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FIBER LASER WELDING OF COPPER BASED OPEN CELL FOAMS

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Abstract

Porous metallic materials with cellular structures are well known to combine many physical and mechanical properties. This mix of different properties makes these systems very attractive for both structural and functional applications, depending on pore size, methodology of production and material characteristics. Because of their porous structure, unconventional machining and more in general unconventional processing is becoming more and more important nowadays for promoting the industrial applications of such a kind of materials.
In this work a study on the fiber laser welding process, performed using a 1 kW continuous wave fiber laser, on Cu based foams is reported. The foams, whose the mean size of the pore is approximately 3.5 mm, were produced by means of infiltration of leachable space holders inside the metal in liquid state. After preliminary welding test in a bead on plate configuration performed only on the surface of the foams, samples in lap joint configuration were realized for evaluating the cross section of the welded bead. The effect of the process speed on the geometrical characteristic features of the joints was studied. The extent of the heat affected zone was evaluated directly by optical microscopy and indirectly by executing micro-hardness test. Then the heat affected zone extension was corrected to the process speed. Besides, electron scanning microscopy, coupled with electron dispersive spectroscopy, was adopted for the compositional analysis of the welded beads.
It was shown that the laser joints could be achieved in lap joint configuration, allowing high reflectivity porous alloys with complex structures and average pore size of the order of millimeters to be connected.

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Keywords: Joining, laser beam machining, metal foam.

1. Introduction

Cellular materials are innovative and challenging materials, able to offer an interesting and almost unique combination in terms of morphology and material performances [1,2]. This fact allows these materials to show an interesting mix of physical-chemical-mechanical properties, making them very attractive for structural and functional applications in different industrial sectors. Depending on the pore size and shape, material and dimensions, different processes are available for the realization of cellular structures [3].

One of the most innovative foaming process concerns the infiltration of leachable solid particles in the molten material [4-6]. In open literature, the most studied metallic foams, obtained by liquid infiltration of leachable space holders, are usually Al or Cu based alloys because these offer lightness, high stiffness, good thermal stability and quite low manufacturing cost [4]. It was demonstrated that the functional response of these cellular materials can be really full of interesting prospective for different applications [7-9].
Literature offers some works, in which laser material processing is studied on cellular materials. In these works the laser beam is adopted for assisting the foaming process [10], for bending [11], for cutting [12] and welding [13] metallic foams.
In this work the authors investigated the welding process, performed using a fiber laser, for joining open cell foams in $Cu_{60}Zn_{40}$ [wt %] brass. The foams, whose pore size was in the range of approximately 3.5 mm ± 0.5 mm, were realized by means of liquid infiltration method, using silica gel as space holder. Preliminary joining tests were done in the bead on plate configuration on the foams but the welded beads were not obtained, because of both the large pore size with respect of the laser beam and because of the high foam porosity (about 66%). Consequently, the laser welding process has been positively approached in the lap joint configuration, using a thin plate placed on the top surface of the foams. The

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effect of the process speed (5-20 mm/s) on the geometrical characteristic features of the transversal section of the joints, such as melted zone (MZ) and heat affected zone (HAZ), was studied. The characterization was carried out through micro-hardness testing, optical microscopy (OM) and scanning electron microscopy (SEM) and compositional analysis with electron dispersive spectroscopy (EDS). The joining of porous alloys with complex structures and with pore size in the order of some millimeters was successfully shown using a CW fiber laser in the lap joint configuration.

2. Experimental

Ingots of $Cu_{60}Zn_{40}$ [wt %] brass were melted in a Aseg Galloni VCMIII induction melting system, under pure Ar flow. Then, the material was foamed with the liquid infiltration method, by using amorphous SiO_2 spheres, whose mean size was 3.5 mm ± 0.5 mm, as space holders. The process details were already described elsewhere [5,8]. After foaming, the space holders were removed with a chemical etching (50% HF and 50% H_2O). A typical cross section of the realized foam is shown in Fig. 1; almost round and interconnected pores are generated and an average pore fraction of 65-70% was reached.

The welding process was performed using a CW fiber laser (mod. YLR 1000, IPG Photonics), whose the main characteristics are: (i) maximum power = 1kW; (ii) central wavelength=1070 nm; (iii) beam quality factor =5.14; (iv) core size of the optical fiber=50 μm.

Laser welding process was firstly studied in bead on plate configuration and secondly in lap joint configuration, where the joining was done using a 1 mm thick plate of the same alloy, placed on the top surface of the foam. The effect of the process speed was studied by means of a statistical approach on the welded bead. The process parameters, used in the experiments, are reported in Table 1; three replications for each process condition were performed. Linear regression model was studied on the width of the welded bead, obtained in the plate, while only qualitative analysis was done on the melted material realized in the foam.

