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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF SC-MODIFIED AA2519-T62 LASER BEAM WELDED BUTT JOINTS

ABSTRACT

The fundamental aim of the research is to investigate the microstructure and mechanical properties of the AA2519-T62 laser beam welded joints obtained with various values of welding velocity. For the constant value of laser power (3.2 kW) three joints have been produced with various values of welding velocity: 0.8, 1.1, and 1.4 m/min. The joints have been subjected to microstructure analysis (including both light and scanning electron microscope), microhardness measurements, tensile tests, and fractography of tensile samples. The established values of joint efficiency contain within the range of 55-66% with the highest value (66%) reported for the joint obtained with 1.1 m/min welding velocity. The produced welds have noticeable participation of pores, which tends to increase together with the value of welding velocity. In all cases, the failure has occurred in the fusion zone by ductile fracture.

Keywords: *aluminum; AA2519; microstructure; mechanical properties; laser beam welding; fracture*

INTRODUCTION

High-strength aluminum alloys are one of the most widely used materials in lightweight structures. A high specific strength, low costs of forming, and recyclability make aluminum-based structures one of the most important branches in the present and future automotive and aerospace industries. One of the most recent high-strength aluminum alloys is AA2519 modified by scandium and zirconium, which has been developed by The Institute of Non-Ferrous Metals, Light Metals Division in Skawina, Poland [1]. It is a precipitation-hardened aluminum alloy, what makes it very susceptible to elevated temperature causing an overaging of a strengthening phase and in the consequence the decrease of the material strength [2].

Considering that every welding process relates to the affection of heat on workpieces, a quest for its limitation becomes an important factor in the joining of AA2519. Friction stir welding can provide a welded joint of AA2519 with very good quality, although it is a very adequate solution for butt and lap joints [3]. For performing more sophisticated shapes of welded structures conventional welding processes are far more suitable, especially laser beam welding, characterized by very small affection of heat on a workpiece [4].

In this welding technique, a laser beam of coherent, monochromatic light with high power density is used to locally melting of workpieces, which are joined by a solidification process [5].

In some cases (e.g. ferrous alloys), the high density of energy allows to influence the microstructure of processed materials in a profitable way [6]. When it comes to aluminum and its alloys one of the most serious obstacles in laser beam welding is the problem of welds porosity. Due to the high solubility of hydrogen in the molten aluminum, it is rejected during solidification as fine metallurgical porosity [5]. The presence of these pores reduces the load area of the welded joint causing stress concentration and also strongly promotes solidification cracking [7]. Nevertheless, it can be avoided by appropriate preparation of the workpiece's surface before the welding process, including cleaning with acetone, wire brushing, and etching with 10% NaOH [5]. Another issue concerns the 2XXX and 7XXX alloy series which is the dissolution of the strengthening phase [3].

For the precipitation-hardened aluminum alloys processed by a laser beam, the strength can be partly recovered after post-weld heat treatment, what is a potential solution for a decrease in mechanical properties [8]. The reduction in mechanical properties can be partly compensated during the welding process by the formation of ultrafine grain microstructure [3,9].

During the solidification of AA2519, the hot-cracking can occur due to a high concentration of copper (6.3% in this research), what is a commonly known problem in this group of materials. Another factor that influences the formation of the joint in a welding process is the participation of scandium and zirconium in the chemical composition of AA2519 [1]. These elements not only provide higher strength to the alloy and increase the recrystallization temperature but also cause grain refinement during the solidification [10-11]. Due to this phenomenon, predominantly scandium plays a very profitable role in the welding process and is used in some filler wires as an alloying element [12-13]. The fact that AA2519 is a precipitation-hardened alloy forces to take into account significant losses in materials strength after the welding process [2,3,5].

In recent years, much scientific effort is put into laser beam welding of Al-Cu alloys, mostly dictated by the aerospace industry applications e.g. use of laser beam welding for joining stringers and other airframe components [4,14]. The welding parameters severely influence the grain size in the welded zone, what partially dictates the mechanical properties of the welds e.g. crack propagation [4,15-16]. Although joints produced by laser beam welding of various aluminum alloys have been subjects of investigation in recent years, the properties of Sc-modified 2XXX alloy welds are still a major gap in the current state of the art. Our previous research on welding of AA2519 in non-heat-treated condition revealed that laser beam allowed to produce the joint of decent quality with low participation of pores and without cracks [17]. The current investigation is concerned with AA2519 in the precipitation-hardened condition. The fundamental aim of the research is to investigate the microstructure and mechanical properties of the welded joints obtained with various values of welding velocity.

