted zone prevents its expansion before the solidification.
Finally, after being welded by RLW, aluminum alloys use to have cracks due to residual stresses [Stritt et al., 2012]. This is the reason why often the RLW process on aluminum alloys requires the use of filler aluminum for filling the porosity and cracks that have arisen due to residual stresses
This paper debates an initial experimental study to understand the feasibility of the RLW implementation with two aluminum alloys, through the study of the relation between the porosity and the geometrical characteristics of the weld bead. This objective is carried out looking for an empirical model based on experimental data, which links the quality of the welds with their section geometry. Both the quality of the weld beads and its geometry derive from the examination of the section of the weld itself. The quality of weld beads is expressed as a percentage, in terms of porosity, i.e. the ratio between the area of defects (pores or cracks) and the area of bulk material. Understanding those factors – which can affect the quality of the welds – is a key issue to make RLW feasible, even if the analysis is conducted here as a first attempt, and with a restricted number of predictors. In fact, the presence of bubbles or pores, or even cracks, in the welded metal may be a serious limitation to the use of this technology, since the structural duty of joints may be granted no more, due to a reduced resistant section.
The experimental data to investigate the existence of relations among the amount of defects in welds and their geometrical parameters were collected through the metallographic examination of the transverse section of fifty-six specimens, made of AA5182 or AA6170.

3. Experimental data and methods

Experimental data are collected measuring the extension of defects in terms of cracks and pores detectable in fifty-six aluminum joints, made of AA5182 and AA6170, and obtained by the RLW. Measures were taken looking at the transverse section of the weld by the scanning electron microscopy technique (SEM) and post processing photos through a dedicated software. The RLW process requires at least three elements in order to be executed: a laser beam, an industrial robot, and a laser scanning system. The adopted laser source is a Nd:YAG one [AlShaer et al., 2014]. This laser, also used in the automotive field, employs power ranges between1 kW and 5 kW. The robot allows an easy placement of the scanner around the parts to be welded, to remove the work piece repositioning operations. The used robot for obtaining joints through RLW is a COMAU® C4GNH3, programmable via PLC language. This robot, programmable by PLC, is able to accurately execute very complex laser welds. The scanner, equipped with an optics, makes the detection of those profiles that have to be welded easier, carrying out the reduction of the downtime between the first welding and the following one.
The fifty-six samples were joined through an edge welding obtained by the RLW methodology, employing the laser head TRUMPF® PFO-3D which has a focal distance from 290 up to 1530 mm, a working distance of 280 mm, besides being equipped with an optical vision system. Each specimen includes thus a weld, made by RLW and it can be made of the AA5182 or the AA6170 alloys. These joints are carried out through a non-standard conditions RLW. In fact, the aluminum alloys use to be welded within an inert atmosphere, using a filler metal [Pardal et al., 2017] but, the fifty six specimens, employed in the present analysis, have been welded using none of the two conditions.
Before the cutting of specimens, the laser cleaning was employed for achieving the surface cleaning. The adopted procedure consists in subjecting the aluminum alloys to a pulsed laser for eliminating the tough layer of Al_2O_3 (alumina) on the metallic surface.
Removing this oxide layer significantly improves the quality of welded joints in terms of the amount of porosity in the weld bead. The adopted choice about the cleaning technique is supported by many examples from literature of porosity reduction as a result of the exposure of metal to a pulsed laser cycle. The porosity reduction in AA6014 aluminum joints from an extent of 10-80% to a value of 0,5%, after the exposure to pulsed Nd: YAG laser cycle is reported by [AlShaer et al., 2014]. Similar results have been found using a pulsed CO_2 laser cycle [El-Batahgy et al., 2013] on the AA5052, AA5083 and AA6061 aluminum alloys.
The acquisition of the experimental data has been set as a four phases procedure (specimen preparation, polishing of the specimen, analysis of specimen, and imaging) with the goal to speed up the analysis on the whole batch of samples. Then a metallographic analysis is carried out on each specimen. The metallographic analysis has been optimized for reducing the downtime among its different sub-phases, thus speeding up the whole process. Once the experimental

