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Mechanical behavior of aluminum sandwiches made by laser welding

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Abstract

Aluminium sandwiches are interesting subcomponents for lightweight structures applied in rail cars for high speed. A method to realize aluminium sandwiches consists in welding sheets to elementary extruded profiles. Laser welding is the production technology that promises the better features in terms of quality and productivity. Thanks to concentrate energy and very small Heat Input (HI), the laser welding process minimizing the wide of the Heat Affected Zone (HAZ) and the distortions and allow high welding speed. In this work laser technique was applied to join a mock-up of a large aluminium sandwich panel. The mechanical behaviour of the assembled panel was investigated in the two main orthogonal direction of load by four point bending tests.

Elastic-plastic FE Analysis confirm the results of bending tests and it is possible to appreciate the quality of welding process that produce joint strength and ductile. In fact in the both load direction it's possible to evaluate the plastic deformation on the welded beam without visible cracks in the welds. The data about the mechanical features of the welds for the FE analysis, about the 80% of the base materials, was achieved by tensile test on elementary but joint. The SEM fractography of the butt joint shows dimples in all the surface of the fracture, confirming the good quality and ductility of welds also in presence of some little micro porosity.

The present paper is based on the achievements of the TRAIN Consortium within the research project SIFEG (Integrated freight transport rail-road), granted by the Italian Ministry of Economic Development for the Program "Industria 2015 – Mobilità Sostenibile".

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Keywords: Laser Welding; Aluminum Sandwich; Mechanical Properties; Finite Element Model; Four Point Bending Test.

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1. Introduction

Aluminum sandwiches are interesting subcomponents for lightweight structures applied in the field of transport. A method to realize this kind of subcomponents consists in welding sheets to elementary extruded profiles. Aluminum alloys welding process is affected by the issue of softening, in particular at the level of the Heat Affected Zone (HAZ) [1]. Aluminum alloys don't show any allotropic variation of the crystal structure and the improvement of the mechanical properties takes place by thermal treatments (hardening by solid solution or precipitation) or cold working. Both these treatments are wiped out by the welding process, in particular at the HAZ level. For this reason in the various design codes, a softening factor is defined that doesn't exceed the 80% of material base strength (e.g. UNI EN 1999-1-1:2007 "Eurocodice 9"). Aluminum alloys welds can be realized with MIG technologies, Friction Stir Welding (FSW) and laser welding. MIG technologies, although are automated, have a low productivity and induce a high heat input with a large extension of the HAZ, which is the weak part of all aluminum alloys welds. FSW is a solid state joining process, the alloy is not melted but is softened by friction. This process allows an excellent quality of the joint but it is not very flexible and require the Royalties payment to TWI which holds the international patent of the technology. Laser welding proves to be the most productive and the most flexible process [2]. Furthermore, new high brilliance fiber lasers with high efficiency and modular power source, make this technology promising for industrialization. Some of the challenges of the aluminum alloys laser welding process, concern aluminum alloy reflectivity, cracking susceptibility and the formation of porosity [3, 4, 5]. To overcome these issues has been developed a laser welding process using an innovative wobbling welding head, that allows the oscillation of the focused laser beam. These features have positive effects on the welds quality. The aim of this paper is to examine the wobbling welding process applied to the realization of aluminum sandwich structures. After preliminaries studies on the welding parameters and the qualification of welding process by digital radiography, micro hardness and tensile tests, sandwich structures have been realized joining together EN AW 6082 T6 aluminium alloy sheets and rectangular extruded profiles in EN AW 6060 T6. Mechanical features of the sandwich structures have been simulated by FE analysis and investigated by 4 Point Bending Test (4PBT) in the two orthogonal direction of load. The FE modeling technique proposed considers a differentiation of the material around the weld, considering the heat affected zone [6-9].

2. Materials

Sheets in EN AW 6082 T6 aluminium alloy and rectangular extruded profiles in EN AW 6060 T6 aluminium alloy were used in present work to realize sandwich structures. The welding wire used in the process was the AA5356. Alloy's chemical compositions are summarized in Table.1 and the mechanical properties are summarized in Table 2 with f_0 characteristic value of 0.2% proof strength, f_u characteristic value of ultimate tensile strength, A elongation value measured with a reference length $5.65\sqrt{A_0}$, $f_{0,HAZ}$ 0.2% proof strength in HAZ, $f_{u,HAZ}$ ultimate tensile strength in HAZ.

