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Mechanical Properties and Other Characteristics of Ultrasonic Welded Joints in Absorbers of Solar Panels in Respect of Performance Requirements

Abstract: The study presents the geometry as well as results of the peeling, shearing and metallographic tests of copper and aluminium welded joints used in the absorber panels of flat solar collectors. The article discusses desired characteristics and mechanical properties of ultrasonic welded joints and compares the latter with laser welded joints. In addition, the study indicates prospective implementation areas of ultrasonic welding technologies.

Keywords: solar collector, ultrasonic welding, laser welding

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Introduction

Ultrasonic welding belongs to methods enabling the joining of both similar and dissimilar materials using mechanical vibration (the frequency of which is restricted within the range of 4 kHz to 175 kHz [1]) supplied to the interface of materials being welded [2]. The process is performed using a station equipped with a high frequency generator and the winding on a magnetostriction transducer, transformer, sonotrode as well as mechanisms for supporting and holding elements and mechanisms for adjusting welding parameters [3].

The primary parameters of the above-named typically mechanical welding process are the following:

- welding power restricted within the range of 0.02 kW to 8 kW,
- sonotrode mechanical vibration frequency restricted within the range of 4 kHz to 175 kHz,
- sonotrode force of approximately 60 MPa in relation to aluminium (and slightly higher in relation to copper),
- linear welding rate restricted within the range of 2 m/min to 15 m/min,
- sonotrode vibration amplitude restricted within the range of 5 m to 35 m,
- shape of the area of contact between the sonotrode and an element subjected to welding.

The above-presented parameters are strictly interrelated, where a change in one of them usually results in the maladjustment of the entire process leading to the formation of a significantly weaker joint and its lack. Additional negative consequence may be the damage to the sonotrode beyond repair as lower values of amplitude correspond to higher sonotrode force and vice versa. The properly performed ultrasonic welding process is characterised by numerous advantages including:

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- possibility of joining numerous metals and their alloys, ceramics and plastics, both identical and having different mechanical properties,
- low range of process temperature, resulting in the formation of the narrow heat affected zone and leading to the generation of low stresses and strains in joints [4],
- lenient requirements related to the purity of elements prepared for welding,
- good mechanical properties of joints, favourable heat and electric conductivity and high corrosion resistance as well as the lack of intermetallic phases, cracks, gas pores etc. (in terms of related materials),
- possibility of obtaining strong joints close to plate edges as well as strong joints of thin wires and foils and materials significantly varying in thickness,
- low power demand in comparison with, e.g. resistance welding machines, restricted within the range of approximately 5% to 10% in relation to copper and aluminium as well as high efficiency, restricted within the range of 80% to 90% [5],
- absence of welding fumes, dusts and gases during the process,
- possible automation and robotisation of the process.

Ultrasonic welding is a technologically advanced, efficient and stable process characterised by both ecological and energy-related advantages, used in many industries, including power generation. One of the popular ways of utilising renewable energy in one or multi-family buildings is the use of solar energy panels to heat water in the household. Solar collectors are composed of an aluminium or copper plate absorbing infrared radiation emitted by the sun, connected to a pipe coil (the so-called harp) made of a metal or alloy (usually copper or aluminium) characterised by high thermal conductivity, absorbing heat generated by the plate. Therefore, it is very important to provide the largest possible area of contact between the collector plate and tubes with a heated medium.

There are several methods enabling the obtainment of a continuous metallic joint between the plate and the pipe, including brazing, pressure welding and, under certain conditions, fusion welding. Both fusion welding and brazing entail a significant heat input and the use of a filler metal (needed during brazing).

The properly performed ultrasonic welding process guarantees the obtainment of all favourable features of joints including the significant and continuous area of the direct contact between the plate and the tubes, low stresses and strains as well as high strength and formability. The use of the filler metal in the joint is unnecessary.

Presently used collectors are made of copper, aluminium alloys or include an aluminium plate connected with copper tubes.