process is defined, the data acquisition is performed**.** In the preparation, the sample was cut into two sections: the transverse and longitudinal ones. Later, digital images are acquired for each section, as well as the dimensional parameters of the weld bead: the height T and the depth P. Subsequently, the samples, dissected and divided, are subjected to a vacuum cycle to remove any impurities that may cause conflicts with the resin. After being assembled in panels, the samples are mounted in the EPOFIX STRUERS® resin. Then they are dried in air through a 4 hours long exposure. Specimens are removed from the molds, and initially flattened through a 80 pcs card, to obtain a specimen opposite to the regular section to be analyzed. Subsequently, specimens are polished using abrasive cards (120, 240, 360, 600, 1200 pcs). Finally, all five specimens are polished to the cloths before using a diamond paste suspension by 6 pM and its velvety cloth from 6 pM, then a velvet cloth was used from 3 pM, and a diamond paste suspension by 3 µm. After, specimens have been subjected to acid attack through a 0.4% HFL solution for about 3 minutes. Finally, the appearance of the metallic surface has been observed through the microscope for acquiring the characteristic parameters of the weld bead.
The Figure 1 shows the geometrical parameters of the weld bead which are measured for each specimen. Referring to the picture, W is the weld bead width, H is its height and P is the cord depth. Finally D_m is the best fit diameter of the defect (the best fit diameter of a pore for instance).

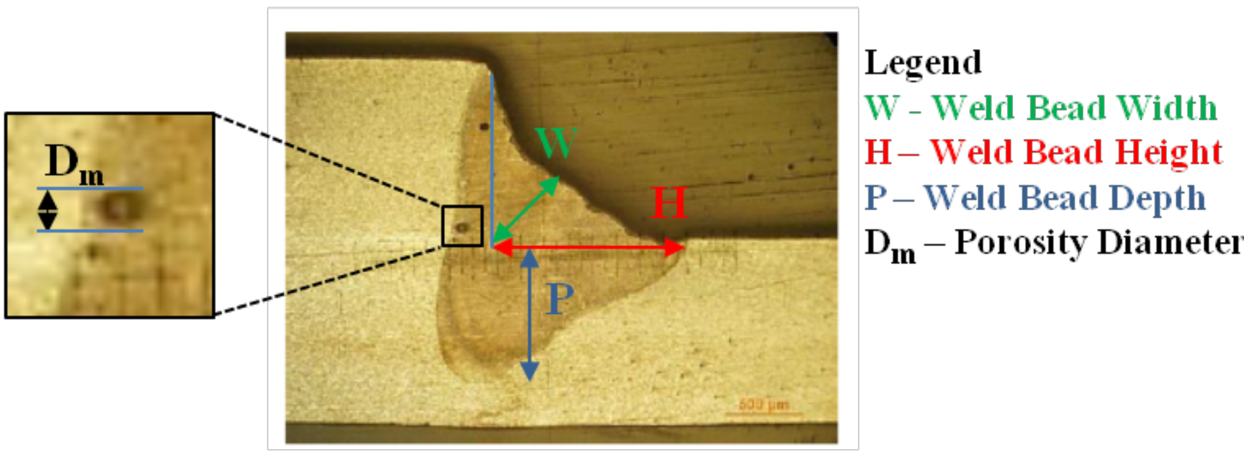

Figure. 1. Sample A7.1 (transverse section).

The results of the micrographic analysis are reported below. An analysis of all the micrographs of samples made of both the alloys (AA5182 and AA6170) shows that, on analyzed samples, only seven do not have a pronounced porosity. The micrographs of the four samples with lower porosity are here reported in Fig. 2-3. The others samples show a porosity not just present in the transverse section, but also in the longitudinal one.

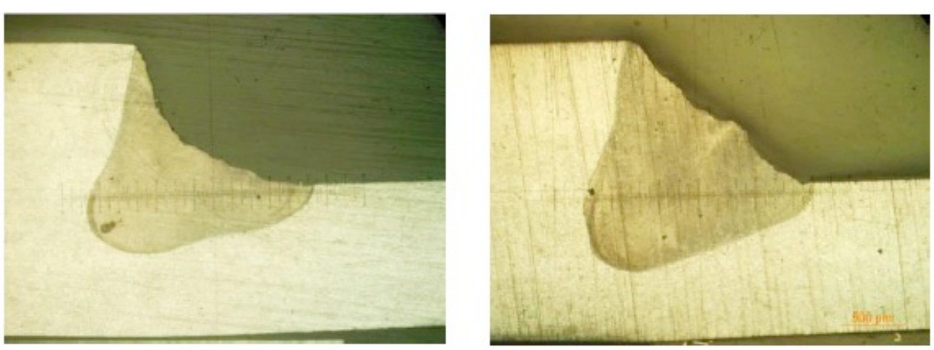

Figure. 2. Sample A23.3 (transverse section) and sample A35.1 (transverse section).