EXPERIMENTAL

The material to be welded was a 5 mm-thick AA2519-T62 extrusion. The chemical composition and mechanical properties of the alloy are given in Tables 1 and 2.

Table 1. Chemical composition of AA2519 (% weight)

Fe	Si	Cu	Zn	Ti	Mn	Mg	Ni	Zr	Sc	V	Al
0.11	0.08	6.32	0.05	0.08	0.17	0.33	0.02	0.19	0.16	0.10	Base

Table 2. Mechanical properties of AA2519-T62

Young Modulus (E)	Yield Strength (YS)	Tensile Strength (UTS)	Elongation (A)
78 GPa	312 MPa	469 MPa	19 %

The welded joints have been produced using Fanuc 710i industrial robot equipped with YLS-6000 6 kW laser beam source (Figure 1). The basic welding parameters with the samples designation are set in Table 3.

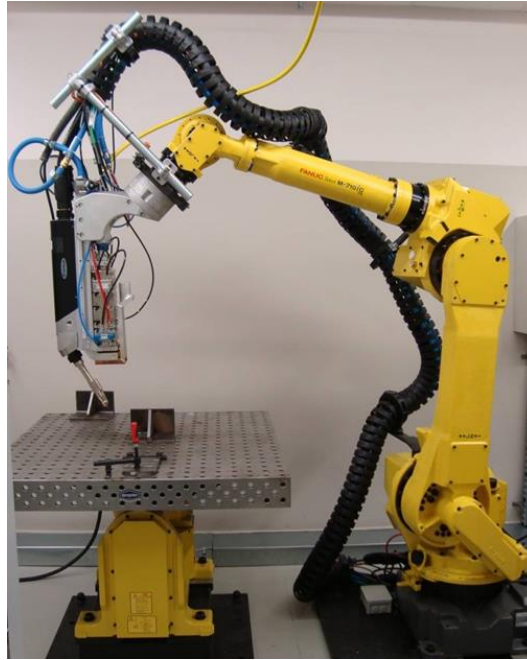


Fig. 1. Fanuc 710i industrial robot

Table 3. Welding parameters and sample designation.

Sample designation	Welding velocity [m/min]	Laser power [kW]
X8	0.8	3.2
X11	1.1	
X14	1.4	

The other process parameters were constant: 0.2 mm laser beam diameter, 10° laser beam inclination angle, and 10 L/min shielding gas (argon) flow. The laser beam has a Gauss shape and has been focused on the workpiece surface ($f=0$). Following the welding process, samples have been cut perpendicular to the welding direction and subjected to metallographic preparation including mounting in resin, grinding, and polishing. For the observations of grain microstructure on a digital light microscope Olympus LEXT OLS 4100, the samples have been etched with Keller reagent (20 mL H₂O + 5 mL HNO₃ + 1 mL HCl + one drop of HF) for 10s. Microstructure analysis has been supplemented by observation on a scanning electron microscope (SEM) Jeol

JSM-6610 and Vickers microhardness distribution (0.98 N load) at a distance of 2.5 mm from the weld face. The tensile tests have been conducted on INSTRON 8802 MTL and after the test, the fracture surfaces have been analyzed on SEM. The extensometer gauge length was equal to 50 mm.

RESULTS AND DISCUSSION

The macrostructures of the obtained joints are presented in Figure 2a-c.

