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An overview on laser welding of metal foams: techniques, advantages and challenges

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Abstract

Due to the manifold properties of porous materials in general, and metal foams in particular, they are increasingly used in industrial, structural and functional applications. The properties of metal foams depend on: chemical composition, metallurgical aspects, processing morphology (the type of porosity: open or closed), amount of porosity, cells size and shape. There are challenges and difficulties encountered in welding and bonding metal foams from wider use in the production of complex-shaped components. Some of the problems that associate with welding processes in metal foams are reduction in mechanical properties, intermetallic compound formation, microstructural inhomogeneity and low fatigue strength. More complicated challenges are envisaged during welding metal foams with other dissimilar materials. Laser welding technologies seem to be the most promising joining techniques. This paper presents an overview on laser welding and joining techniques involving metal foams based on laser technology in similar and dissimilar combinations, with and without filler metal. The discussion on laser welding of metal foams is presented keeping the focus on CuZn open-cell foams, lotus type porous iron, foam-filled steel sandwich beams, aluminum foam cores inside a hollow profile and sandwich panels.

Keywords: metal foams, porous materials, laser welding, joining, mechanical properties.

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1. Introduction

Metal foams, due to their structural shapes and gas dispersion in solid metal (see Fig. 1), besides good mechanical properties, combine unique physical properties such as low density and attenuation of sound and vibrations (Banhart 2001). The consolidated knowledge allows the manufacturing of many metals and alloys with porous structure: aluminum (Costanza et al. 2003), titanium (Matsushita et al. 2017), iron (Costanza et al. 2016), copper (Singh et al. 2019), lead (Costanza et al. 2013), superalloys (Banhart et al 2001) and many others. The base metal, the porosity morphology (such as open or closed-cell, size and shape) and the relative density are the main parameters that are to be considered when applying the material for the respective application.

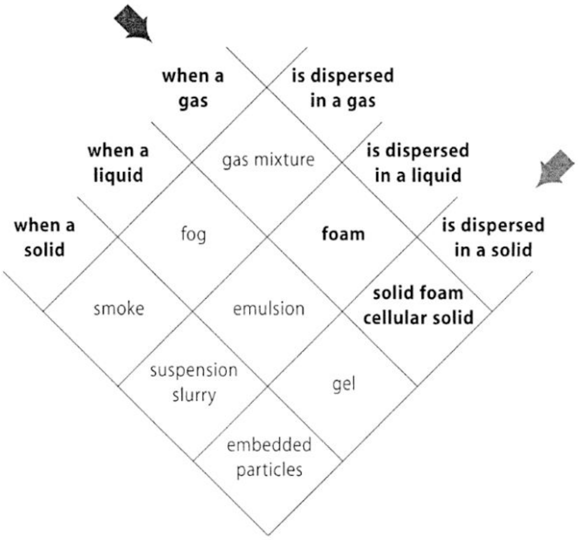


Fig. 1. Scheme of dispersion of one phase into another one. Each of them can be in one of the three phases of matter [1].

As mentioned, the foams can be classified according to the morphology of the cavities that can be separated from each other as in closed-cell foam or interconnected, open-cell foam (an example is shown in Fig. 2: the left side is closed-cell foam and the right side is open-cell foam). The former group is preferred in structural applications, e.g. energy absorbers or load-bearing components, in which light structures are usually based on a stiffness/weight ratio as higher as possible (Brugnolo et al. 2015, Costanza et al 2012, Costanza et al. 2014, Costanza et al. 2016 b). The latter group is mainly employed in functional applications: heat exchangers, filters, silencers, catalyst supports, where it is required a liquid or a gas to flow through the foam thanks to the various degree of open porosity. In the last two decades, the attention of the researchers has been focused on the development of many production methods for foams manufacturing. A possible classification can be performed according to the state of the processed metal: from vapor, from liquid or solid metal in a powder form (Bhate et al. 2019). Some studies have been focused on the optimization of the powder mix composition and its effects on the foam morphology in closed-cell foams (Costanza et al. 2005, Costanza et al. 2018 and the energy absorption features (Biffi et al. 2014). Despite of this, difficulties have been evidenced while joining these porous metals. Besides, the welding of porous metals enables extensive application in different engineering fields. Various joining technologies have been developed, and among them, laser welding has become the most promising one. In this study, the overview on laser welding applied to metal foams is presented keeping the focus on CuZn open-cell foams, lotus-type porous iron, foam-filled sandwich beams, aluminum foam cores inside a hollow profile and sandwich panels. For the laser welding of metal foams the processing details, current challenges and open problems are discussed within the aforementioned main subsections.