Table. 1. Aluminium alloys chemical composition extracted from Table 6 UNI EN ISO 573-part 3 [10].

Alloy designation		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	
Numerical	Chemical Symbols									Each	Total
EN AW-6060	EN AW-Al MgSi	0.30-0.6	0.10-0.30	0.10	0.10	0.35-0.6	0.05	0.15	0.10	0.05	0.15
EN AW-6082	EN AW-Al Si1MgMn	0.7-1.3	0.50	0.10	0.40-1.0	0.6-1.2	0.25	0.20	0.10	0.05	0.15

Table. 2. Aluminium alloys mechanical properties extract from UNI EN 1999-1-1:2007 "Eurocodice 9", and mechanical properties from our tests.

Alloy EN AW	Temper	EUROCODICE9					Our Tests		
		f_0	f_u	A	$f_{0,HAZ}$	$f_{u,HAZ}$	f_0	f_u	A
		N/mm²		%	N/mm²		N/mm²		%
6060	T6	140	170	8	60	100	-	-	-
6082	T6	250	290	8	125	185	311	349	12.6

3. Welding Process

Laser welding process allows to realize very narrow beads with the lowest Heat Input (HI) minimizing the Heat Affected Zone and the distortion of the welded components. The laser source used in the welding process was an IPG Ytterbium Fiber Laser System (YLS-2000-CT-Y12) with an output power of 2300 W. The welding head was constituted by a collimator, a wobble module, and a focusing lens, as shown in Fig.1-a); the welding set-up is shown in Fig.1-b). The wobble module allows the focal spot rotation and the consequent mixing of the molten bath: this promises a reduction of the welding porosity, that is the main defect of the aluminium laser welding. The maximum oscillation diameter is about 2.9 mm and the oscillation frequency is up to 300 Hz. For the identification of the best welding parameters, a series of preliminaries welding tests has been performed. In particular, the influence of diameter and frequency of Wobble (D 0.25-0.5 mm & 50-300 Hz) and welding speed (1-1.5 m/min) on the shape of the cross section and the porosity of the welds were investigated. The target was to realize welds in compliance with the level B of UNI EN 13 919-2. The main welding parameters and typical aspect are summarized in Table 3.

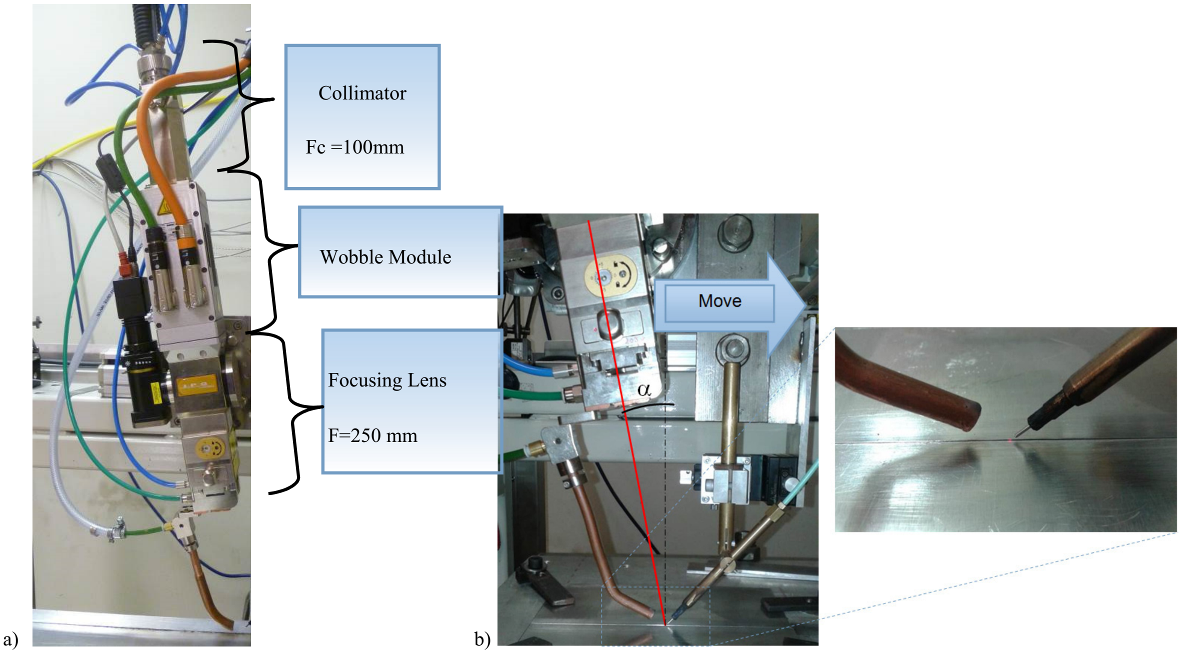
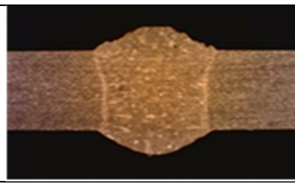