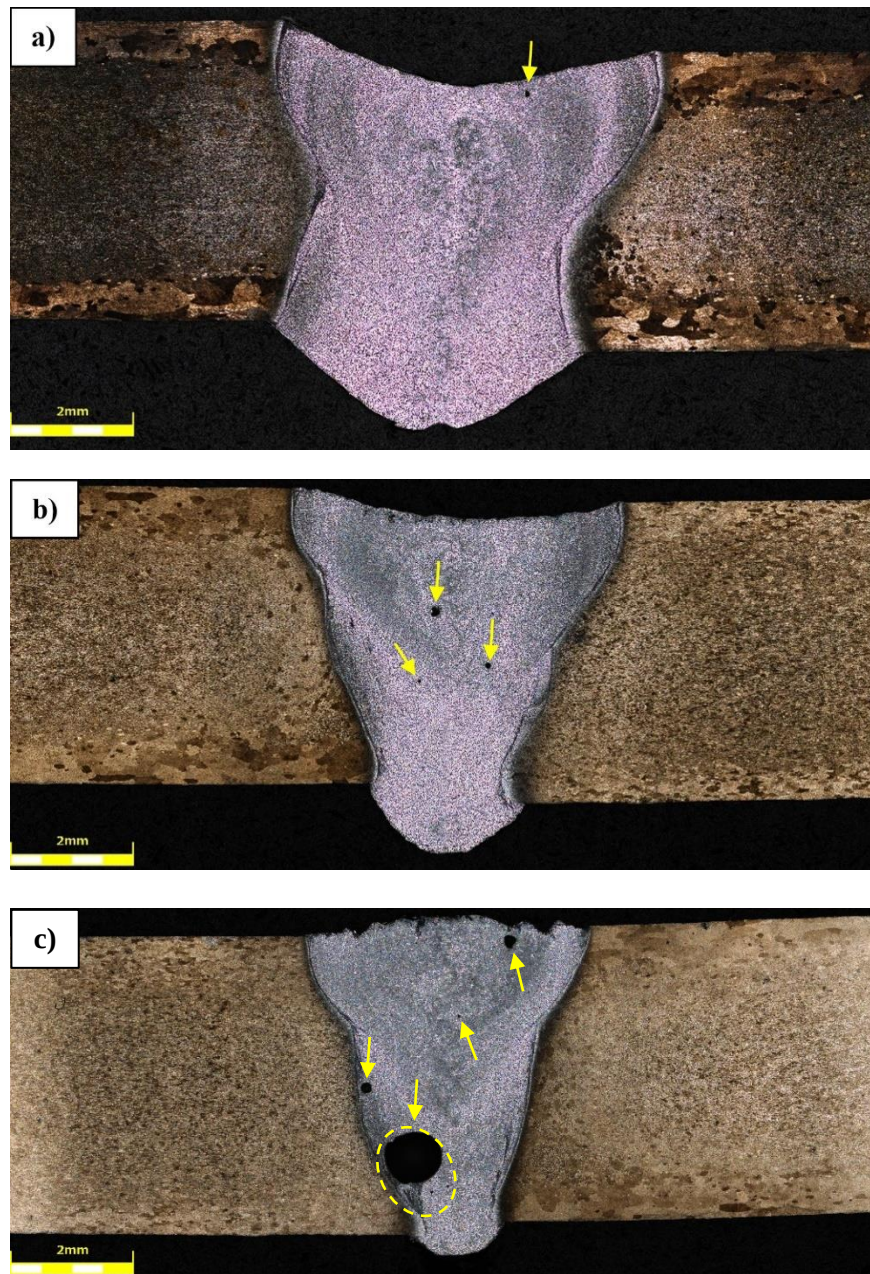


Fig. 2. Macrostructure of the welded joints a) X8, b) X11, c) X14. The pores marked with yellow arrows

It is possible to observe that together with the increase in welding velocity the weld face changes from concave (0.6 mm for X8, 0.3 mm for X11) to convex (0.2 mm for X14). At the same time, it can be stated that the welding velocity affects the porosity of the weld. In the joint obtained with the lowest value of welding velocity, the porosity level is very low (Figure 2a). It increases together with the welding velocity, and for the next two samples, it can be observed that X11 (Figure 2b) has small pores in the weld's centrum, and X14 (Figure 2c) is characterized by the highest porosity level localized mainly in the bottom and central part of the fusion zone. Considering the size, shape, and distribution of the pores it can be stated that it is the metallurgical porosity, probably of hydrogen origin. During cooling the supersaturated hydrogen rejects from the molten pool and the increase in the welding velocity causes the stopping of the gas bubbles and remaining them as pores for they do not have enough time to float out from the liquid metal [7]. Despite these imperfections, the macroscopic observations did not reveal any presence of solidification cracks.

The obtained microhardness distributions (Figure 3) present a typical characteristic for a welded joint of precipitated-hardened aluminum alloy. The width of the fusion zone has been established basing on the obtained distribution and it changes along with the welding velocity adopting a value of 3, 2.5, and 2 mm respectively.