An ultrasonic welding station presented in Figure 1 and used for the joining of elements of the solar collector absorber is composed of a transducer converting electric energy to mechanical energy in the form of vibration having a frequency of 20 kHz and a booster changing the amplitude of vibration between the sonotrode and the transducer. The value of vibration amplitude and sonotrode force depend on the thickness of elements being joined, i.e. the tube and the plate of the absorber, as well as types of materials used to make a welded joint. The amplitude of vibration corresponds to a half of the mechanical deflection of the sonotrode.

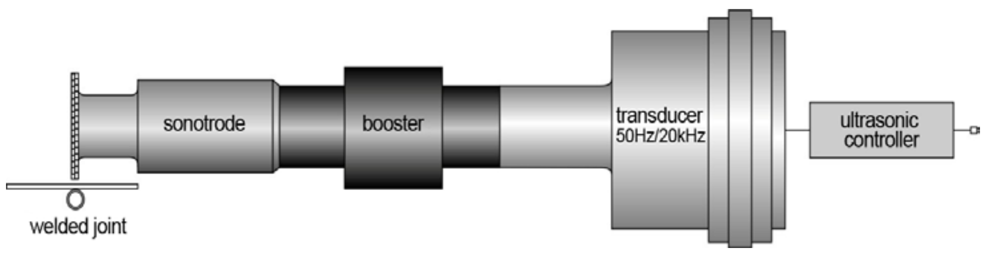


Fig. 1. Schematic diagram of the station for the ultrasonic welding of the solar collector absorber

Ultrasonic vibration of appropriate power provided to the area of contact between related surfaces transfer energy to grains, which, remaining in contact and hitting neighbouring grains, lose oxides, and, because of the presence of normal and tangent forces, undergo plastic strains and move closer to the neighbouring opposite surface. As a result, despite relatively low temperature (not exceeding 350°C for copper and aluminium), adhesive-cohesive joints at the molecular level are formed [6]. They only may contain phase transformations such as recrystallization and diffusion. Neither of the surfaces subjected to welding undergoes partial melting. However, it is necessary to effectively apply mechanical vibration of appropriate amplitude and power on the edges of the joint. It is estimated that the local temperature at the interface should not exceed 30–50% of the melting point of metals being joined.

The "classical" ultrasonic welding technology requires the application of appropriate force, which, due to the collector absorber, cannot be excessively high because of the possible deformation of tubes. In addition, force must be directed so that the tubes do not become oval in cross-section. The aforesaid issue has been addressed by providing the surface of the disc sonotrode with an appropriate shape (Fig. 2).

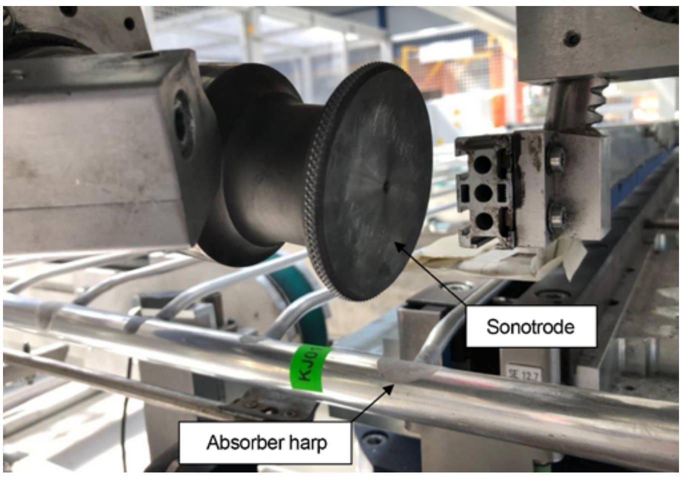


Fig. 2. Sonotrode for the ultrasonic welding of solar collectors

Ultrasonic welding does not require the very thorough pre-weld cleaning of the surfaces of elements to be joined as is the case with, e.g. diffusion or pressure welding. However, cleaning performed directly before the process facilitates the decomposition and fragmentation of oxides, which is particularly important in terms of aluminium and its alloys (quickly becoming covered by a layer of oxides).