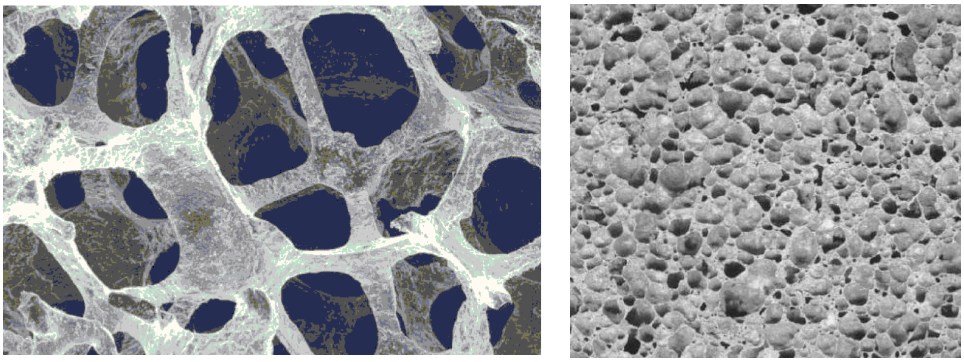


Fig. 2. left) Closed-cell foam; right Open-cell foam (Banhart et al. 2001).

2. Laser beam welding of CuZn open-cell foams

The laser welding of open-cell Cu60Zn40 (wt%) using a 1 kW continuous-wave fiber laser was investigated in Biffi et al. 2014 and Biffi et al. 2015. Ingots of Cu60Zn40, 60 mm diameter, have been melted, under a pure Ar flow, by induction melting. The material was foamed with the liquid infiltration method: amorphous SiO_2 spheres were used as space holders. SiO_2 was removed, after foaming, via chemical etching: 50% H_2O and 50% HF was used, obtaining 65-70% pore fraction, estimated via image analysis measurements. First preliminary welding tests in the bead-on-plate configuration were performed. Experiments of foams joining have been successively carried out in the lap joint configuration. Foams were joined to a 1-mm thick cold rolled plate of the same material placed on the top surface of the foam. Welding speeds were applied ranging from 5 to 20 mm/s. To cover the weld bead with a sufficient Ar flow during the laser joining process a multi-nozzle system was used. After processing, the weld beads were cross-sectioned and the metallographic sections were observed by optical microscopy (OM) and scanning electron microscopy (SEM). Microhardness measurements were performed both on the base material and on the welded joint to obtain the hardness profile across the weld bead. The performed experiments on the bead-on-plate mode showed that the welding process can’t be successfully achieved without filler material. This because the pore size is larger than the laser spot; furthermore there are little contact areas between the foam materials that need to be welded. During the joining process the thin plate material partially falls into the cellular structure, which allows it to join to the substrate. A joining process of a plate and foam could occur only where the cellular structure presents a border. In Fig. 3 a cross-section of a welded bead in the lap joint configuration at 10 mm/s (Biffi et al. 2014) is reported. The penetration of the joint was varied as a function of the cellular structure encountered by the laser beam. A microhardness test was applied for the most two relevant welding conditions, respectively: the lowest speed (5 mm/s) and the highest speed (20 mm/s), (see Fig. 4). The results showed that in the center of the welded joint the highest hardness (125-130 HV) has been measured.

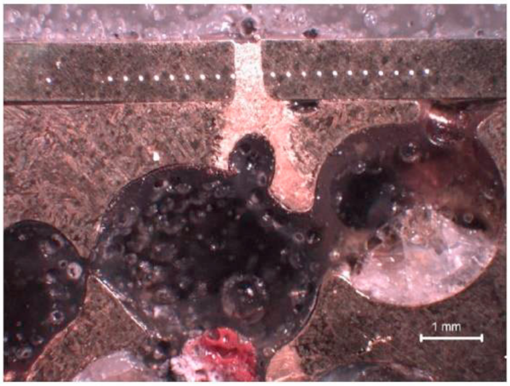
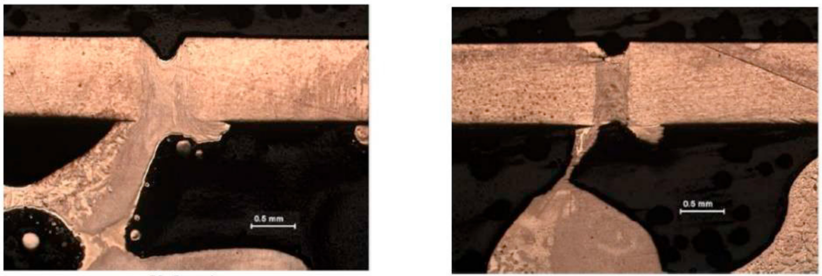
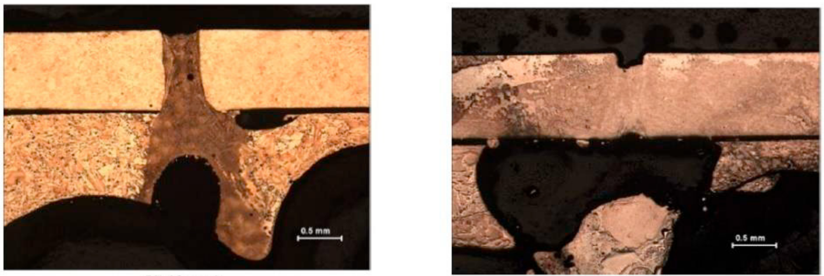