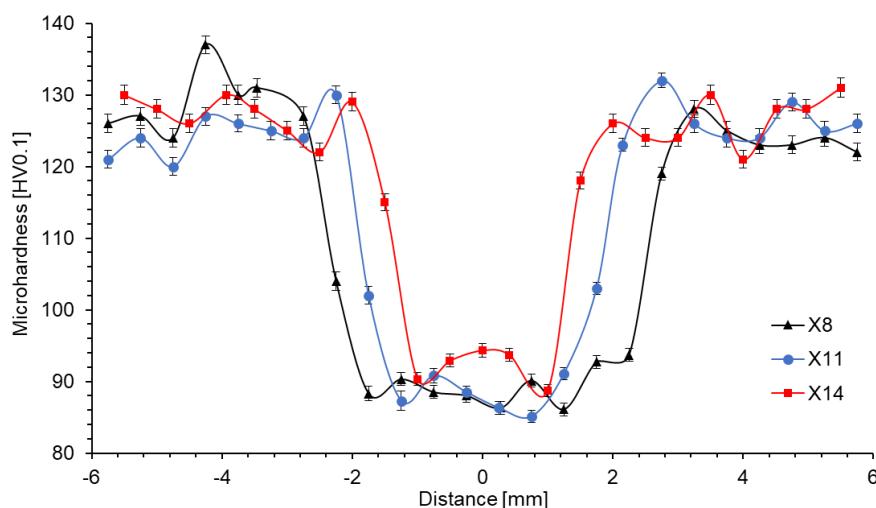


Fig. 3. Microhardness distribution of the welds cross-sections

The reduction of microhardness in the fusion zone is very similar for all analyzed samples, it changes from about 125-135 HV0.1 to 90 HV0.1. It is an effect of the dissolution of the strengthening phase in the liquid metal and heat treatment would be necessary to restore this phase in the structure of the alloy [8]. It is also possible to observe some exceptions in this trend, e.g. X14 has a slightly higher value of microhardness in the center of the fusion zone. A possible explanation for this phenomenon is the formation of finer dendrites due to a higher cooling rate [15]. In the area between the fusion zone and the base material, a repetitive increase in microhardness has been reported, what is connected to the formation of the equiaxed grain zone [17]. The selected images of the microstructures of the welds are presented in Figure 4a-d.