Experimental tests

To verify the quality of ultrasonic welded joints in absorbers of solar collectors, the former were compared with laser welded joints. Related tests involved the comparison of metallographic specimens as well as mechanical properties of specimens sampled from solar panel absorbers made of aluminium plate connected with aluminium tubes (type I) or copper tubes (type II) respectively (see Figure 3). The panels were made by joining aluminium plates having thickness g = 0.4 mm (type I and II) and aluminium tubes having diameter d_1 = 8 mm (type I) as well as copper tubes having diameter d_2 = 6 mm (type II) and wall thickness of t_1 = 0.8 mm and t_2 = 0.4 mm respectively, using two heat-based joining technologies:

- ultrasonic welding involving the making of a continuous longitudinal weld along the tube (type I absorber).
- laser welding triggering the pulsed melting of copper with aluminium and the making of spot welds every approximately 4.4 mm (type II absorber).

The main view of both types of absorbers (Fig. 3) indicates that the heat effect accompanying the laser beam welding of the absorber (type II) leads to significant longitudinal deformations resulting in the local corrugation of the aluminium plate across the entire area of the absorber. The above-named defect triggered by tangent stresses indicates the permanent presence of stresses in the absorber, which combined with temperature changes during operation and significant differences in the linear expansion of aluminium and copper generates further accumulation of stresses during the operation of the absorber. In many cases, the oscillation of tangent stresses may trigger the cracking of individual welds and, consequently, an inevitable decrease in the area of contact between the plate and the pipes. This, in turn, results in the decreased absorptivity of heat by tubes with active medium and, in critical cases, may lead to the separation of the absorber plate from the so-called harp. The absorber welded using the ultrasonic method (type I) is free from the above-presented defects resulting from the application of the laser welding process (Fig. 3).

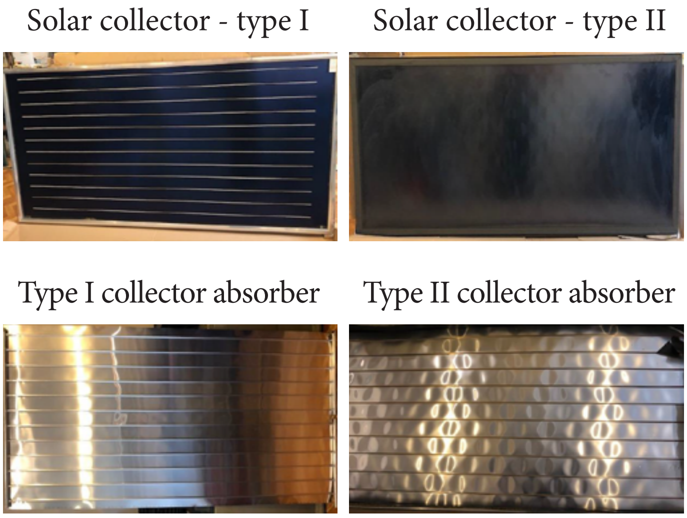


Fig. 3. Elements of type I collector (ultrasonic welded) and type II collector (laser welded)

The tests aimed to determine the resistance to mechanical damage of both types of panels as well as to estimate relative contact areas of welds in the cases under consideration. The tests involved tearing the tube off the plate as well as the shearing of the weld along and across (perpendicular to) the tube (Fig. 4). Test-related measurements were concerned with the maximum breaking force, the displacement of the elements in relation to each other up to their separation (rupture of the joint) and energy needed to damage the joint beyond repair.