Fig. 3. Welded bead in a lap joint configuration at 10 mm/s (Biffi et al. 2014).

Due to the high cooling speeds, characteristics of laser welding, higher hardness values characterized by a fine microstructure have been evidenced. From the molten zone (MZ) to the heat-affected zone (HAZ) a significant reduction in the hardness was detected. The processing speed influences the width of the MZ; only slight variations were observed in the case of the HAZ. The mean width of the welded joint ranged between 0.36 and 0.58 mm. The size of the HAZ was estimated approximately at 4 mm for the lowest speed and 3.5 mm for the highest speed. The hardness investigation showed that the mechanical properties of the material increased from a mean value of 90.1 HV (base metal) to 125-130 (molten zone). The composition analysis did not reveal significant modifications. The study has shown that welding using a fiber laser can be successfully employed for joining Cu-based foams.



V=5 mm/s V=15 mm/s

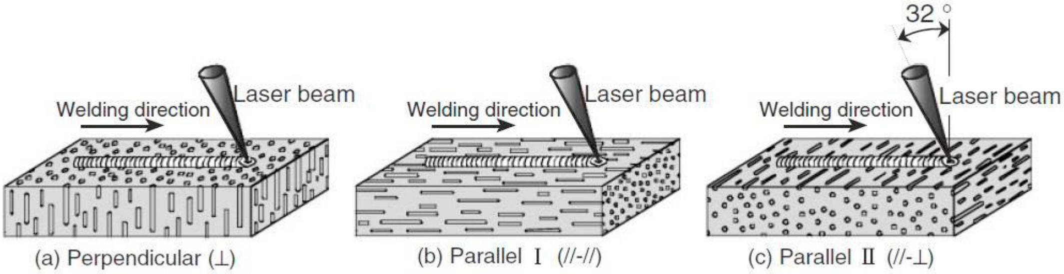


V=10 mm/s V=20 mm/s

Fig. 4. Micrographs of the welded bead in lap joint configuration at varying process speed (Biffi et al. 2014).

3. Laser welding of Lotus-type porous iron

Lotus-type porous iron foams, type AISI 1018, were welded by Yanagino et al. (2006). They were fabricated by unidirectional solidification using the continuous zone melting technique in the form of plates. Nitrogen atmosphere under a pressure of 2.5 MPa was used. The average pore diameter and the porosity of the specimen were equal to 0.37 mm and 17% respectively. Figure 5 shows schematic views of the weld specimen that exhibits relationships among the pore growth direction, the laser beam irradiating direction, and the welding direction. The wavelength of the Nd:YAG laser beam was 1064 nm and was delivered by using an optical fiber of diameter 1.0 mm. Power of 1-2 kW, welding speed 1-3 m/min and Ar as shielding gas were selected. This laser irradiated the surface of the specimen at an angle of 58° to prevent damage to the optics by the reflected laser beam. As a shielding gas, Ar with a flow rate of 4,2 x 10-4 m^3 s^{-1} was used. The diameter of the laser beam on the specimen surface was 1.0 mm.



(a) Perpendicular (⊥) (b) Parallel I (//-//) (c) Parallel II (//-⊥)

Fig. 5. Schematic view of Lotus-type porous specimens showing different combination of welding directions and pore growth directions (Yanagino et al. 2006).

