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FRICTION WELDABILITY OF UFG 316L STAINLESS STEEL

The broad range applications of Ultra-Fine Grained metals is substantially limited by the lack of a welding method that allows them to be joined without losing the strong refinement of structure. From this point of view, the solid state welding processes are privileged. Friction welding tests were carried out on UFG 316L stainless steel. A joining process at high temperature activates the recrystallization, therefore the friction welding parameters were selected according to the criterion of the lowest degree of weakness due to recrystallization in the heat affected zone. In order to characterize the structure of basic material and selected areas of the obtained joint, were performed SEM, TEM and metallographic examinations in terms of hardness and range of softening of the material and tensile test. Despite the short time and relatively low welding temperature, results of the test by scanning electron microscopy and transmission electron microscopy confirmed the loss of the primary ultrafine structure in the Heat Affected Zone of welded joint.

Keywords: UFG metals; recrystallization; friction welding; weldability

1. Introduction

In the past, improvements in the properties of metallic materials were achieved mainly by adding more alloying elements and/or applying complex thermomechanical treatments. The first method is a costly solution and may involve rare or strategic elements while the second is usually limited in terms of the achievable improvements [1-4]. A more innovative approach to improving properties of metallic materials is metal forming process with severe plastic deformation, which is based on the Hall-Petch relationship. An increase in the mechanical properties is obtained by controlled grain refinement at low temperature values [5,6]. Refining grain size of metals to the submicrometer level, achievable by traditional metallurgical techniques by Severe Plastic Deformation processing (SPD), gives a new class of UlTrafine Grained metals (UFG) with significant advantages [6-12].

The ultrafine grained metals have a mean grain size <1 μm and the crystallites often have got one of the dimensions in nanometer size. The UFG metals exhibit higher values of mechanical properties, than the same metals with micrometric structure and are very attractive alternative to conventional high strength structural metallic materials.

The application of bulk metals and alloys with sub-microcrystalline structure is nowadays limited by too small volume of obtained prefabricates. Therefore, the greatest practical interest concerns the SPD method in which large quantities of material can be deformed. However, the larger volume of the processed billets the higher is the cost of equipment because contact friction significantly increases the loading of tool and equipment. Therefore, the majority of SPD methods demonstrate limitations in producing the volume of homogeneously deformed material [13]. Moreover, there are technical limitations in manufacturing of processing equipment for reasonable costs. An alternative approach can be an application of joining technique to manufacture a long enough semifinished product compound of many single billets made of UFG metal for shaping final engineering components in an economical way. The idea requires to develop a joining method of UFG metals for avoiding dimensional limitations, which would allow them to be joined without losing the strong refinement of structure. Thanks to that, there would be the ability to manufacture items for complex geometries made of UFG metals having high strength enabling a significant reduction in their weight. Currently the range of applications of UFG materials is limited to e.g. manufacturing of engineering components and orthopaedic implants [14]. For orthopaedic implants a pure metal is the best material for designed biocompatibility and medical screws require functional physical properties which cannot be easily achieved in the case of pure metals and not heat treated metal alloys. The only way is to combine strain hardening and grain refinement, characteristic of metals obtained to the SPD process.

The effect of severe plastic deformation processing is also to accumulate significant amounts of energy in the material. Therefore, providing too much heat to the UFG material

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starts a process of recrystallization. By welding conventional materials, the occurrence of dynamic recrystallization results in better continuity of the joints [15]. But in case of fine and ultrafine grained metals this phenomenon causes degradation of the microstructure obtained by SPD processing and loss of high mechanical properties. But welding without degrading their properties in the Heat Affected Zone (HAZ) is in the present state of knowledge impossible.

The fusion welding tests of high strength microalloyed steels with a fine-grained structure produced by thermo-mechanically controlled process (TMCP) confirm that in the heat affected zone (HAZ) the grains grow, and the softening of material occurs. In these cases, it is possible to lower the HAZ width by laser or hybrid welding [16-19].