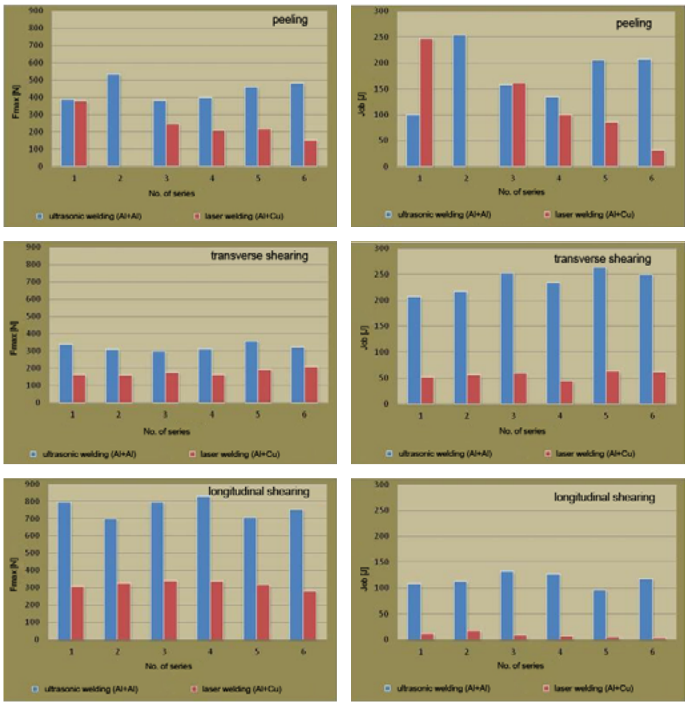


Fig. 5. Comparison of load carrying capacity and impact energy in relation to ultrasonic and laser welded joints

In each case, the results of the destructive tests revealed that the type I welded joint was characterised by peel strength higher by 180%, transverse shear strength higher by 180% and longitudinal shear strength higher by 240% than those of the laser welded joints. In addition, depending on the type of load, in relation to the ultrasonic welded joints of the absorber, the impact energy was by 140% (peel load), 420% (transverse shearing) and as many as 1400% (longitudinal shearing) higher than the aforesaid forces related to the laser welded joints. The above-presented results demonstrate clearly the higher mechanical strength of the joints present in the type I panel (Al+Al). The foregoing results not only from higher force transferred by the joints up to their rupture but primarily from the higher deformability (plasticity) of the peeled/sheared ultrasonic weld than the laser welded spot weld. The laser welded spot welds not only work separately but, are made of the alloy of copper and aluminium (aluminium bronze) characterised by significant brittleness, responsible for the lower deformability of any segment of the panel.

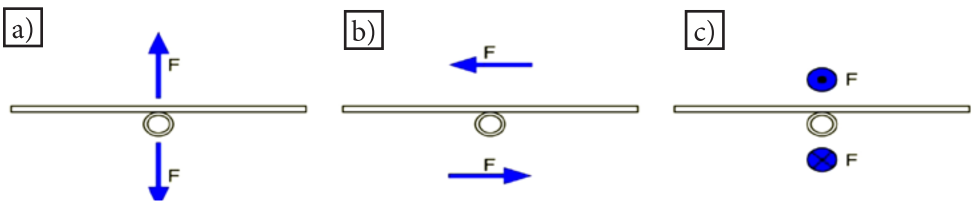


Fig. 4. Directions of forces in destructive tests a) peeling, b) transverse shearing and c) longitudinal shearing

The metallographic tests involving the observation (Table 1) of the cross-sections of the tube-plate joint cross-sections (every approximately 0.1–0.2 mm) perpendicular to the tube axes revealed the following:

- laser weld has a drop-like cross-section containing cavities (Fig. 6) significantly decreasing the cross-section of the weld and affecting its strength. Cavities and gas pores constitute a geometrical notch, additionally worsening the quality of the joint. The notch of the shape is also the root and the unfavourably formed face of the weld, constituting an acute angle with the tube;
- weld is formed as a result of the melting and stirring of aluminium and copper (partially molten in the joint area). Individual cross-sections reveal cracks of the weld;
- welding is made along the entire length of the tube. Locally, it is possible to notice one-sided incomplete fusions.