Fig. 6 shows that the weld bead surface of the lotus-type porous iron is rough with pits and dents were not depending on the pore growth direction—perpendicular (⊥), parallel I (// - //), or parallel II (// - ⊥) to the specimen surface. The phenomenon is ascribable to the volume reduction on melting the porous metal and blowing the remaining gas from the closed pores. The penetration depth in the perpendicular (⊥) case was found slightly more than that in the parallel I (// - //) and parallel II (// -⊥) cases. However, the remarkable effect of the pore growth direction on the penetration depth of the weld joint, as already observed in the case of the lotus-type porous copper and magnesium, has not been observed in this study. The reason is the unstable weld bead formation caused by the relatively large-sized pores associated with the blowing of the remaining gas from the closed pores as well the smaller anisotropy of the thermal diffusivity in comparison with the copper and magnesium cases. The hardness of the weld bead increased as compared to that of the base metal, whichever is the direction of the pores. This is due to the martensitic transformation in the weld bead due to the rapid cooling rate of the laser welding, as shown in Fig. 7 in comparison with the ferritic structure of the base metal. It can be concluded that in the laser welding of the lotus-type porous iron, prevention of volume reduction due to pore's melting by providing the filler metal, pretreatment for eliminating the remaining gas in the closed pores by heat treatment, and smaller diameter of the pores are required for ensuring successful fusion welding.

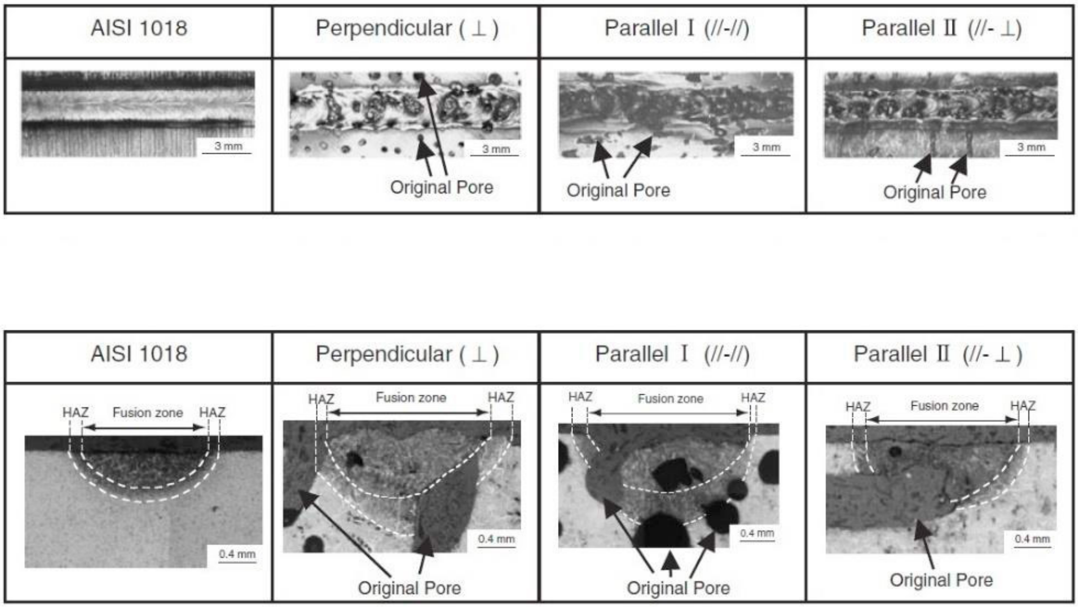


Fig. 6. Laser weld beads (top) and cross section view (bottom) of the lotus-type porous iron (Yanagino et al. 2006).

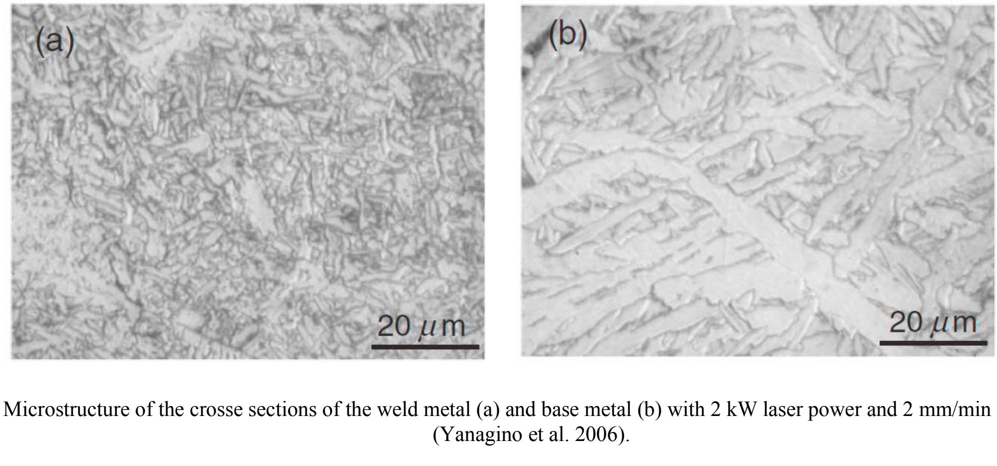


Fig. 7. Microstructure of the crosse sections of the weld metal (a) and base metal (b) with 2 kW laser power and 2 mm/min welding speed (Yanagino et al. 2006).