Welding methods based on a local melting of the edges of the joined materials cannot be used to join UFG metals for obvious reasons. Therefore, only methods of solid-state bonding, based on metallic bonds, must be involved for such metals. However, the energy required for local activation of a bonding process should be provided in controlled amount and at the highest possible temperature gradient [20-22]. The main goal of experimental investigation into joining of UFG metals with welding methods, that are carried out by the help of heat obtained with conversion of mechanical energy into thermal energy was to reveal the microstructural features in the joint area. In each case, authors attempted maximizing mechanical properties and preventing grain growth in the joint zone based on selection of parameters of welding. Despite this, materials with the initial refined structure revealed an intense reduction of microhardness in the stir zone, which was explained by the grain growth. It was caused by thermal instability resulting from high stored energy during severe plastic deformation. The ultrafine grained structure is being disintegrated (mainly by means of recrystallization) in the HAZ which is accompanied by substantial deterioration of physical properties including the strength of a joint. Also, plates made by isothermal forging from UFG titanium alloy for medical application was joined using linear friction welding (LFW) with similar results as for aluminium [23].

The friction welding is the most convenient method of joining short bar parts into barstock with designed length and it can join non-equal and non-circular cross-sections as well. This method of welding is a promising approach, because the process is conducted in a solid state (well below melting point). Additionally, it brings many advantages, such as absence of porosity, embrittlement, or second phase formation. The presence of stable connection is achieved by mixing the friction-heated, plasticized, and deformed metal along the contact interface of welded elements. It can be performed by rotating one of the parts that is to be welded around its axis, while another is pushed toward the rotated part with in a certain time. When sufficient temperature is reached at friction surfaces, the rotating process is stopped suddenly, the pressure is increased, and the soft material is left to cool under this high pressure. The key factor for obtaining a consistent joint is a large plastic deformation at elevated temperature. It results in bringing-up atoms to a distance similar as in crystal lattice, which allows creation of a metallic bond [24-30].

This paper describes the results of friction welding tests of short rods of UFG 316L steels. The highest strength properties of the joint were obtained for the rotation speed of spindle 12000 rpm.

2. Experimental

2.1. Characteristic of the base material

316L type austenitic stainless steels are common engineering materials characterized by high resistance to corrosion and good formability. To eliminate their moderate strength many efforts to increase their strength are continuously undertaken. The work hardening is the only way in which austenitic stainless steels can be hardened. Because of the high work hardening rate characteristic of 316L type stainless steels plastic deformation operations require higher force in comparison to carbon steels [5]. For strong grain refinement of 316L steel a high-pressure torsion (HPT) [6] and cold deformation [7] was used. In these methods, the increase degree of grain refinement (and mechanical properties of UFG metals) depends, among on the number of repetitions of the cycle. In this paper, the samples were made on the UFG 316L steel obtained by means special, rarely applied method of hydrostatic extrusion (HE) [5]. The material subjected to hydrostatic extrusion was austenitic stainless steel AISI 316L (1.4404) with the composition and properties according to the ASTM A182 standard in the shape of a rod 55 mm in diameter manufactured by: the Cogne Acciai Speciali, Italy. The chemical composition of steel is given in Table 1.

TABLE 1

Chemical composition (wt%) of the examined stainless steel 316L (*manufacturer specification*)

C	Si	Mn	P	S	N	Cr	Mo	Ni	Cu	Co
0.017	0.36	1.82	0.30	0.026	0.077	16.88	2.04	10.14	0.38	0.10

The mechanical properties of the as-received rods are given in Table 2. The grain size was between 5-7 of the ASTM E112 inspection which corresponds to the average grain diameter ranging from 32 to 62.5 μm. More detailed investigations revealed that the microstructure of the stainless steel was typical, with equiaxed grains and annealing twins, Figure 1.

TABLE 2

Initial mechanical properties of the stainless steels examined in the present experiments (*manufacturer specification*)

	Ultimate tensile strength	Yield stress	Elongation to fracture	Reduction of area	Hardness
	UTS (MPa)	YS (MPa)	ε_f (%)	Z (%)	HB
316L	612	283	56	77.3	180

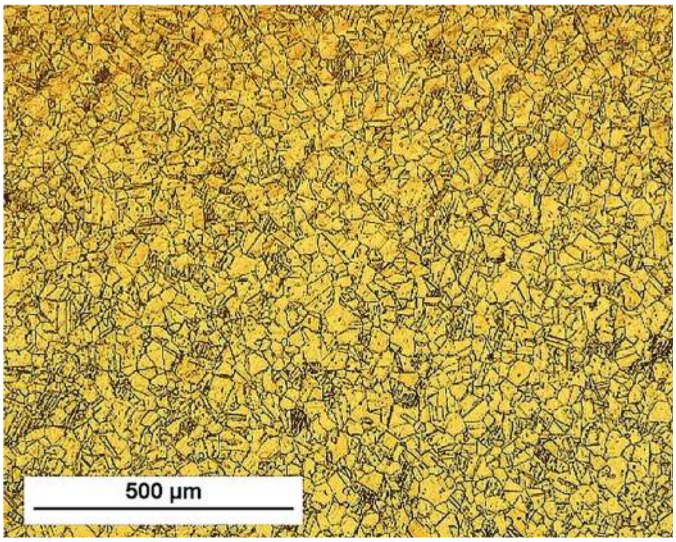

Fig. 1. Light microscopy image of the microstructure of 316L at the initial (as-received) state