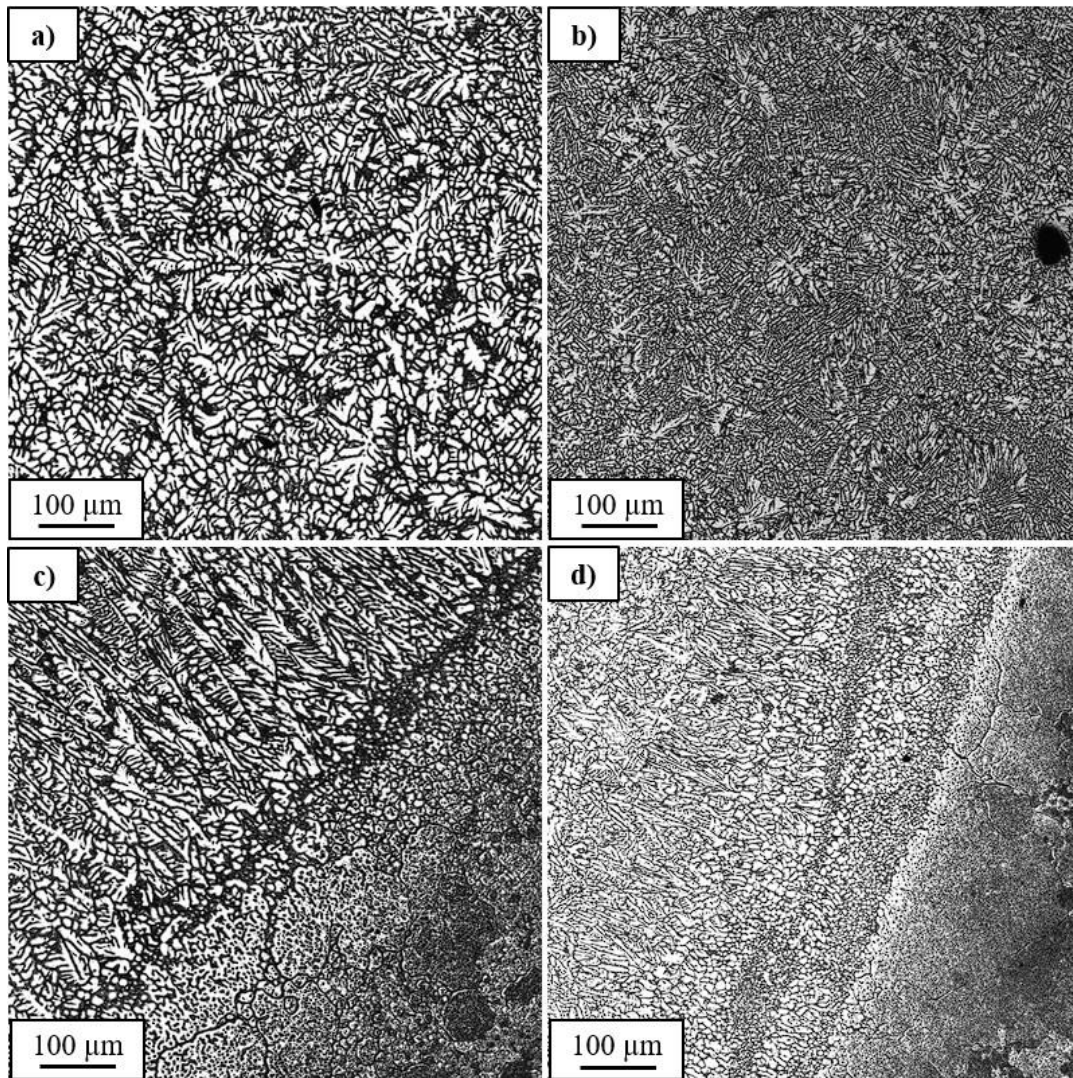


Fig. 4. Microstructure comparison between the X8 (a,c) and X14 sample (b,d) in terms of fusion zone (a,b) and fusion boundary interface (c,d)

The increase in welding velocity has an impact on each analyzed zone of the obtained welds. The central part of the fusion zone consists of equiaxed dendrites, which size depends on the used welding velocity and strongly decreases from 0.8 m/min (Figure 4a) to 1.4 m/min (Figure 4b). For the size of the dendrite is inversely proportional to the energy density, the obtained results comply with the literature [18]. Another area that is highly affected by welding velocity is the fusion boundary interface. The fusion boundary constitutes a border between the partially melted zone and the equiaxed grain zone. Next to the equiaxed grain zone, the columnar dendrites zone is present with its dendrites oriented in accordance with the heat flow [17]. The equiaxed grain zone of the X8 has a fine microstructure with a grain size of $7.9 \pm 3.3 \mu\text{m}$ and it is characterized by noticeable irregularity in width containing within the range of 50-150 μm (Figure 4c). The slightly higher values have been reported for the X14 sample, locally reaching 170 μm width (Figure 4d). The noteworthy aspect is the different structure of this zone in the case of the X14

sample, where it is subdivided into two ultrafine grained bands (about 1 to 5 μm) separated by relatively coarser, equiaxed grains with their size of 10-15 μm (Figure 4d). For this reason the ultrafine grains can be present in form the regular bands up to 100 μm from the fusion boundary (Figure 4d). The formation of equiaxed grain zone is strongly promoted by the presence of scandium in an alloy structure [13,17]. The equiaxed grain zone and partly melted zone constitute the transition zone [19]. In the obtained samples the partly melted zone can not be clearly identified. The transition zone in the X14 sample has been the subject of analysis on a scanning electron microscope in terms of chemical composition. The results are presented in Figure 5a-c.