4. Laser welding of foam-filled steel sandwich beams

Due to their high stiffness-to-weight ratios, foam-filled steel sandwich panels are widely employed in engineering applications. Usually the joining of these panels can be done by bolting, riveting, adhesive bonding or laser-welding. A laser-welded T-joint of a web-core sandwich panel has two crack-like notches on each side as the weld thickness is significantly smaller than the web plate thickness. When a web-core panel bends, the shear deformation opposite to the web direction causes local bending of the joined plates near a welded T-joint. This leads to tension stress at one notch tip and compression at another. A fatigue crack starts at the tensile tip and propagates through the weld under cyclic loading until the plates are separated and the sandwich effect is lost. It was demonstrated that different loading conditions cause different stress at the critical notch tip and that the slope value appears to depend on the concentration level. Therefore, to control the fatigue life the loading, experienced by the stake-weld can be affected by using a filler material (Romanof, 2014 and Frank et al. 2013).

An investigation on the fatigue strength of an empty and foam-filled laser-welded steel sandwich beams was carried out by Karttunen et al. (2017) (Fig. 8). The beams have been tested under 3-point-bending for stiffness, ultimate strength and fatigue (see Fig. 9).

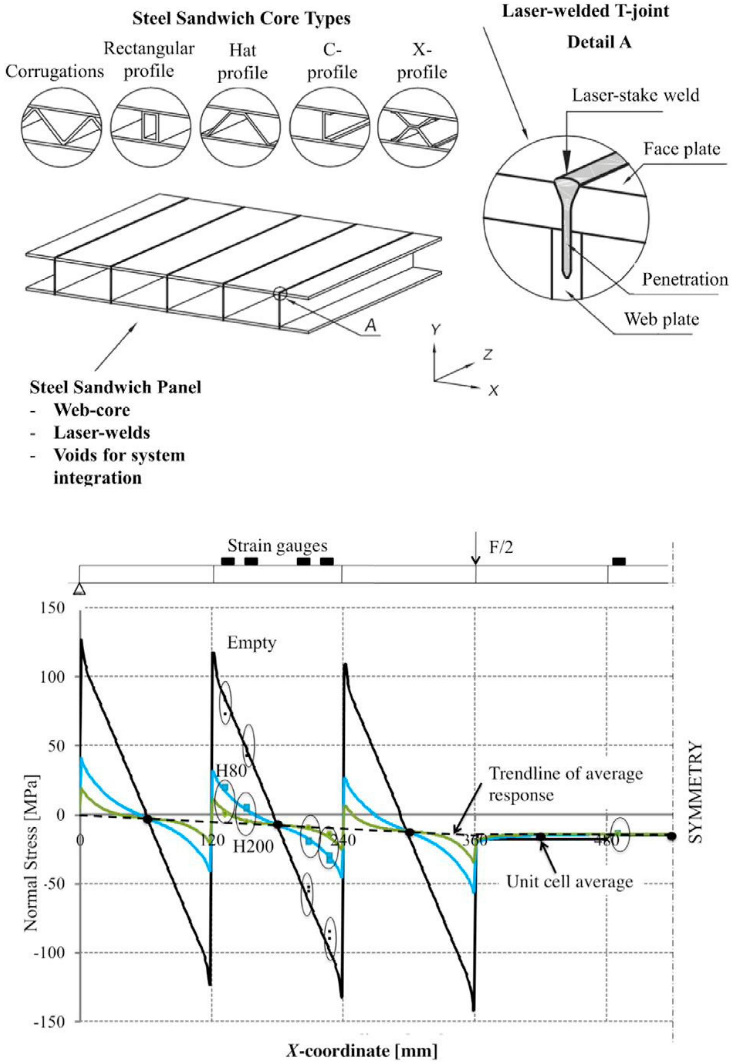


Fig. 8. Top. Laser-welded steel sandwich panels. Bottom. Reduction of shear-induced local stresses due to filling material (Karttunen et al. 2017).

