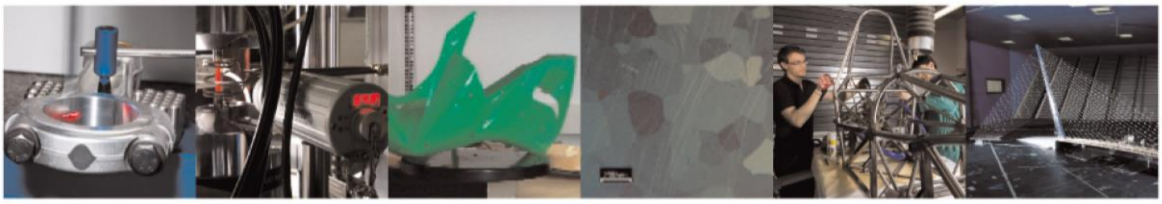

Microstructure and calorimetric behavior of laser welded open cell foams in CuZnAl shape memory alloy

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LASER WELDABILITY OF OPEN CELL FOAMS IN CUZNAL SHAPE MEMORY ALLOY

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Abstract

Cellular shape memory alloys are very promising smart materials, able to combine functional properties of the material with lightness, stiffness and damping capacity of the cellular structure. Their processing with low modification of the material properties remains an open question. In this work the laser weldability of CuZnAl shape memory alloy in the form of open cell foams was studied. The cellular structure was proved to be successfully welded in lap joint configuration by using a thin plate of the same alloy. Softening was seen in the welded bead in all the investigated range of process speed as well as a double stage heat affected zone was identified, due to different microstructures; the martensitic transformation was shifted to higher temperatures and the corresponding peaks were sharper with respect to the base material, due to the rapid solidification of the material. Anyways, no compositional variations were detected in the joints.

Keywords: Shape Memory Alloy, Metallic Foams, Laser Welding, Calorimetry.

Introduction

Shape memory alloys (SMAs) are smart materials able to offer unique functional properties, namely pseudo-elasticity (PE) and shape memory effect (SME) [1]. SMA cellular materials are a novel class of tailored materials because they can offer unique combinations of several properties: functional performances previously mentioned, lightness, damping capacity and stiffness lower than the corresponding bulk material [2]. The mix of these properties make these materials very attractive for different applications, like ship building, aerospace industry and civil engineering, for light-weight constructions, energy absorption, acoustic and thermal control [3]. Processing and manufacturing of these materials become relevant for their large diffusion in several applications; since some production methods have been deeply studied [1,4-6], the manufacturing requires investigations because it is quite difficult without damaging both functional properties and cellular structure. Few works investigating unconventional processes for foam machining have been studied in literature and laser material processing appears one of the most interesting candidates for this issue. The laser beam was adopted for assisting the foaming process [7], bending [8], cutting [9] and welding [10] of sandwich aluminum panels. Peculiar characteristics of these works are the microscale pore size and the close cell structure of the foams. These two characteristics are of great importance, because they affect not only the performances of the foam but also the final results of the process. On the contrary, it was found that the processing of open cell structures with quite large porosity, in the order of millimeters, appears more difficult, as the pore interconnections should be maintained in their initial state. Only few works deals with the laser welding of CuZn foams with these characteristics [11,12] while only other two works, dealing on laser cutting [13] and welding [14] of CuAl based SMAs, were found. Anyway, no information on the machining of SMA cellular materials could be found.
In this work laser welding of an open cell CuZnAl shape memory alloy foam with large pore size was investigated; the beads were characterized and it was found that the calorimetric properties were not affected by the welding process.