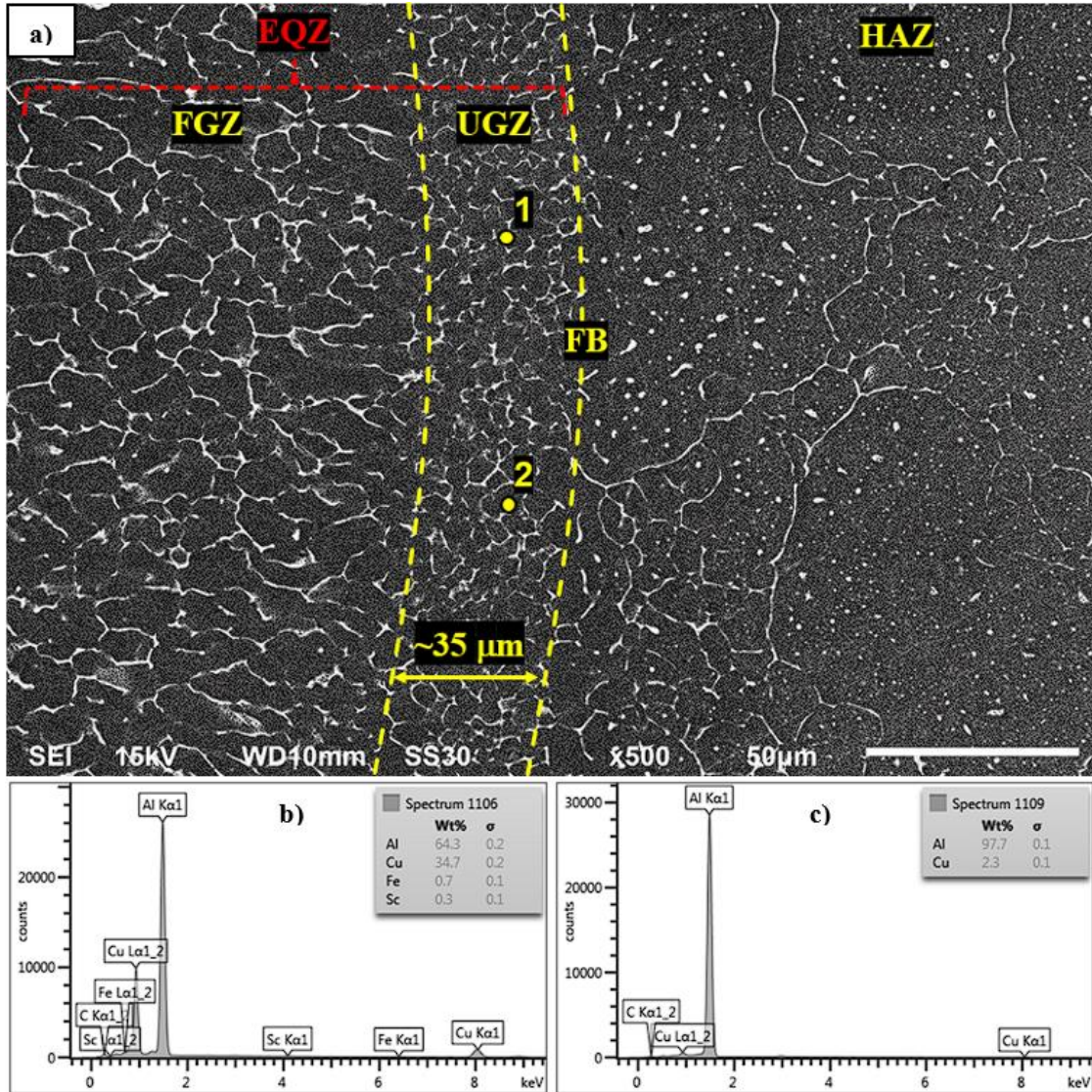


Fig. 5. SEM image of the transition zone in sample X14 (a) together with the EDS chemical composition analysis of the precipitate (b) and the matrix (c) corresponding to points "1" and "2" respectively.. EQZ – equiaxed grain zone, FGZ – fine grain zone, UGZ – ultrafine grain zone, FB – fusion boundary, HAZ – heat-affected zone

The obtained SEM image allows to observe a distribution of copper-containing precipitates into equiaxed grain zone and heat-affected zone (Figure 5a). The distribution in the heat affected-

zone occurs in the form of small spheroids and continuous layers on the grain boundaries. Starting from the fusion boundary the secondary phase undergoes severe evolution as the result of the welding process. In the equiaxed grain zone, the precipitates are localized predominantly on the grain boundaries. The width of the first band of the ultrafine grain zone has been established as 35 μm (Figures 4d, 5a). The results of the chemical composition analysis indicate that the precipitates are mostly composed of Al_2Cu with the participation of iron and scandium (Fig. 5b). At the same time, the matrix has been identified as a solid solution of 2.3 % copper and 97.7 % aluminum (Fig. 5c). These results overlap with the previous study on laser beam welding of non-heat-treated AA2519 extrusion [17]. The representative curves obtained from the tensile tests are presented in Figure 6. The established values of tensile strength, joint efficiency, and failure locations are set in Table 4.

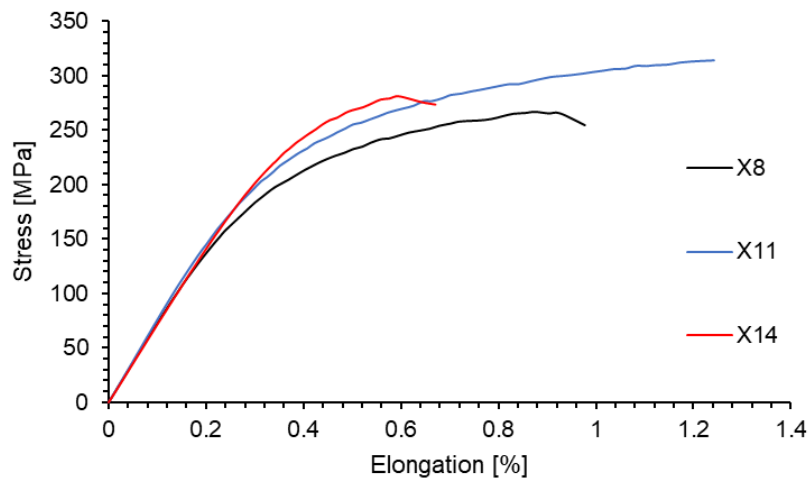


Fig. 6. Stress-strain curves of the investigated welded joints

Table 4. The established values of tensile strength, joint efficiency, and failure location