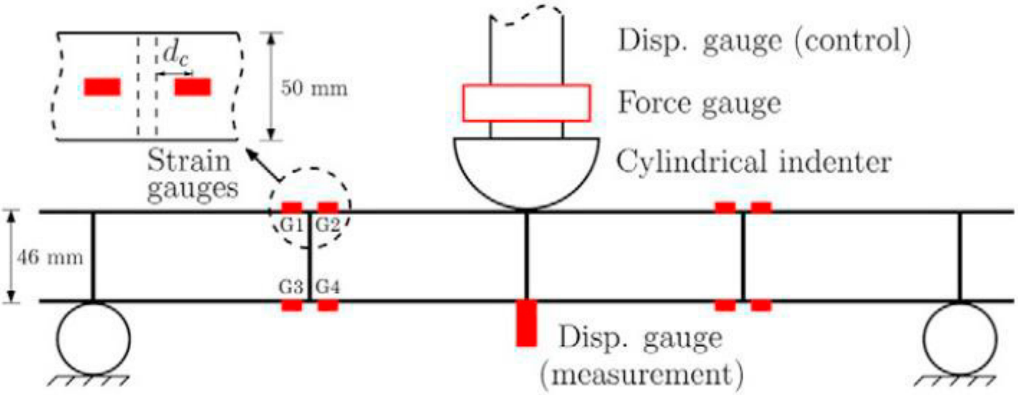


Fig. 9. Schematic presentation of the three-point bending test setup. The distance dc between the center of a 5 mm long strain gauge and the edge of a web plate was for the static and fatigue specimens 7 and 9 mm, respectively. The latter value allowed an easier installation of the gauges (Karttunen et al. 2017).

During fatigue failure mode, cracks were initiated and propagated at the laser-stake welds, consequently, cohesive fracture occurs in the foam. Fig. 10 shows results that are similar to the literature in terms of static and ultimate strength, but the fatigue life improvement is far better than expected; as the load level at 2 million cycles was increased by a factor of 8.5 when the beams are filled with a low-density polyvinylchloride foam (Divinycell H80). This is a clear indication that filling technology is an effective technique to improve the fatigue strength of lightweight sandwich panels. This means that the order of limit states needs to be reconsidered in design. The fatigue problems in laser-welded sandwich panels are due to shear-induced warping and these deformations are often very local in the plate domain. Thus, it is recommended that the filling of a sandwich panel is carried out only at the locations of high out-of-plane shear opposite to the web-plate direction. However, before applying such functional grading an investigation of the underlying physics of crack propagation in three-dimensional plate structures is required.

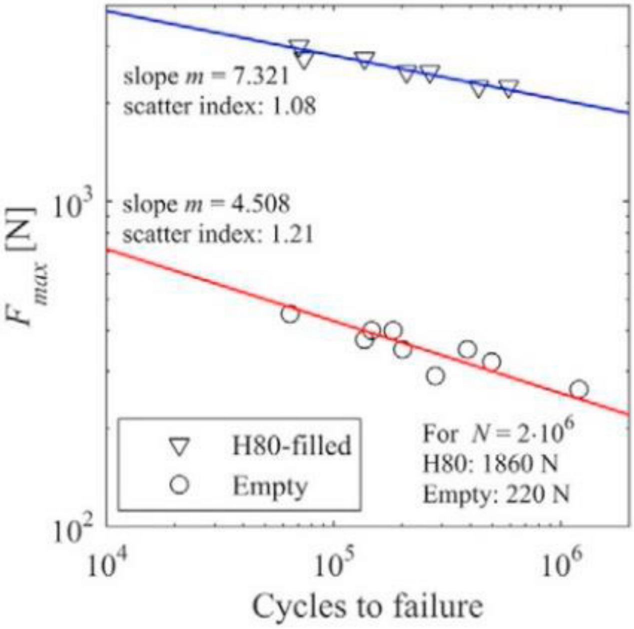


Fig. 10. Fatigue strength from experiments. The slopes and the scatter range indices related to 10-90% probabilities of survival are given (Karttunen et al. 2017).

5. Laser foaming for joining aluminum foam cores inside a hollow profile

The feasibility of the joining process of two aluminum foam cores contained in a tubular profile exploiting laser foaming of a solid precursor was investigated by Campana et al. (2013). They examined the foaming process utilizing external laser irradiation of a hollow steel profile, containing two separated aluminum foam cores intermingled by a foamable solid aluminum precursor (Fig. 11). The process consists in irradiating by means of a CO_2 laser beam the external surface of a stainless steel tube containing the resident foams and the solid foamable precursor. The laser beam is moved around the rotating surface of the tubular through a brushless motor.

Experimental process feasibility areas were assessed and mathematical formulas have been calculated to identify the relationships between the main process parameters. From the experimental analysis three process parameters should be taken into account to obtain a sound foam: laser beam power density, interaction time and the total amount of beam energy delivered to the work-piece.