Experimental

Laser welding was studied in lap joint configuration, by using a 1 mm thick plate of the same material. SMA $Cu_{68}Zn_{19}Al_{13}$ [at %] ingots were melted in an induction melting system (Aseg Galloni VCMIII), under pure Ar flow for avoiding oxidation. Then, the ingots were foamed by means of the liquid infiltration of space-holders method [4,6]. Amorphous SiO_2 spheres (Sigma S7500 Type II) were used as space holders, having a size distribution of 3.5 mm ± 0.5 mm; after the foaming process, the space holders were removed using an aqueous solution with 25% HF. Small samples, 15 x 15 x 40 mm^3 in size, were cut and welded in lap joint configuration, as described elsewhere [11]. For this issue, a 1 kW continuous active fiber laser (mod. YLR 1000 from IPG Photonics) was used; the main characteristics of the laser source are: (i) maximum power 1 kW; (ii) emission wavelength: 1070 nm; (iii) beam quality factor: 5.14; (iv) core diameter: 50 μm. The welding experiments were performed by using the process parameters listed in Table 1.

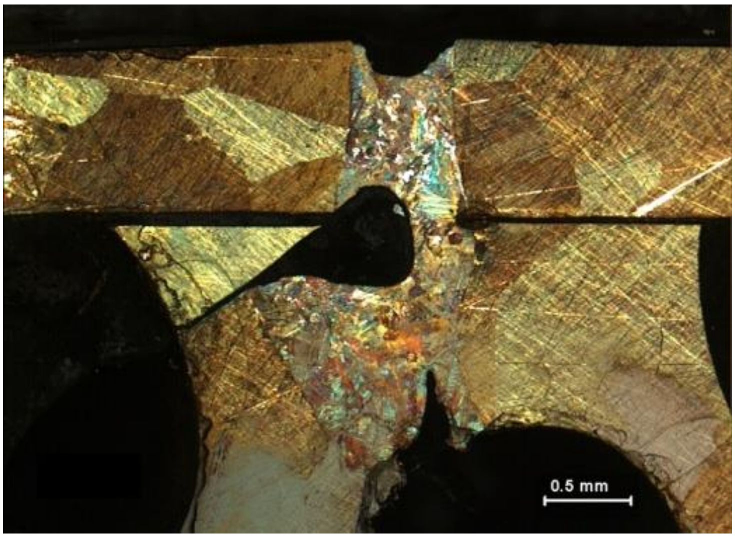
Process speed	10-15-20 mm/s
Power	1 kW
Laser spot size	0.54 mm
Assist gas/ pressure	Argon @ 5 bar
Gas flow	40 l/min
Inclination of the laser beam	10°
Collimation/ focusing length	100/200 mm
Focal position	+ 3 mm

Table 1: Process parameters used for the welding of the foams

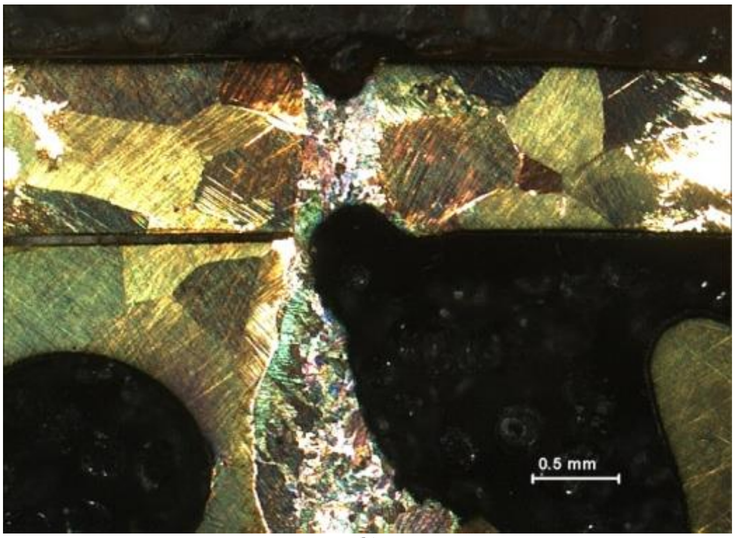
Cross sections of the weld beads were examined via optical microscopy OM and via scanning electron microscopy (SEM), equipped with energy dispersive spectroscopy (EDS), for the compositional analysis. Hardness profile, using a load of 200 g, was obtained across the welded bead, present in the plate, to estimate the mechanical properties. Functional properties of the welded beads were studied via differential scanning calorimetry (DSC, model Q100 from TA Instruments) with a heating/cooling rates of 10°C/min.