Joint	Tensile strength [MPa]	Standard deviation [MPa]	Joint efficiency [%]	Failure
X8	264.7	2.1	56.4	FZ
X11	310.1	3.9	66.1	FZ
X14	258.5	22.6	55.1	FZ

The highest joint efficiency has been obtained for the X11 sample and it equals 66%, what is a fine result for laser beam welded aluminum-copper alloy [20]. All samples have very low values of elongation to break (about 1%) with a failure occurring in the fusion zone, although it has to be noticed that the values are the result of the extensometer gauge length of 50 mm. For a laser beam welded joint takes below 10% of this length and the plastic deformation cumulates in the fusion zone referring it to a 50 mm base gives very low values of elongation despite the ductile failure. This phenomenon is called strain localization and it is described in the literature [21]. The overall view of the tested samples' fractured surface are presented in Figure 7a-c.

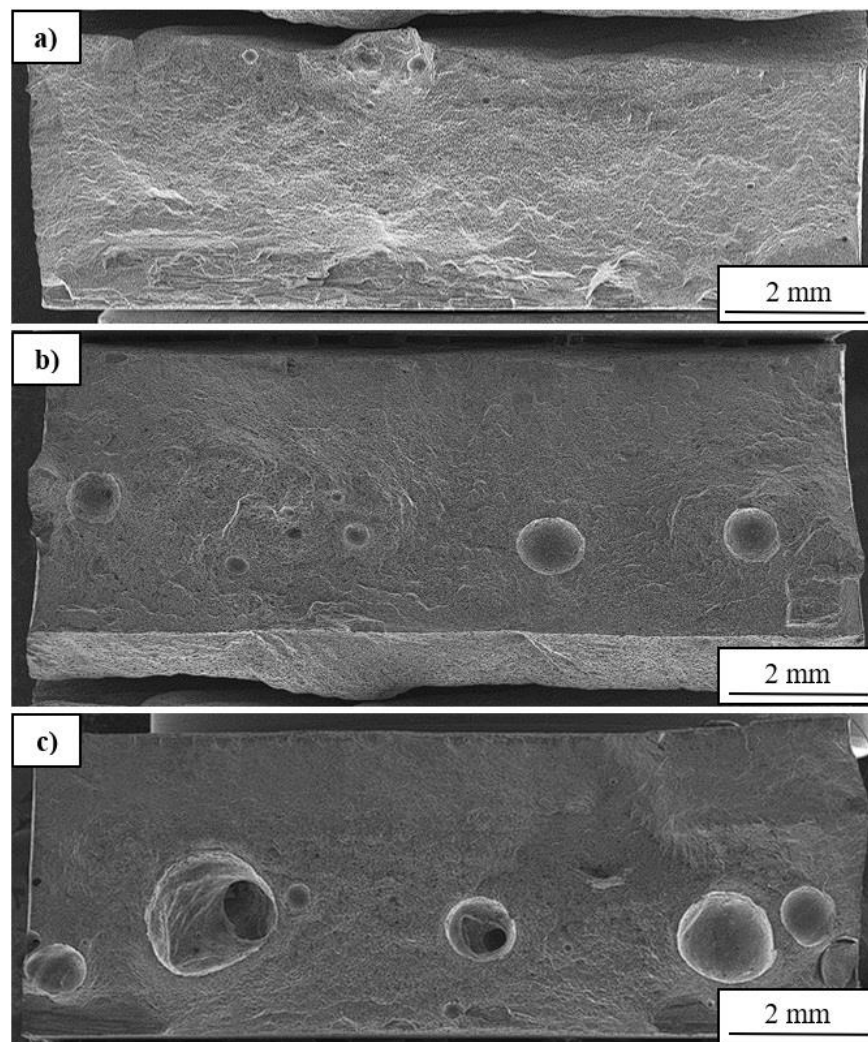


Fig. 7. Fracture surfaces of the tested welds: X8 (a), X11 (b), and X14 (c)

All tested joints tend to fail in the fusion zone, which has been identified as the softest region of the welded joint (Figures 3 and 7). The obtained fracture surface of the fusion zones allow to examine the influence of the welding velocity on the porosity of the joints. The established participation of pores on the surfaces for the samples X8, X11, and X14 equal 0.5 ± 0.02 %, 3 ± 0.15 %, and 11.4 ± 0.57 %, respectively. These results overlap with the macroscopic observations (Figure 2a-c) and confirm the joint's porosity increases together with the welding velocity. In order to identify the fracture character selected parts of fracture surfaces have been examined and presented in Figure 8.