Table 1. Definition of the process parameters, used in the welding experiments

Parameters/ values	
Process speed	5-10-15-20 mm/s
Power	1000 W
Laser spot	0.54 mm
Assist gas	Argon
Gas pressure	5 bar
Gas flow	40 l/min
Inclination of the laser beam	10°
Collimation length	100 mm
Focusing length	200 mm
Focal position	+ 3 mm

Metallographic cross sections of the laser welded beads were prepared, etched (chemistry of the etchant: 36% of H_20, 36% of NH_4OH, 28% of H_2O_2) and analyzed by means of both optical microscopy (OM) and scanning electronic (SEM) microscopy. Mechanical testing was done through micro-hardness (test load of 200 g) for obtaining the extent of the heat affected zone (HAZ). Moreover, compositional analysis was also proposed for evaluating the modification of the chemical composition in proximity of the laser joint, by using energy dispersive spectroscopy (EDS).

3. Analysis of results and discussion

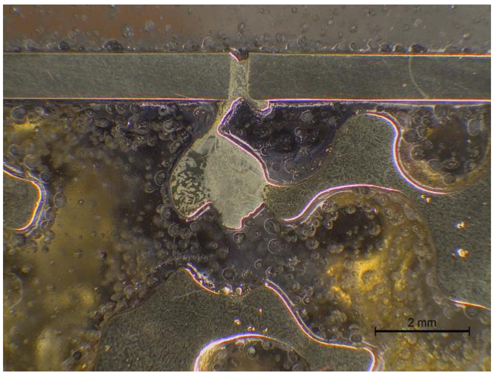
Some preliminary tests of laser welding of foams were carried out in bead on plate configuration. As it can be seen in Fig. 1, the laser beam did not allow the joining of the cellular structure but only a degradation of the foam was obtained. This effect can be explained through two reasons: (i) the pore size is definitely larger than the laser spot size; (ii) the high porosity of the foam as well as the pore size guarantee small portions of material placed between large voids. As a result, the separation of the cellular structure was obtained, as depicted from both the lateral and top views of the foam laser processed of Fig. 1.

Fig. 1. Trial of joining of the foam in the bead on plate configuration

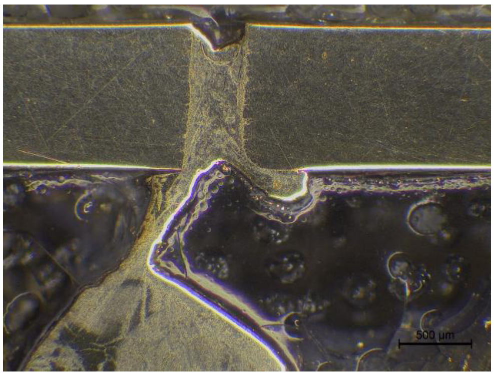
From this first results, the investigation was orientated in the direction of the addition of material for the realization of the joint. Consequently, the welding was studied in the lap joint configuration, where a 1 mm thick plate of the same material was welded to the top surface of the foam. A representative cross section of the welded bead, realized in this second configuration, is depicted in Fig. 2a. It can be seen that an almost vertical welded bead was produced in the thin plate; a part of the melted material fell down from the plate to the cellular structure, as it can be also expected from the presence of the cavity placed at the top surface of the welded bead in the plate. The joint between the plate and the foam is depicted in the magnification of Fig. 2b, where a thin layer of melted material was spread in proximity of the bottom surface of the plate. Moreover, the propagation of the laser beam in the foam could be demonstrated for the melting of a part of the foam (see Fig. 2c), placed below the upper welded bead. It can be stated that the joining of this cellular structure requests the presence of material to be filled for the realization of a bridge of melted material among adjacent pores [14].

In fact, the material of the plate partially falls down in the cellular structure, allowing its joint with the cellular substrate and filling up the pore voids, as shown. Moreover, the penetration of the welded bead cannot considered constant, as it happens in bulk structures, but it varies in function of the morphology of the cellular structure, in terms of voids and inter-pore material.

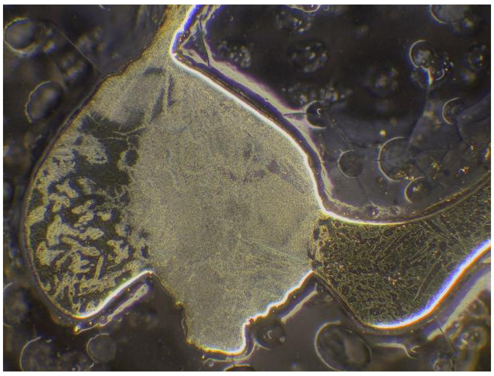
Because of the well-know difficulties in the welding of Cu based alloys [15], it is important to underline the absence of cracks in the area around the joint.