Analysis of results

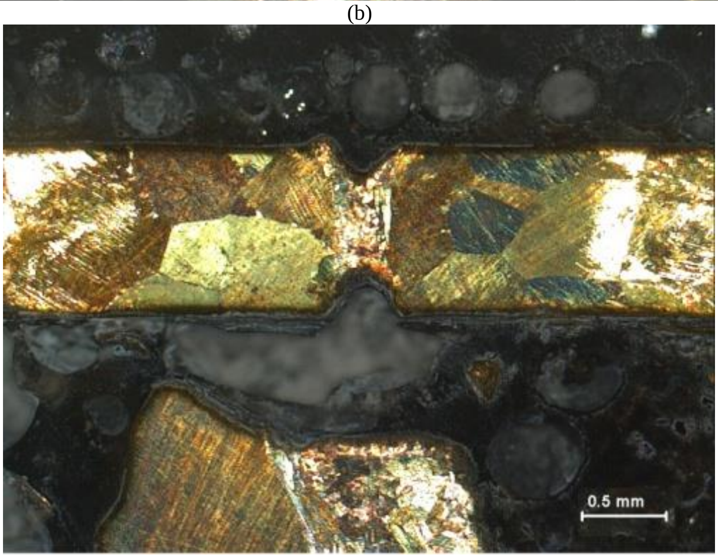
Fig. 1 shows the cross section of the welded beads, realized varying the process speed from 10 mm/s up to 20 mm/s. First the plate is melted by the laser beam, then the heat can penetrate through the melting pool into the cellular structure, due to its high irradiance, and it can melts even the foam itself. Even if a portion of the foam can be melted, the joint can be realized in the lap joint configuration, only thanks to the filling of the pores with a portion of the plate melted. This approach allows cellular structures without filler material to be successfully joined. In fact, preliminary test of laser welding in bead on plate configuration was even done on the foam itself but no successful beads were obtained, because of the degradation of the cellular structure [11]. The following characterization would be focused on the welded beads, realized in the plate placed on the top surface of the foams; this is due to the large variability of the portion of joints in the foam, depending on the large alternation among voids and foam ligaments, which cannot allow a reasonable study of the result. As it can be seen from the micrographs of Fig. 1, both the shape and the size of the joints depend on the process speed, according to the literature results on brass alloys [11-12,15], and on the morphology of the cellular structure. The realization of the joint between the plate and the foam was successfully reached, even if it is not continuous along the welding line because of the alternative presence of voids and ligaments. The micrographs, shown in Fig. 1, show a modification of the microstructure from the base material (BM) to the melted material.



(a)



(b)



(c)

Fig. 1. Cross section of the welded beads, realized varying the process speed: 10 mm/s (a), 15 mm/s (b) and 20 (mm/s) (c)

The BM shows a large microstructure, with grain size in the order of millimeters, while the melted material indicates an evident grain refinement, due to the fast heating and cooling of laser welding [15]. The shape of the joints did not show any significant variations by changing the process speed, as already seen even in the laser welding of brass [11,12]. On the contrary, the penetration of the laser beam in the cellular structure could depend on the presence of voids/ligaments. Due to an incident power density of about $4.37 \cdot 10^5$ W/cm^2, it can be stated that deep penetration could be reached: this is in good agreement with the literature [16]. The micrograph of Fig. 2, showing the welded bead realized by using the same process conditions in the CuZnAl SMA with larger thickness, confirms the deep penetration mode in welding by using the considered set of parameters. Consequently, the penetration of the keyhole allows the melting even for several millimeters without a great enlargement of the bead, which could damage the cellular structure; in the case depicted in Fig. 2 the penetration is about 4 mm.