Fig. 1. (a) Welding Head constituted by a collimator, a wobble module and a focusing lens; b) Welding set-up.

Table. 3. Main welding parameters and typical welds aspect.

P (W)	V_s (m/min)	Wobbling (Hz)	D [mm]	V_w (m/min)	Gas Process (Nl/min)	Typical Macro Cross Section
2100	1	200	0,25	2	30 He *Shielding & plasma* 15 Ar *Backing*	

P is the laser power source, V_s is the welding speed, V_w is the welding wire speed. The preliminary qualification of welding process was done through Digital radiography, micro hardness and tensile tests. In terms of expected tensile strength the main transport design standard were analysed and summarized in the Table 4.

Table. 4. Main transport design standard in terms of tensile strength.

Alloy	RINA	DNV		EUROCODICE9		
	$R_{m\ Weld}$	$R_{p0.2\ haz}$	$R_{m\ Weld}$	$f_{o,haz\ 0,2\ \%}$	$f_{u,haz}$	f_w/γ_{Mw}
AA 6082 T6	165	115	175	125	185	168

The tensile tests on the butt joint, show the minimum values achieved of about 245 MPa. The fracture surface obtained in transversal tensile test is shown in the Figure 2.

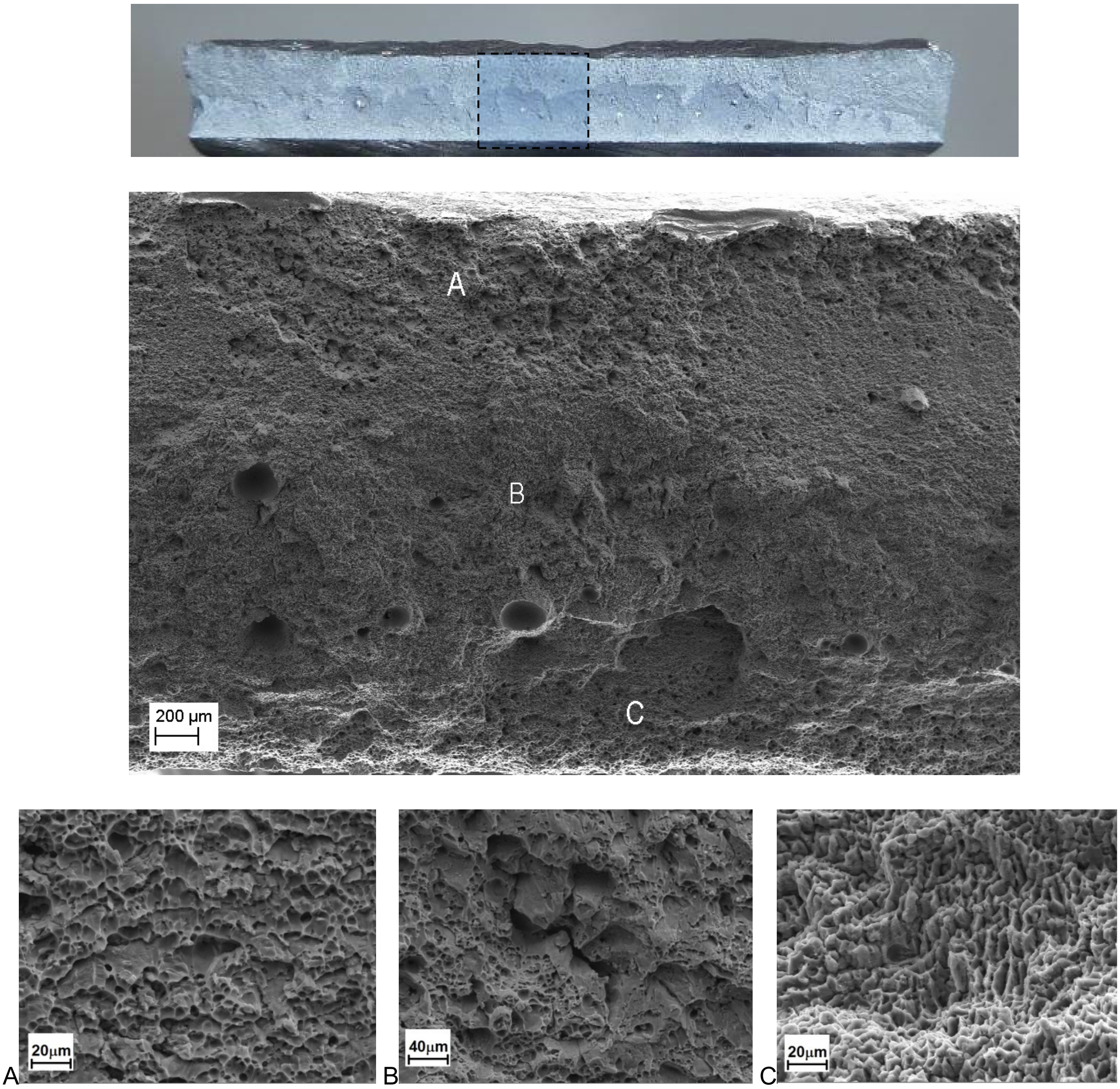


Fig. 2. Fracture surface of transversal tensile test. From top to bottom: optical image of the fracture; SEM image of the highlighted part of the section; Magnifications of the surface parts marked with letters A, B, C.

The fracture occurs in a ductile way, in fact it's possible to observe deformation of grain before rupture with the presence of dimples in all the different regions of the fracture.

4. Sandwich Structures