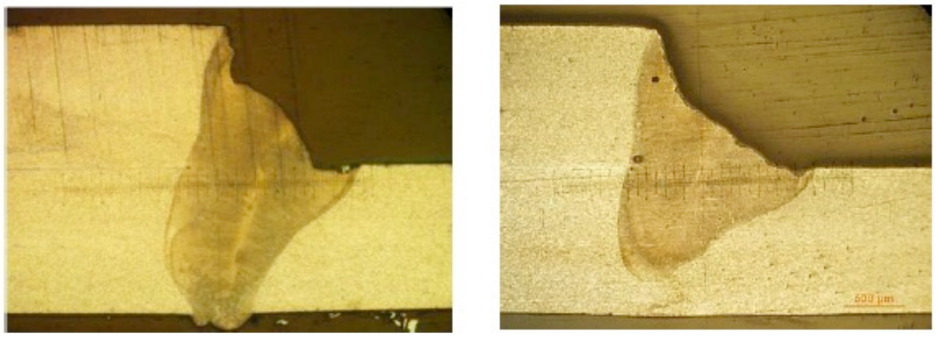

Figure. 3. Sample A55.1 (transverse section) and sample A41.1 (transverse section).

Once data had been collected, the relationship among the quality of welds and their geometrical parameters was investigated to single out a model capable to predict quality as a function of the transverse section geometry. The selected output of the model is the porosity of the welds *p*, expressed as the percentage of the defects area compared to the bulk section of the weld, both expressed in mm^2. The inputs of the model are the three geometrical dimensions which characterize the transverse section of the welded joint (H, P and W).
Collected data are featured in Table 1 and Table 2 for AA5182 and AA6170 alloys respectively. Each specimen is characterized by the three main dimensions of its transverse section, defined according to Figure 2, and to the corresponding porosity.

Table 1. Weld bead parameters and its porosity for AA5182 samples.

H (mm)	P (mm)	W (mm)	Porosity (%)
1,02	1,63	0,64	0,09
0,82	0,48	1,7	0,17
0,47	0,6	0,85	0,12
0,78	0,84	1,97	0,50
0,26	0,18	0,86	0,13
0,8	0,91	1,2	0,15
0,41	0,33	0,48	0,04
0,38	0,49	0,65	0,10
0,8	0,51	0,68	0,10
0,3	0,38	0,72	0,10
0,8	0,51	0,74	0,10
0,7	0,5	0,75	0,11
0,85	0,5	0,77	0,11
0,65	0,67	0,53	0,05
0,54	0,45	1,72	0,18
0,94	0,74	1,76	0,20
0,28	0,2	0,78	0,11
0,7	0,5	0,8	0,11
0,52	0,55	0,82	0,11
0,6	0,4	0,84	0,12
0,91	0,54	0,61	0,07
0,64	0,5	0,82	0,12

0,34	0,13	1,77	0,24
0,3	0,6	1,8	0,25
0,4	0,9	1,81	0,25
0,9	0,53	1,86	0,32
0,26	0,18	0,62	0,08
0,2	0,3	0,88	0,13
0,31	0,4	0,89	0,13
0,35	0,15	0,9	0,14
0,15	0,35	0,91	0,14
0,15	0,35	0,94	0,14
0,88	0,97	1,02	0,14
0,8	0,29	0,63	0,08
0,83	0,72	1,6	0,16
0,63	0,36	1,89	0,32
0,6	0,5	1,91	0,40
0,67	0,6	1,93	0,41
0,75	0,55	1,97	0,45
0,91	0,54	0,61	0,07

Table 2. Weld bead parameters and its porosity for AA6170 samples.

H (mm)	P (mm)	W (mm)	Porosity (%)
0,92	0,62	0,82	0,11
0,92	0,62	0,82	0,11
0,47	1,2	0,86	0,12
0,43	0,44	0,88	0,13
0,43	0,44	0,91	0,13
0,44	0,45	0,94	0,13
0,45	0,4	1,02	0,15
0,9	0,54	1,6	0,15
0,42	0,63	1,72	0,16
0,4	0,3	1,76	0,16
0,62	0,2	1,8	0,18
0,77	0,7	1,81	0,18
0,62	0,2	1,91	0,18
0,6	0,3	1,93	0,21
0,85	0,55	1,95	0,21
0,41	0,36	1,96	0,23