The comparison of the areas of contact between the plate and the tube in the type I and type II joints justifies the statement that the difference is restricted within the range of 5.5 times to 8 times to the disadvantage of the type II joint (i.e. Al+Cu laser welded joint). In relation to the type I solution, the above-named proportion is responsible for the reduction of the area of contact and conduction of heat between the aluminium absorber and the copper tube, which could result in the lower thermal efficiency of the collector.

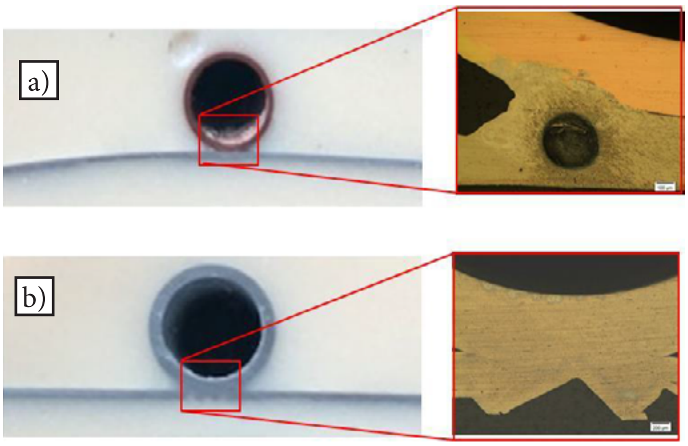
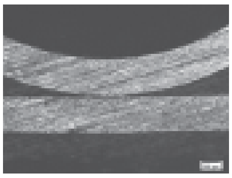
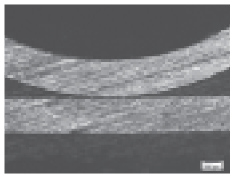
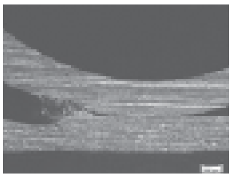
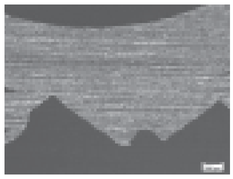
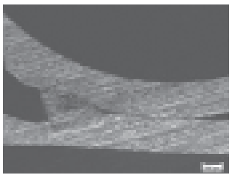
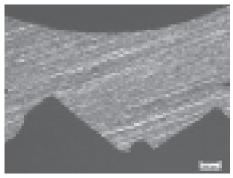
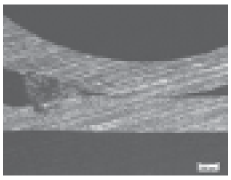
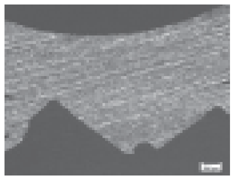