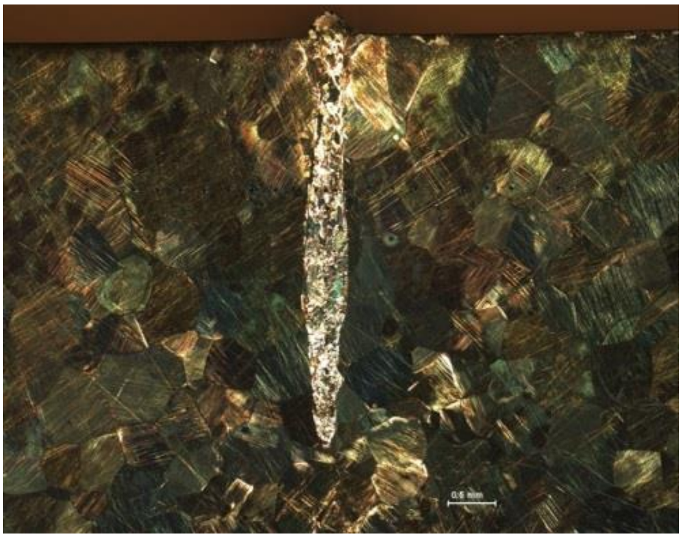


Fig. 2: Welded bead, realized on the bulk CuZnAl SMA at 10 mm/s

Mechanical properties of the beads were evaluated through micro-hardness profiles. A representative trend of the micro-hardness is shown in Fig. 3, performed at half of the thickness of the plate joined to the foam at the intermediate process speed (15 mm/s). The center of the welded bead (x=0 mm) was characterized by the lowest values of microhardness (180 HV). This behavior is completely different than the one observed in the laser welding of brass [11], where the melted zone (MZ) was harder than the BM: nether less the high cooling rate in laser welding and the resulting small grain size in the MZ of CuZnAl alloy, a softening was evident in the center of the bead. In Fig. 3 it can be detected a heat affected zone (HAZ), given by a variation of the microhardness between the MZ (≈180 HV) and the BM (≈235 HV). The symmetric trend of the microhardness on the right and on the left from the center of the welded bead can confirm the repeatability of the results.

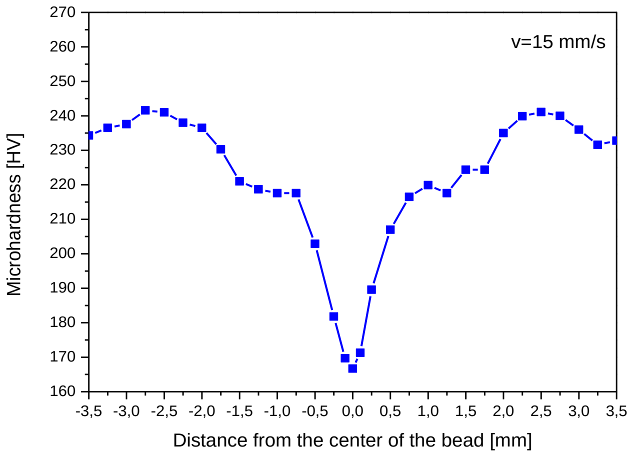


Fig.3. Hardness profiles across the welded bead, realized at a process speed of 15 mm/s

Two average levels of microhardness were detected in the HAZ (see Fig. 3): 220 HV and 245 HV, respectively. The micrograph of Fig. 4 can confirm the presence of a double stage HAZ, having different microstructures. The first one closer to the MZ, defined by the dash line, shows a lamellar structure, indicating the presence of martensite (see the arrow in Fig. 4); the second one, defined by the continuous line, free lamellae structure, probably due to less rapid thermal cycle performed at lower temperatures.