The character of the failure is predominantly ductile (Figure 8a) with a typical dimple structure containing Al_2Cu precipitates (Figure 8b). Despite the relatively low values of elongation to break, the fractured surface observations prove the ductile failure in the fusion zone due to strain localization. The fractured surface exhibits the features of a fractured 2XXX alloy in the annealed condition [22].

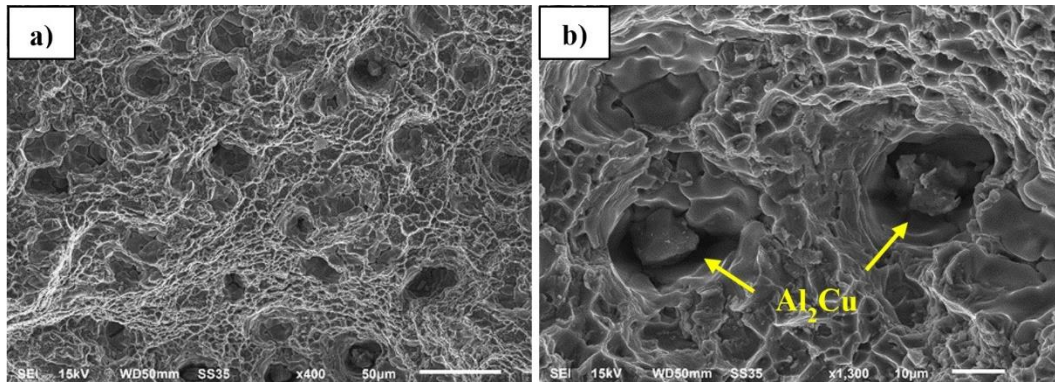


Fig. 8. Fracture surface microscopic image of the X11 sample: a) dimple structure b) Al₂Cu precipitates

On the microscopic level, no welding imperfections have been identified as additional factors promoting decohesion. The formation of the porosity in the welded joints can be connected with an insufficient removal of oxide layers, which contains a potential source of moisture, before the welding process [7,23]. The obtained joints are characterized by relatively high sizes of root reinforcement, especially the X8 sample, which has been produced with the lowest value of welding velocity (0.8 m/min). Taking into account its underfill, the conclusion can be drawn that this set of welding parameters has too high heat input [24]. On the other hand, the lowest welding velocity allowed to reduce the hydrogen porosity noticeably (Figure 2,7a). In these terms, the X11 sample gives the best outcome in terms of combining welds geometry and porosity, what has been partly confirmed in the tensile test (Figure 6). The obtained microstructure of the welded joints corresponds to the literature reports on joining Al-Cu alloys by a laser beam. The crystallized fusion zone has the lowest value of microhardness due to the dissolution of strengthening phases and according to the literature contains within the range of 60-110 HV0.1, depending on used welding parameters [19,24-25]. Referring to this research it can be stated that the obtained values (85-95 HV0.1) are closest to the maximum value than to the minimum one (Figure 3). It is the fusion zone as the weakest point of the weld dictates the load-carrier capability of the joint. The values of tensile strength reported in the literature for Al-Cu-Li alloys welded joints often pointed out the range of 220-225 MPa [19,24]. Better results have been obtained for 2219-T62 alloy with a tensile strength of 337 MPa using optimized welding parameters [20]. Generally, a joint efficiency above 60% is considered a good result for Al-Cu laser beam welded, what has been achieved in this study (Table 4).

CONCLUSIONS

The following conclusions can be drawn from this study:

- The produced welds have noticeable participation of metallurgical pores, which tends to increase together with the value of welding velocity. Despite these imperfections, the macroscopic observations did not reveal any presence of solidification cracks.
- As the result of the dissolution of the strengthening phase, the reduction of microhardness in the fusion zone occurs. It is very similar for all analyzed samples, and it changes from about 125-135 HV0.1 (base material) to 90 HV0.1 (fusion zone).

- The size of the equiaxed grain zone is influenced by applied welding parameters and its width increases together with welding velocity. Additionally, the formation of ultrafine grainy microstructure containing the precipitates composed of Al_2Cu with the participation of iron and scandium.
- The established values of joint efficiency contain within the range of 55-66% with the highest value (66%) reported for the joint obtained with 1.1 m/min welding velocity. The strain localized in the fusion zone, what results in relatively low values of elongation to break (about 1%).
- In all cases, the failure occurred in the fusion zone with the ductile fracture character and the formation of a typical dimple structure.

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Conflicts of Interest

The authors declare that they have no competing financial interests or personal relationships that could have seem to influence the study reported in this paper.

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