Panels have been realized with three extruded profiles (length 500 mm) with shaped edges to accommodate six sheets in AA6082 (122 × 500 × 3 mm). The welding of the panels has been made with a specific sequence, starting from the central part of the panel and proceeding outwards. In Fig. 3-a) is shown one of the panels that demonstrate very good flatness and in Fig. 3-b) is shown the sections of the panels used for the 4 Point Bending Test (4PBT) mechanical characterization in the two orthogonal direction of load.

a) b)

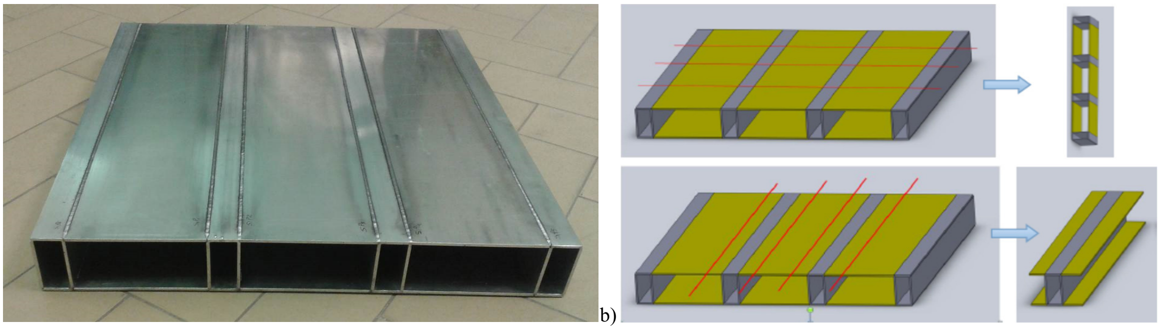


Fig. 3. (a) Sandwich panel (b) sections of the panel used for the bending tests.

5. Results and Discussion

5.1. Four Point Bending Tests

An electro-mechanical machine (DMG, Denison Mayes Group) was used to conduct the 4 point bending tests. Maximum load capacity was ± 100 kN and the crosshead speed was in the range between 1 and 2 mm/min. The applied load was measured by a strain gauge, the deflection on the middle of the beam was monitored by a Linear Variable Displacement Transducer (LVDT). Tests machine has been set up to comply with the requirements of ASTM C393 "Flexural Properties of Sandwich Constructions" [11,12]. Results of bending tests have been compared with those obtained using FEA. FE model of specimens are modelled with shell elements with 4 nodes and 6 degrees of freedom, considering the symmetry of the structure. Multilinear isotropic hardening model of materials has been introduced, introducing actual stress–natural strain curve by data of EN AW 6082 T6 rectangular extruded profiles in EN AW 6060 T6. The modelling technique proposed considers a differentiation of the material around the weld, considering the heat affected zone [6-9]. Contact elements are used in order to account for the connection between punches and panels (surface-to-surface model with a classical Coulomb-friction model).