The proposed model is built through a regression analysis on the experimental data and consists of a polynomial function, defined according to Eq. (1) below, where H, P and W (expressed in mm) are the input predictors, and *k* represents all the non controllable factors, including the noise contribution.

$$\boldsymbol{p}\% = \boldsymbol{f}(\boldsymbol{H}, \boldsymbol{P}, \boldsymbol{W}, \boldsymbol{k}) \qquad \text{Eq.(1)}$$

The same analysis is conducted on both the two alloys to spot a dedicated solution for each alloy. This way to proceed is adopted to take into account the contribution of those parameters which have not been measured, and change from an alloy to another, like the chemical composition, the types of secondary phases, etc. As a first result, the effect of P and H on the porosity variation seems to be not significant for both the two alloys. This result is outlined in Figure 4, where both high and low values for porosity are found for a wide range of H and P values.

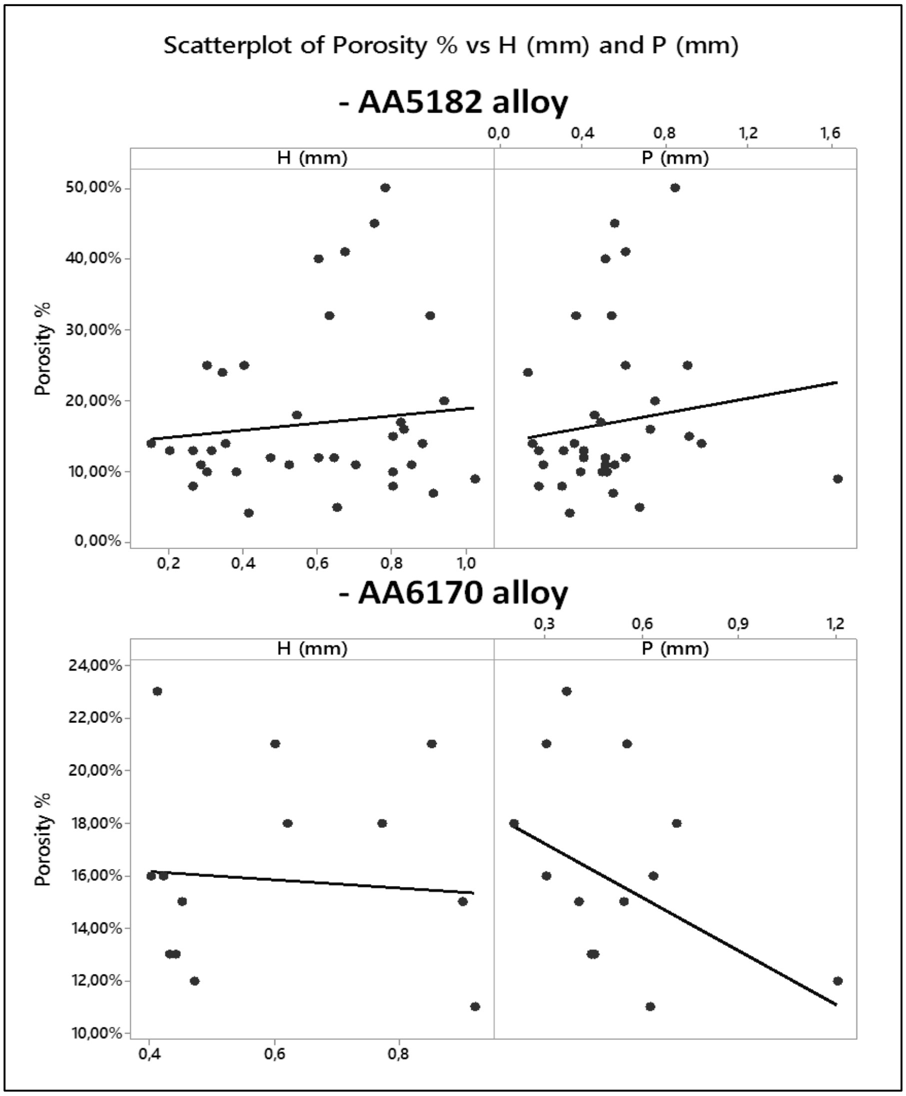

Figure 4. Scatter plots spotting the relation between porosity and H, besides the one between porosity and P for both alloys.