(a)



(b)



(c)

Fig. 2. Welded bead, performed at 15 mm/s in lap joint configuration: complete view (a); magnification of the thin plate (b) and of the foam (c)

Fig. 3 shows the box plot, reporting the evolution of the width of the welded bead w, measured at half of the thickness of the plate, in function of the process speed v.

A significant reduction in the width of the weld beam is observed from a mean value of approximately 0.58 mm to 0.36 mm, being directly associated with increasing the process speed and with consequent decreasing the specific energy density. As for the process variance, a relatively high 95% confidence interval (CI) for the mean is observed at all the values of process speed.

The statistical influence of the process speed is described from the regressive model, reported in Table 2. In this case, the linear behavior between process speed and width of the welded bead was described by the regressive model, shown in Fig. 4. The corresponding confidence and predictive intervals are also shown in Fig. 4.

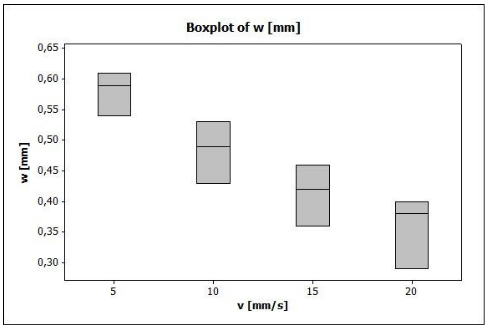


Fig. 3. Box plot of the width of the welded bead

Table 1. Regression analysis of the width of the welded bead

The regression equation is:
w [mm] = 0,643 - 0,0148 v [mm/s]

Predictor	Coef	SE Coef	T	P
Constant	0,64333	0,03227	19,94	0,000
v [mm/s]	-0,014800	0,002357	-6,28	0,000

S = 0,0456362
R-Sq = 79,8% R-Sq(adj) = 77,8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0,082140	0,082140	39,44	0,000
Residual Error	10	0,020827	0,002083		
Lack of Fit	2	0,001227	0,000613	0,25	0,784
Pure Error	8	0,019600	0,002450		
Total	11	0,102967			

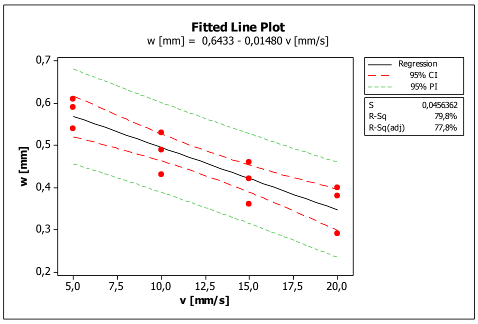


Fig. 4. Regressive model of the width of the welded bead

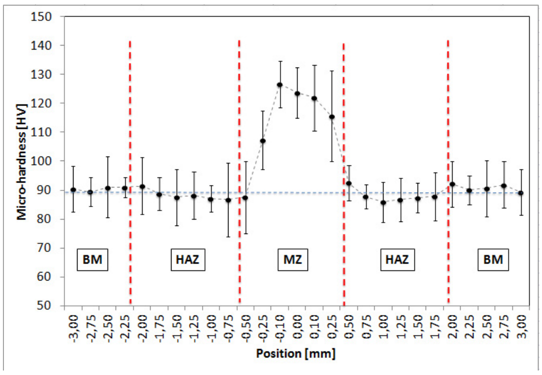
Another representative variable that is characteristic of the weld beads is the HAZ.

From the analysis of the micrographs of Fig. 2 it can be stated that a microstructure modification of the material, even if present, is very hard to be seen near the MZ. This could be explained due to the fast cooling rates, characteristics of the laser welding; moreover, the high thermal conductivity of the copper alloy as well as the quite fine grain size of the plate don't allow for a significant variation of the material microstructure.