5.1.1. Longitudinal Bending Tests

Panels geometry has been chosen to allow test with span L = 450 mm. Punches were positioned at L/3 (150 mm): in this way the central part of the panels wasn't subjected to shear stress. Load profiles for 2 samples are shown in Fig. 4(a). They have a similar trend: after the linear elastic region, until about 45 kN, is observed the general plasticization of the components until the maximum load value of 58 kN was reached. The subsequent load reduction occurs by local plastic deformation near central punches. Tests were interrupted at the maximum value allowed of the LVDT (about 22 mm) without observe any visible crack on the welds. The graphs show also a fairly good elastic recovery. In Fig. 4(b) are shown the pictures of the elastic stage (A), maximum stress (B), final deformation (C). Non linear FE analysis has been performed imposing a y-displacement at punches and considering the contact with the sheets of the specimen. Results, in terms of equivalent Von Mises stress and equivalent Von Mises plastic deformation, are shown in Fig. 5.

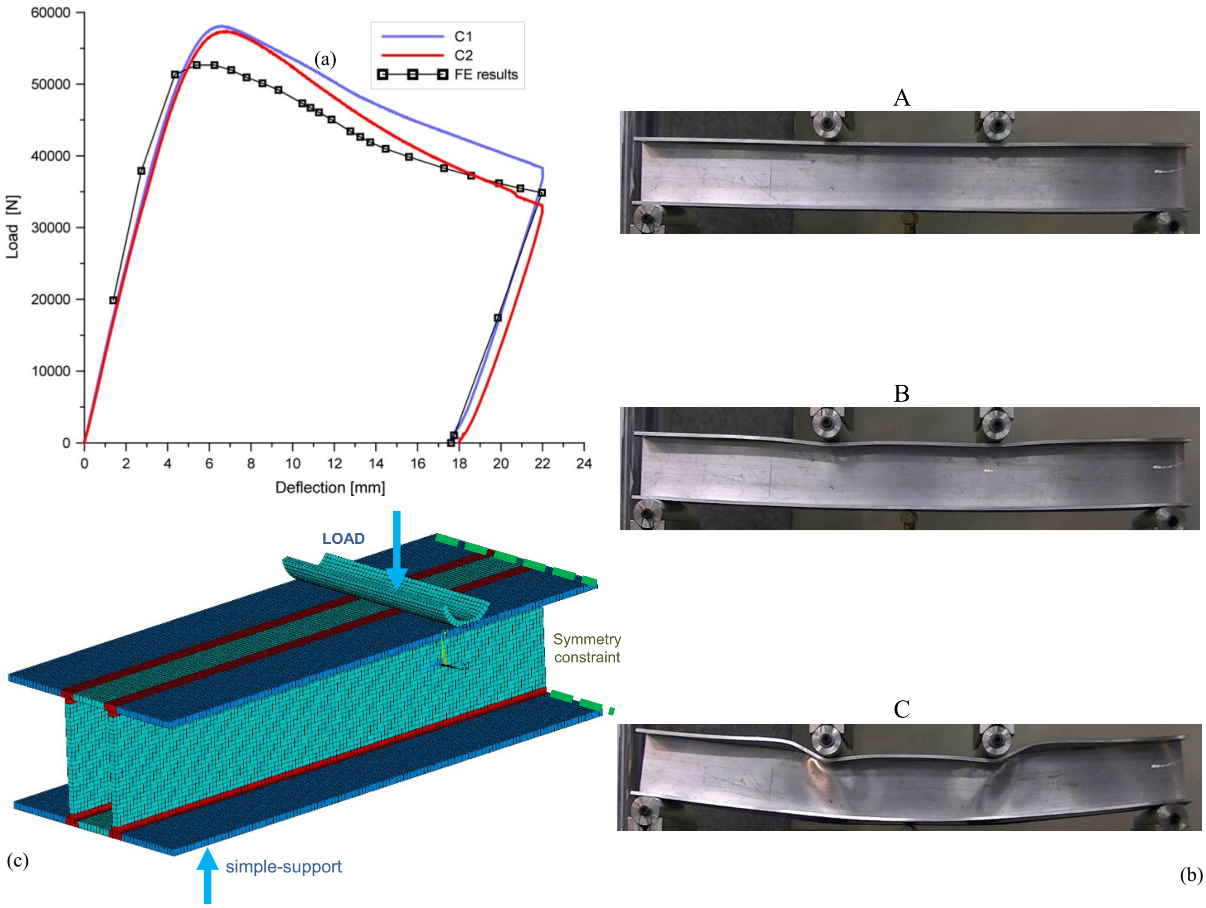


Fig. 4. Longitudinal bending tests.(a) load profiles; (b) sample status in the elastic stage (A), maximum load (B), final deformation (C); FE model.