The computation of two graphs, a laser beam power density vs. interaction time one and process energy vs. interaction time one, see Fig. 12, were selected as optimized process parameters which can achieve good foaming conditions.

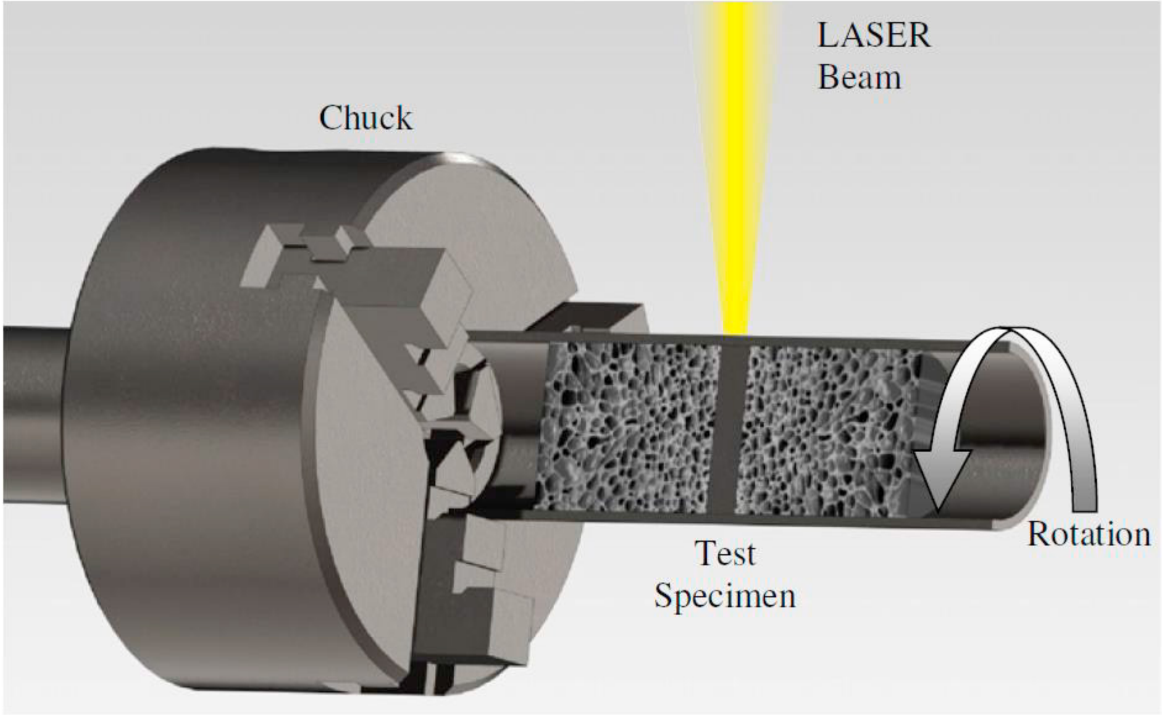


Figure 11. Sketch of the experimental setup (Campana et al. 2013).

Code	Image	E_{proc} [kJ]
LF01	 Not acceptable	360
LF11	 Not acceptable	277
LF04	 Acceptable	188
LF06	 Foaming start	146
LF12	 No foam	77

Figure 12. Laser foamed samples (power density 76 W/mm^2, t int. 0.974 s) (Campana et al. 2013).

6. Laser welding of sandwich panels

The possibilities for structural optimization of laser-welded sandwich panels with an adhesively bonded core and uni-directional vertical webs were investigated by Kolster and Wennhage [22]. In ship-building, the replacement of stiffened plate structures by laser-welded sandwich panels offers considerable advantages for production as well as vessel operation. Surface flatness and high stiffness, in particular, make these sandwich panels well suited to span large open areas such as accommodation decks and hoistable car decks, or to be used as supporting bulkheads and partitioning walls. Due to the low weight requirements in space application, this topic has become high-interest incorporation with adhesively bonded core materials, see Fig. 13.

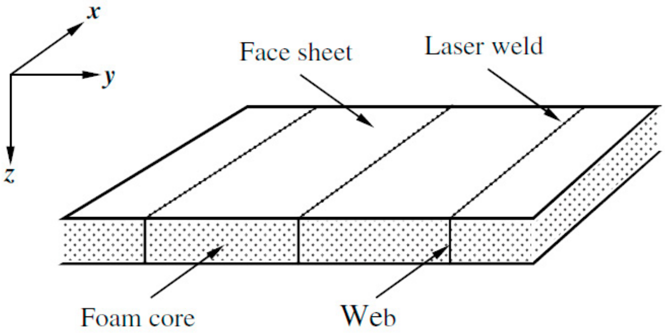


Figure 13. Laser welded sandwich panel with vertical webs and core material (Kolsters et al. 2009).