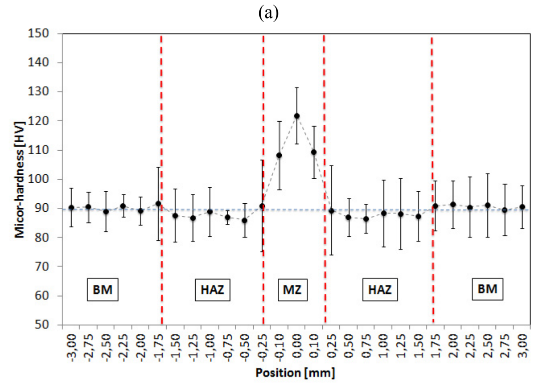
However, because of the initial cold rolled condition of the plates, a stress relieve can occur in the HAZ; in fact, this effect is confirmed by the hardness profiles, shown in Fig. 5, where a softening of the material can be seen for both the samples, realized at the two extreme process conditions.

Therefore, the HAZ was considered as the extent of the zone near the weld bead, where an hardness value lower than the one of the base material (about 90 HV) is observed, by evaluating the microhardness profile across the weld bead at half of the thickness of the thin plate.

A mean hardness value of 90.1 HV with a 95% CI between 89.1 HV and 91.0 HV was calculated for the base material [16].



(a)



(b)

Fig. 5. Micro-hardness evolution across the welded bead at different process speed: 5 mm/s (a) and 20 mm/s (b)

The micro-hardness trend at process speed of 5 mm/s is shown in Fig. 5a. The centre of the welded bead exhibited the highest hardness (about 125-130 HV); rapid solidifications of the melted pool, due to the high cooling rates, usually generate a fine microstructure with a significant increase of the hardness. Thus, a significant reduction in the hardness was observed passing from the MZ to the HAZ. The softening appears in the HAZ, even if the hardness reduction between the HAZ and the BM is limited but still present. The extent of the HAZ was estimated as the distance above which the hardness had stabilised to the value of the BM; therefore, the extent of the HAZ, in correspondence of 5 mm/s, was estimated to be approximately 4 mm (MZ included).

Fig. 5b shows the hardness profile measured for the welded bead produced at the highest process speed (20 mm/s). Here, it can be seen a relatively smaller HAZ of about 3.5 mm. A similar softening effect of the 5 mm/s welding condition was also seen at the highest process speed.

Because of that the extent of the HAZ, ranging from 4 mm (5 mm/s) to 3.5 mm (20 mm/s), does not appear to be strongly influenced by the process speeds in the investigated range.

Compositional analysis was also performed across the welded bead, as done for the micro-hardness profile, for the evaluation of the chemistry of the joint. As shown in the compositional profile of Fig. 6, no evident change in the chemical composition was detected, considering that the experimental error of EDS is about 1 %wt. The loss of Zn content was avoided during the welding; this is a relevant result, because Zn is usually a critical element for thermal material processing for its low melting and boiling points [14]. In this case, the pushing action of the assist gas flow was able to contrast the Zn evaporation.

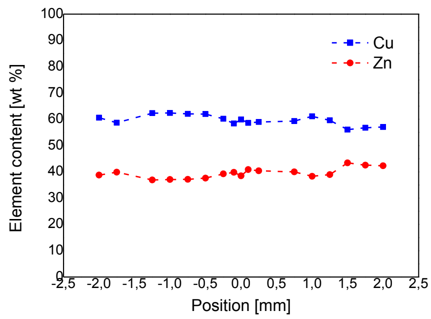


Fig. 6. Compositional analysis across the welded bead

4. Conclusions

In this work the welding process using a 1 kW CW fiber laser was studied for joining cellular materials, under the shape of open cell Cu60Zn40 [wt %] brass foams. The main conclusions that were drawn are the following:

- Laser welding of foams in bead on plate configuration did not show the possibility of obtaining the joint, because of the degradation of the cellular structure.
- On the contrary, welded beads were realized through the connection between the plate and the some pores of the foam in lap joint configuration. The material, melted from the thin plate, was necessary for producing the joining, thanks to its fall in the gap of the bulk and cellular materials. No evident cracks were observed in proximity of the welded bead.
- The process speed was able statistically to influence the width of the welded bead. The increase of the hardness (125-130 HV) was detected in the MZ for

the finer microstructure, obtained thanks to a rapid solidification of the material.

- The extent of the HAZ was defined through an observation of a softening of the material (about 85 HV) in the order of 3.5-4 mm (melted material included); Only a small reduction of the extent of the HAZ was seen from 5 mm/s to 20 mm/s.
- Compositional analysis did not show any significant modification of the material chemistry in both the MZ and the HAZ. The laser welding did not allow the Zn vaporization, which is usually quite common.

Here, it was shown that the welding process using a fiber laser can be adopted for the joining of CuZn foams, having pore size in the order of few millimeters. The presence of the thin plate, place on the top surface of the foam, helped the generation of the welded bead, as that melted material could fall down for filling up the pore voids.

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