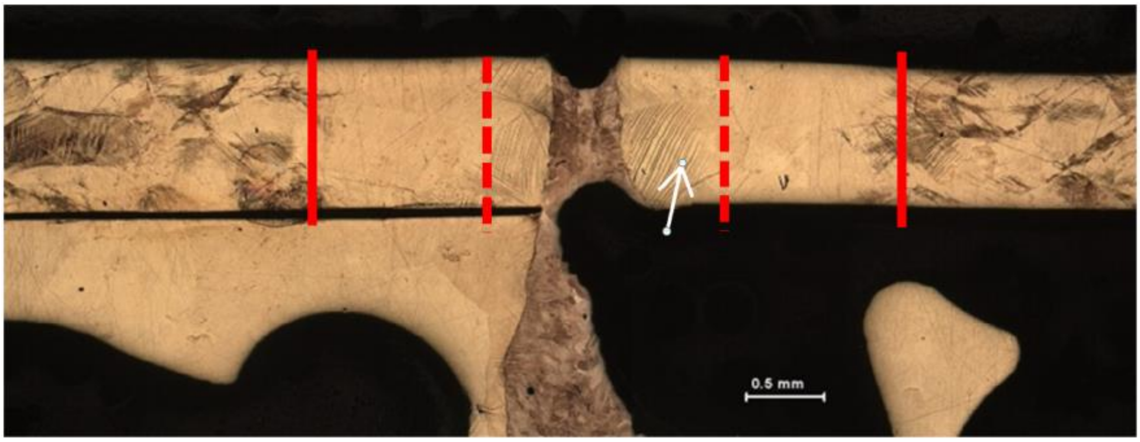


Fig.4: Identification of double stage HAZ in the cross section of the welded bead, realized at 15 mm/s; polarized light was used for the OM observation.

Anyways, no significant variations concerning the microhardness profiles were detected by changing the process speed. The extent of the HAZ was estimated about 3.0 ± 0.5 mm from the center of the welded bead for all the investigated values of process speed: similar effect of process speed on the HAZ was obtained in the laser welding of CuZn alloy but smaller extent of the HAZ was measured in the brass [11], probably due to the lower thermal conductivity of the CuZnAl alloy. Due to this evident modification between the BM and the MZ, the calorimetric properties of these two regions were investigated, as shown in Fig. 5. First the martensitic transformation (MT) appears even in the MZ: sharper peaks of the MT and an increase of the characteristic temperatures can be detected from the DSC scans. The modification of the peaks' shape may depend on the finer grains, obtained in the MZ due to the DSC scans. The modification of the peaks' shape may depend on the finer grains, obtained in the MZ due to the high cooling rate of laser welding, and on the high degree of homogeneity of the alloy after the melting; moreover, this effect may be even due to a stress release, because the initial state of the plate of cold rolled. However, the alloy after welding remains pseudo-elastic, as the BM. Additionally, the temperature shift depends on the thermal treatment induced by the laser beam. On the contrary, this effect cannot be due to a compositional variation: EDS measurements were done across the welded bead and no evident compositional change was detected, as depicted in Fig. 6.