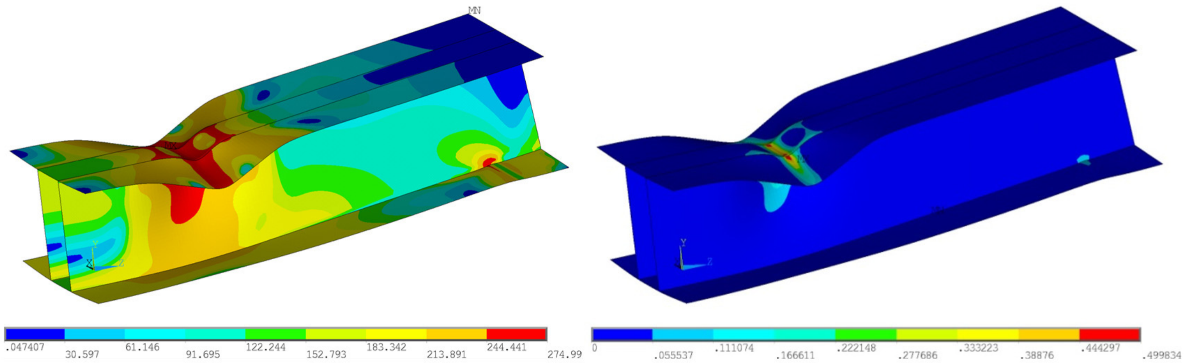


Fig. 5. Equivalent Von Mises stress and equivalent plastic strain contours on specimen. Load P = 52720 N/deflection 5.43 mm.

5.1.2. Transversal Bending Tests

Samples geometry has been chosen in order to have punches and supports on the extruded profiles. Load profiles are shown in Fig. 6. In this case, the linear part is extended until about 5 mm. Load value is very low compared to longitudinal tests; this happens because the sheets aren't connected together but operates in independent way, is not present the "sandwich effect" [13].

For the sample T1, the test was carried out in two steps; in the first step deflection was measured by the LVDT until 22 mm, in the second step deflection was measured by the displacement transducer of the machine crosshead. Despite a low stiffness, transversal bending tests confirm the ductility of the longitudinal bending test and the good behaviour of the welds that don't show any failure even if subjected to very high local deformation.
Results, in terms of equivalent Von Mises stress and equivalent Von Mises plastic deformation, are shown in Fig. 7, observing the large zone where large values of plastic deformation are present.