A possible way to compare the merits of different sandwich configurations is to calculate the surface weight W and midpoint deflection δ then finding out the structural performance η as 1/Wδ. As high stiffness and low structural weight yield high values of η, if these values are normalized to η_0 for a reference panel, it is possible to check the contribution of the core (whether is positive or negative). Fig. 14 shows an example of where η/η_0 was evaluated for a uniformly loaded simply supported sandwich plate with three different values for the web-pitch 2p. The structural response of the panel would be dominated by bending along the webs and the midpoint deflection is determined at first by the bending stiffness Dx, on which the web spacing and core modulus have small effect. Nonetheless, η/η_0 reaches a maximum for non-zero core modulus as the web-spacing becomes large and the contribution of the core is to limit the shear deformation in normal to the webs. On the other hand, as a structure has high stiffness and low structural weight, does not mean necessarily that it is efficient (making optimum use of the available material).

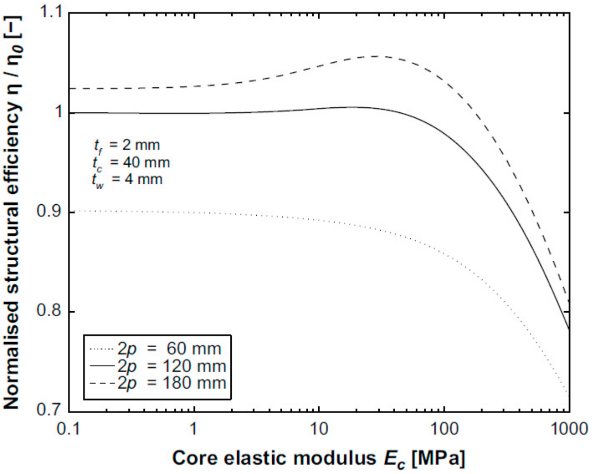


Figure 14. Structural efficiency based on midpoint deflection for sandwich plate of 2.5 X 6.8 mm normalized to empty reference panel (Kolsters et al. 2009).

In a first approach, a qualitative judgment cannot be made before the structural response is correlated to rule requirements, material allowable, and various failure criteria. For this reason, multiple design constraints need to be accounted. Due to the number of design variables and constraints, a structural optimization method based on moving asymptotes was implemented. It can be used to minimize the structural weight per square meter of a panel that has a typical accommodation deck configuration. As a result, within the span of production parameters and rule requirements, substantial improvements can be made with or without an adhesively bonded core. Without core material, the structural weight for standard production panels can be reduced considerably, by reducing the faceplate thickness by using thinner and fewer webs. Additional weight can be saved by removing all but a few webs and injecting low-cost polyurethane foam into the cavities, giving added thermal–acoustic insulation, or by incorporating a more structural core with greater thickness and higher density, as the free span of the sandwich panel can be increased.

7. Discussion and conclusions

In this study, a comprehensive and critical review on laser welding technologies of metal foams has been presented addressing the aspects of welding process, materials, process parameters, microstructural transformations, mechanical behavior, modelling and industrial applications. Metal foams show a set of weldability problems mainly related to the intrinsic porous structure, phase transformations on fast cooling and compositional variations in the heat-affected zone. However, laser welding has been recognized as the most studied process due to the minimal thermal effect on the base materials. A large number of experimental studies have been found and described. A detailed discussion has been devoted to this overview study, through analyzing the microstructural changes observed and its influence on the mechanical properties in general and the fatigue behavior in particular of such welds. Both metal foams and sandwich panels laser-welded have been discussed in this work.

Despite the ongoing research on laser welding of metal foams, there are specific areas that need to be addressed, such as:

1) In-situ analysis of the mechanical behavior of welded joints for a better comprehension of the load transfer mechanism in different joint zones, based on the micromechanical models which take into account the microstructural changes induced by the welding process.
2) New filler materials/interlayers need to be studied to increase the joining efficiency and weldability of metal foams. A better knowledge of the joining mechanism, based on thermodynamic calculations, can be useful for the optimization materials selection for the interlayer.
3) Researchers can be attracted to join metal foams topic through combinations of functional features alongside high thermal and electrical conductivity, typical of Cu-based systems.
4) Further experiments on new base material combinations are necessary, involving porous metals in the production of complex-shaped porous components.

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