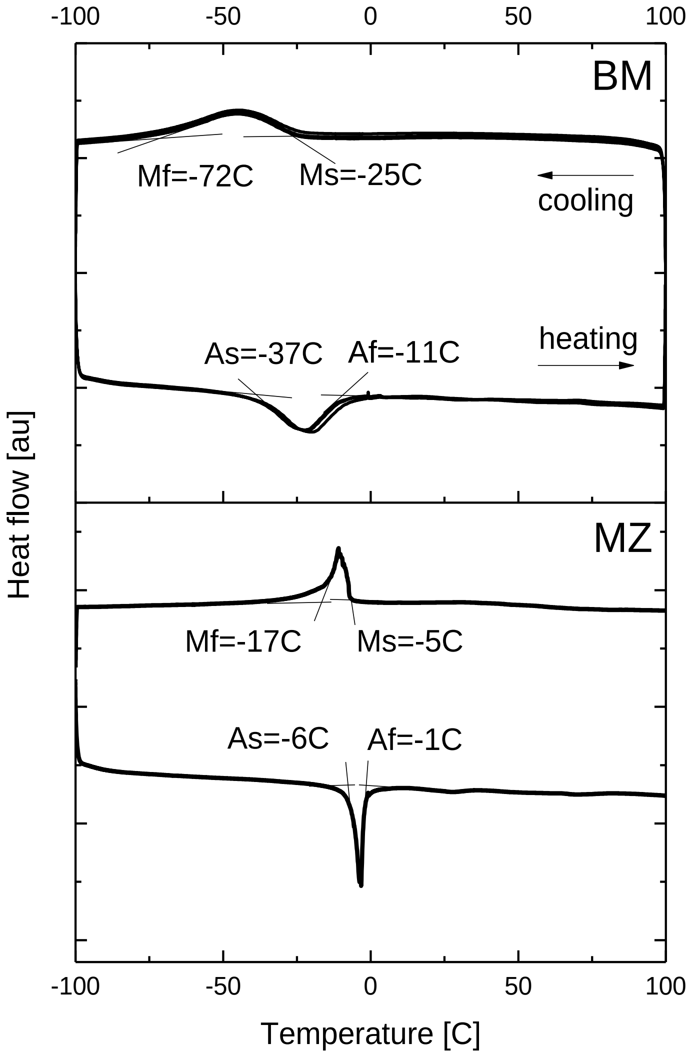


Fig.5. DSC scans of the BM and of the MZ, extracted from the welded beads realized at 15 mm/s as process speed

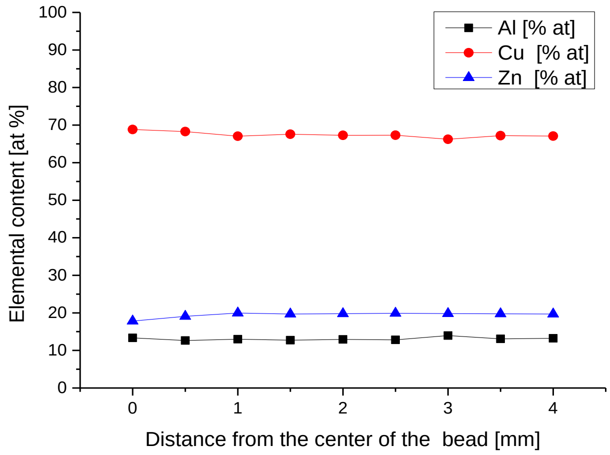


Fig.6. Compositional profile across the welded bead, realized at 15 mm/s

Conclusion

The laser weldability of CuZnAl shape memory alloy foams, having open cellular structure, was demonstrated in lap joint configuration without filler material. The welded beads were realized across the thin plate, placed on the top surface of the foams, and they penetrate in the cellular structure. It was found that the HAZ was characterized by two sub-regions, having different mechanical properties and microstructures. Calorimetric analysis of the welded bead confirms the presence of the MT: an increase of the characteristic temperatures was detected, due to microstructural modifications but not due to compositional variations in the bead.

Acknowledgement

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We hope that this work can be considered suitable for a rapid communication in Smart Materials and Structures, because it can offer several differences among the literature as well as some innovative results.

We found that only few papers (only one reported in the introduction of this work) reported the effect of laser welding of Cu based shape memory alloys. As NiTi shape memory alloys (SMAs) have well studied during the laser welding process in the previous years, the laser welding of Cu ones is not really investigated, because of the difficulties in its laser joining for the low absorption coefficient. However, we believe that Cu SMAs can be very interesting alloys and nowadays they start to be present in the market, because lower price than NiTi and higher damping capacity.

The current study investigates even the contribute of the cellular foam during the welding process: the joining of foams is an applicative problem and few open literature is available.

We think that the overlapping among a unconventional joining technique, a smart material and a cellular structure can offer a unique option to study a complex and innovative problem like the one presented here.

We hope that both Your opinion and Your reviewers' opinions will be in the same direction. The results reported here are not complete but they have been selected for a rapid communications, which will be followed to deeper investigations on this issue.

Highlights:

- Laser weldability of open cell CuZnAl foams was studied using a fiber laser without filler material.
- Welded beads in lap joint configuration were reached, using a thin plate of the same material.
- Softening was found in the welded bead; a double heat affected zone was characterized from different microstructures.
- Compositional analysis of the welded bead did not show any significant modifications.
- Martensitic transformation was found wider in the initial material than in the welded bead.