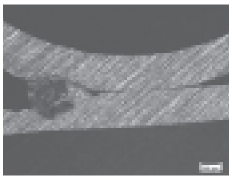
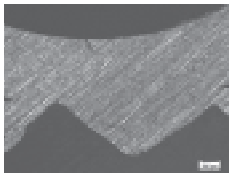
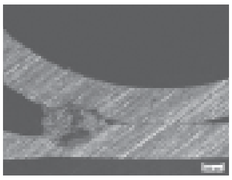
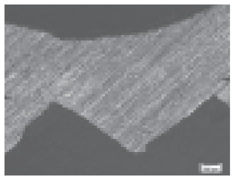
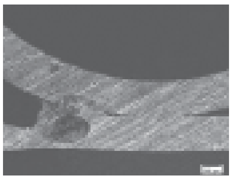
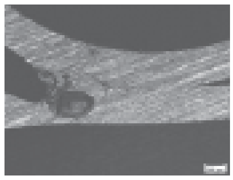
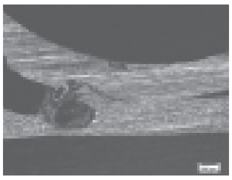
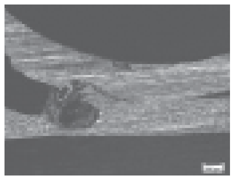
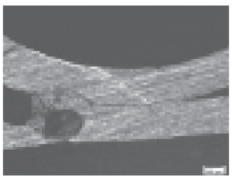
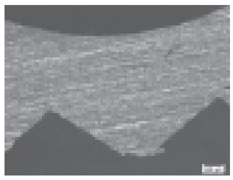
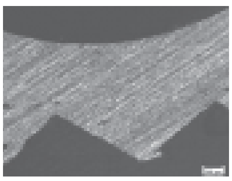
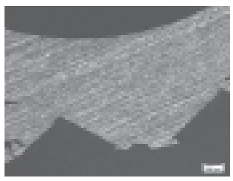
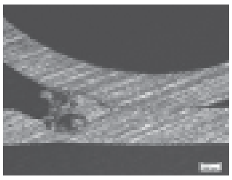
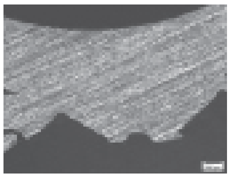
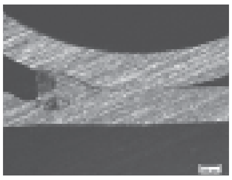
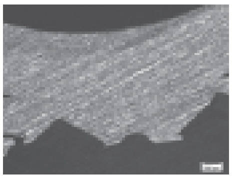
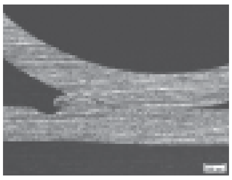
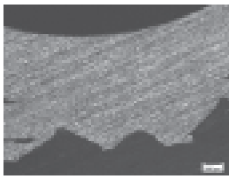
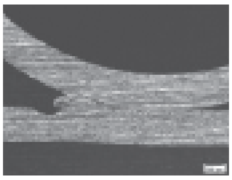
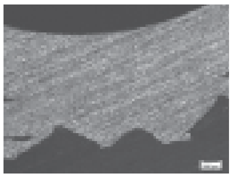
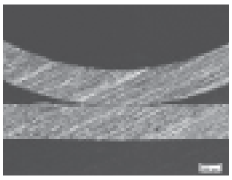
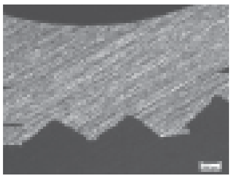
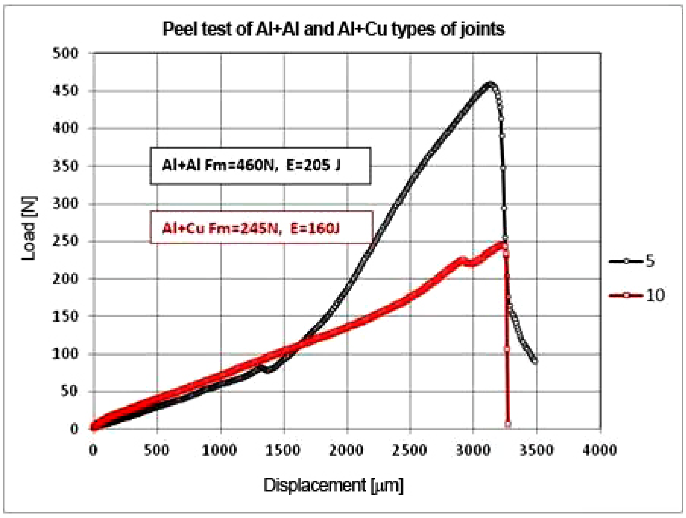