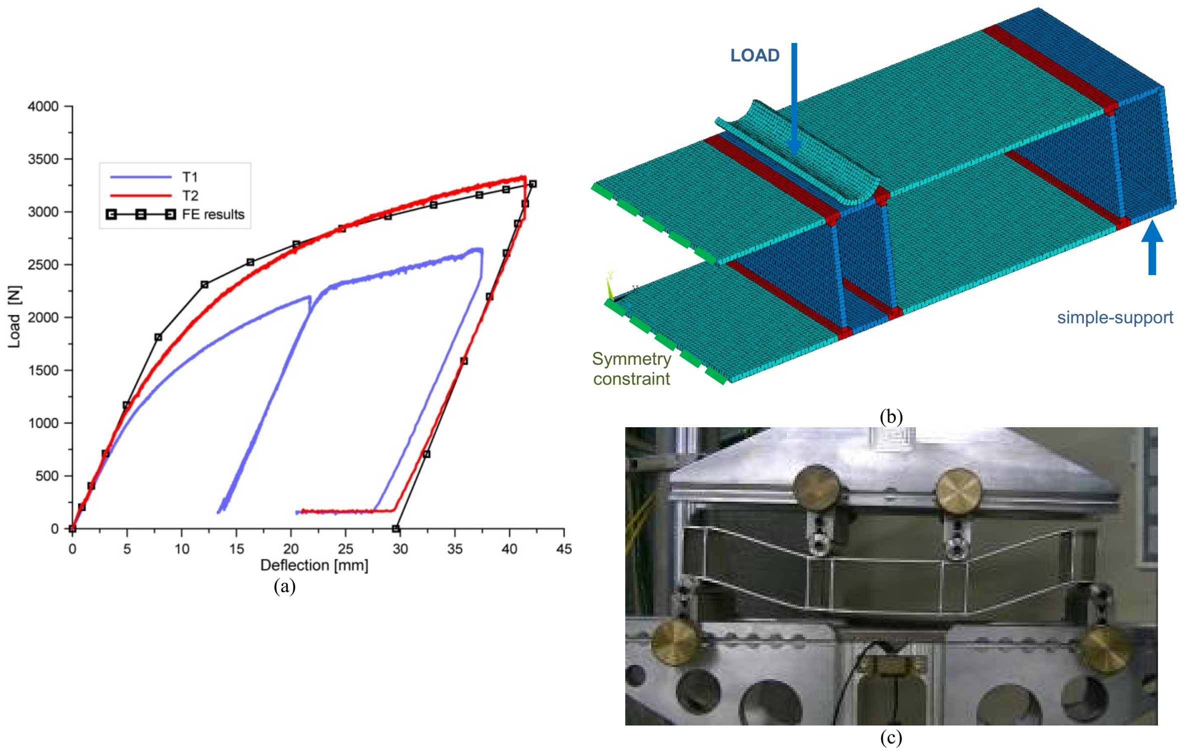


Fig. 6. Transversal bending tests. (a) load/deflection curves; (b) FE model; (c) sample status at the final deformation.

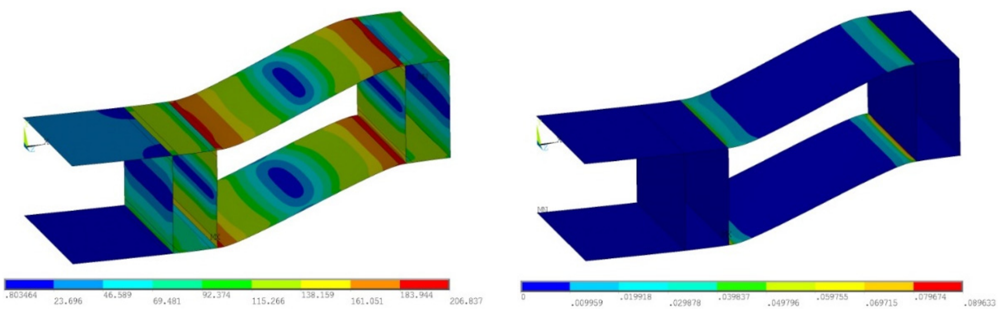


Fig. 7. Equivalent Von Mises stress and equivalent plastic strain contours on specimen. Load P = 3265 N/deflection 42.13 mm.

6. Conclusions

Laser welding technology was applied in the realization of aluminium alloy sandwich structures. The mechanical behaviour of the assembled panel was investigated in the two main orthogonal direction of load by four point bending test. It's possible to observe very high difference in strength in the two direction, in this case the mechanical behavior of the panel is orthotropic and the panels needs to be designed in function of the main load direction. In the transversal direction of load we observe high deformation with low load. The welds bend in correspondence of the extruded profiles, where was applied the load, without crack demonstrating high ductility. The low load is due to the absence, in this direction, of links between the external plates. In the longitudinal direction the portion of panel shows high strength. The load is transmitted between the two faces and between extruded profiles. The non-linear elastic-plastic FE analyses confirm results of bending tests. These last confirm the quality of welding process that produce joint strength and ductility, in fact in both load direction it's possible to observe the plastic deformation of the welded beam without visible cracks in the welds. The data about the mechanical features of the welds for the FE analysis, about the 80% of the base materials, were derived from tensile tests on elementary butt joints. The SEM fractografy of the butt joint shows dimples in all the surface of the fracture confirming the good quality and ductility of welds also in presence of some little micro porosity.

Acknowledgments

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