The regression analysis carried out on experimental data aims to find out an equation to link porosity to geometrical parameters. The goodness of regression fit is evaluated through Rsq% and Rsq% adjusted indexes, besides the P value associated with the obtained equation coefficients. Rsq% index represents the amount of the output variability that is explained by the input variation. The Rsq% adjusted has the same meaning, but it is referred to the dimension of the sample (here fifty-six elements). Both indexes represent how the model is suitable to reproduce the output, given certain inputs. Furthermore, the significance of the found coefficients for the equation is assessed through their associated P value and the table of ANOVA. The P value represents the probability to make a mistake, assuming that

the found coefficient (or its corresponding factor) does not have any significance. In order to assess if the coefficient (and its corresponding variable) has any significance or not, the calculated P value shall be compared with an assigned threshold, usually set at 5%.
Finally, the table of ANOVA gives evidences about the Signal-to-Noise ratio or, in other words, it gives information about the significance of a predictor in respect with the noise.

The regression analysis for AA5182 alloy outlines a cubic dependency of porosity by the bead width W. The other two parameters (H and P) are confirmed as not significant in describing the output variation, therefore they have been removed from the equation. The found equation to compute the percentage of porosity as a function of W is the following Eq. (2) as per AA5182:

$$\boldsymbol{p\% = -0,7232 + 2,475W - 2,328W^2 + 0,6984W^3} \qquad \text{Eq. (2)}$$

Coefficients for W, W^2 and W^3 are all significant, since their corresponding P values are smaller than the set threshold value, and both Rsq% and Rsq% adjusted indexes are higher than 97%.

Figure 5 shows the porosity values in relation to W, and the best fitting curve (continuous line). The dashed line represents the calculated 95% confidence interval, which includes most part of experimental points.

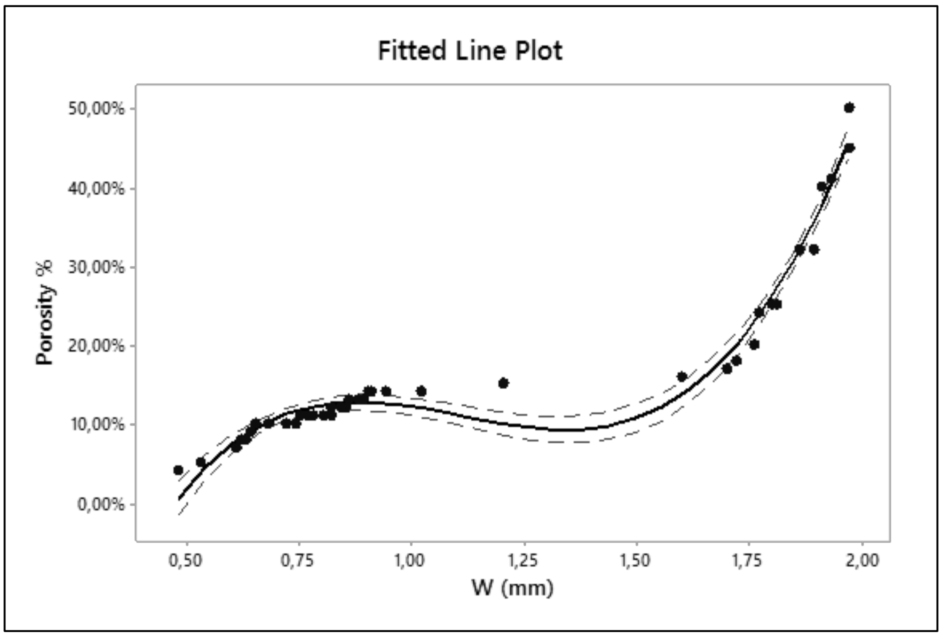

Figure 5. Experimental points with the best fit curve (continuous line) and the corresponding 95% confidence interval (dashed line).

The same analysis, repeated for the AA6170 alloy, gives similar results since a cubic relation is found for linking the porosity to the bead width W. Such relation is represented by the continuous curve in Figure 6 and it is defined through the following Eq. (3):

$$\boldsymbol{p\% = -0,7263 + 2W - 1,498W^2 + 0,3691W^3} \qquad \text{Eq. (3)}$$

Although a minor amount of experimental data for AA6170 alloy, the obtained curve is able to reproduce the porosity variation with good approximation; in fact, both Rsq% and Rsq% adjusted are 95% and 96% respectively.