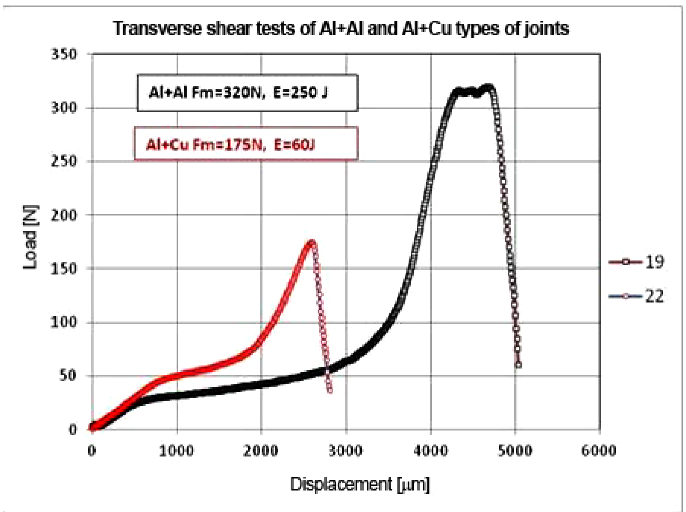
Fig. 6. Structure of
a) laser weld and b) ultrasonic weld

Table 1. macrostructure of Al+Cu laser welded joints and Al+Al ultrasonic welded joints

Layer no.	Al+Cu	Al+Al	Distance [mm]
1			0
2			-0.2
3			-0.3
4			-0.45
5			-0.7
6			-0.85
7			-1.0
8			-1.1
9			-1.2
10			-1.3

11			-1.4
12			-1.5
13			-1.6
14			-1.65
15			-1.80





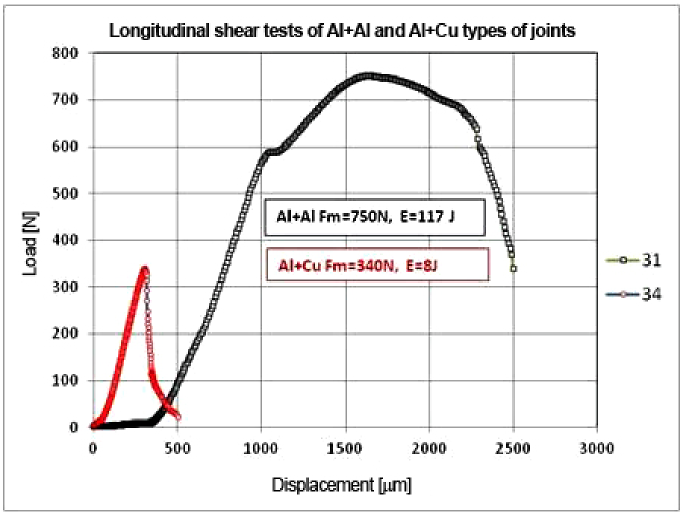


Fig. 7. Average load-carrying capacity values related to laser (i.e. fusion) welded joints (red) and ultrasonic (i.e. pressure) welded joints (black)

Laser welding can be treated as an alternative method to join the tubes with the plates, yet it is necessary to satisfy the following conditions:

- to obtain the heat conduction surface comparable with that of the pressure weld or braze, the ultrasonic (fusion) weld should be continuous;
- to prevent the generation of stresses and the deformation of the absorber, heat input during the welding process should be low;
- weld deposit (formed as a result of melting and stirring) cannot be brittle and should provide the higher strength and deformability of the joint in relation to panels made using various metals characterised by varying linear expansion.

Failure to satisfy the above-presented conditions may result in the lower threshold of the separation of the absorber plate from the tubular coil absorbing heat during the operation of the absorber and, as a result, lead to a decrease in the coherence and efficiency of the panel.

Concluding remarks

Ultrasonic welds are characterised by the monolithic nature of the joint, and, consequently, the proper conduction of heat from the absorber to the utility medium.

In comparison with other joining methods, the application of ultrasonic welding reduces a heat input and, as a result, the deformation of absorber panels.

Because of process control as well as the control of pressure, amplitude and sonotrode penetration, ultrasonic welding enables the deformation-free joining of thin-walled elements (both flat and spatial).

Because of the lack of the metal flow zone and the minimum size of the HAZ, ultrasonic welding can be used to join materials characterised by limited plastic properties.

The ultrasonic welding of absorbers of solar collectors enables the obtainment of the continuous joint along elements to be joined. In comparison with laser spot welds, ultrasonic welds are characterised by very good plastic and mechanical properties.

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