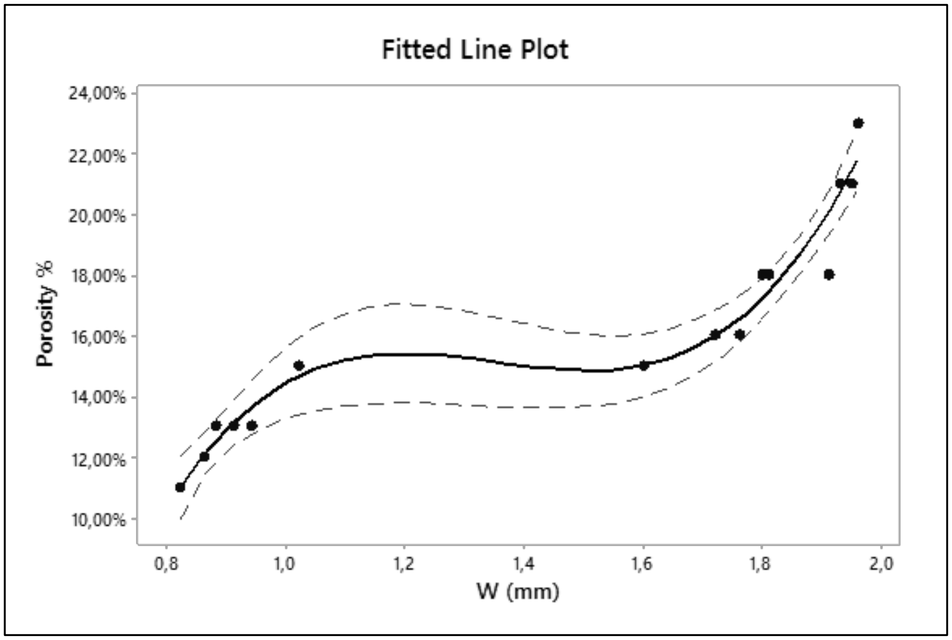

Figure 6. Experimental points with the best fit curve (continuous line) and the corresponding 95% confidence interval (dashed line).

3. Final remarks and conclusions

The automotive industry is trying to reduce the weight of cars since this is a key issue for reducing harmful emissions and thus satisfying regulations like the Kyoto protocol. In order to accomplish this need and, simultaneously providing safer and more reliable cars, manufacturers are looking for lighter materials that can ensure at least the same mechanical resistance for their products. A key role in this challenging scenario is played by new technologies and their right use, since they allow the economic application of these materials and the manufacture of new geometries

The RLW is a very flexible and convenient technology because it can make several kinds of welds and it is able to employ several light alloys, such as aluminum and zinc. These features make its application recommendable for the automotive industry but, on the other hand, it may be pretty difficult on aluminum alloys, because of the material characteristics (high reflectivity, high thermal conductivity and a low viscosity). Furthermore, the remote laser welded joints show very often cracks due to residual stresses; other defects may arise because of the presence of an alumina layer on the metallic surface. These are the reasons why the welding requires the filler aluminum and takes place in an inert atmosphere.

This paper has shown an initial experimental study to understand the feasibility of the RLW implementation with two aluminum alloys, through the study of the relation between the quality of the weld bead and the geometrical characteristics in its transverse section.

The experimental data are obtained through a metallographic analysis performed on fifty six samples obtained through welding two parts by the RLW in non-standard conditions. The specimens observation through the SEM has allowed to measure the geometrical dimension of the joint transverse section. The quality of the weld has been accounted through the calculation of porosity, i.e. the ratio between the area of defects (pores or cracks) and the area of bulk material.

A statistical investigation has revealed that the depth and the height of the weld bead have no significance on the result but there is a cubic relationship between the porosity and the width of the cord.

This study is a first attempt to evaluate the use of RLW for obtaining good quality welds just through the definition of their geometrical dimensions. A further development could be the investigation of the relationship among the porosity and the process variable, here assumed as constant. This future analysis could represent a further step in the understanding the best method to apply the RLW promising technique.

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Biography

Alessio Pasquale Mirarchi is a PhD student at the Guglielmo Marconi University. His PhD is in Physic Science and Engineering of the Industrial Innovation. He is an Industrial Engineer. Currently he works in Maserati and Alfa Romeo as Resident Mechanical Engineer for Harman as CAD audio manager. His research interests include optimization, reliability and lean production methodologies.

Andrea Girgenti is Ph.D Candidate of Physic Science and Engineering of Industrial Innovation at Guglielmo Marconi University , Italy. He has been involved in several R&D projects both in the mechanical and the oil & gas fields. His research interests focus on mechanical design, corrosion testing and control, project management, quality and reliability. He received his Master Degree (2012) from University of Florence in Mechanical Engineering.