The extrusion was performed in a Unipress' Hydrostatic Extrusion Press, with the working chamber diameter of 22 mm and 2 GPa maximum operating pressure, with the die angle $2\alpha = 45°$. The pressure characteristics of the hydrostatic extrusion process of 316L stainless steel is shown in Figure 2. Before hydrostatic extrusion the round rod with a diameter of Ø55 mm was cut into quarters. The billets were cold hydrostatically extruded in one pass to a diameter of 5.95 mm, i.e. with the reduction ratio of $R = 3.42$, which corresponds to true strain of $\varepsilon = 1.23$, where R is the ratio of the cross-section surface areas before and after the extrusion. The process parameters were chosen to enable stability of the extrusion pressure, which results in homogeneity of the material properties along the extruded rod. The hydrostatic extrusion processing has been described in item [9].

The structure were examined by optical microscopes Nikon Eclipse LV150 and by transmission electron microscopy JEOL JEM 1200 EX. The thin foils for TEM observation were prepared

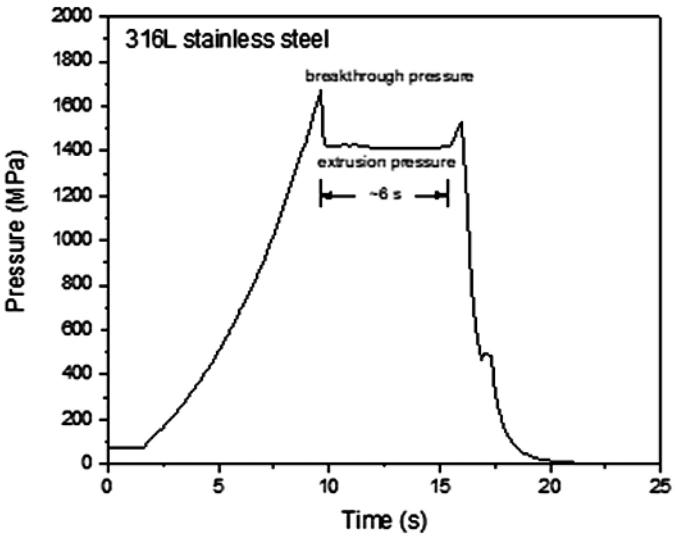

Fig. 2. Pressure characteristics of the hydrostatic extrusion process of 316L stainless steel

from a longitudinal and transverse section of the extruded rods. The microhardness was measured on a transverse sections of the extruded rods using an automated Zwick-Roell ZHV1-A microhardness tester with a load of 200 G and a 15 s test period. The tensile specimens with the length-to-diameter ratio equal to 5 were investigated in a Zwick/Roell Z250kN static tensile machine at room temperature with a constant strain rate of 0.008 s^{-1}.

One-pass cold hydrostatic extrusion results in substantial structural transformations in 316L steel. High strains lead to grain refinement to the nanometric scale. The primary grains become strongly deformed which is accompanied by a considerable increase in the density of internal defects. The grain refinement is associated with the sharp increase in the density of dislocations, deformation twinning and slip bands created during severe plastic deformation [5]. Figure 3 shows the structure of transverse cross-section sample examined by transmission electron microscopy. The characteristic strongly banded structure in the direction of extrusion is shown in the Figure 4. The bands observed on the longitudinal sections were characterized by a thickness of ~100 nm, Figure 4b.

Fig. 3. A bright field TEM images with corresponding SAED patterns, transverse cross-section

Such a strong deformation of the structure and obtaining the grain size in nanometric scale resulted in significant changes in the mechanical properties of UFG 316L steel. Figure 5 shows the comparison of the ultimate tensile strength UTS, yield strength YS, elongation to fracture ε_f and Vickers hardness HV0.2 of 316L stainless steel initial material and after cold hydrostatic extrusion. The drastic increase of YS by more than threefold, UTS by more than 100% and HV0.2 by more than 70% accompanied by over 75% decrease of ductility ε_f should be noted.

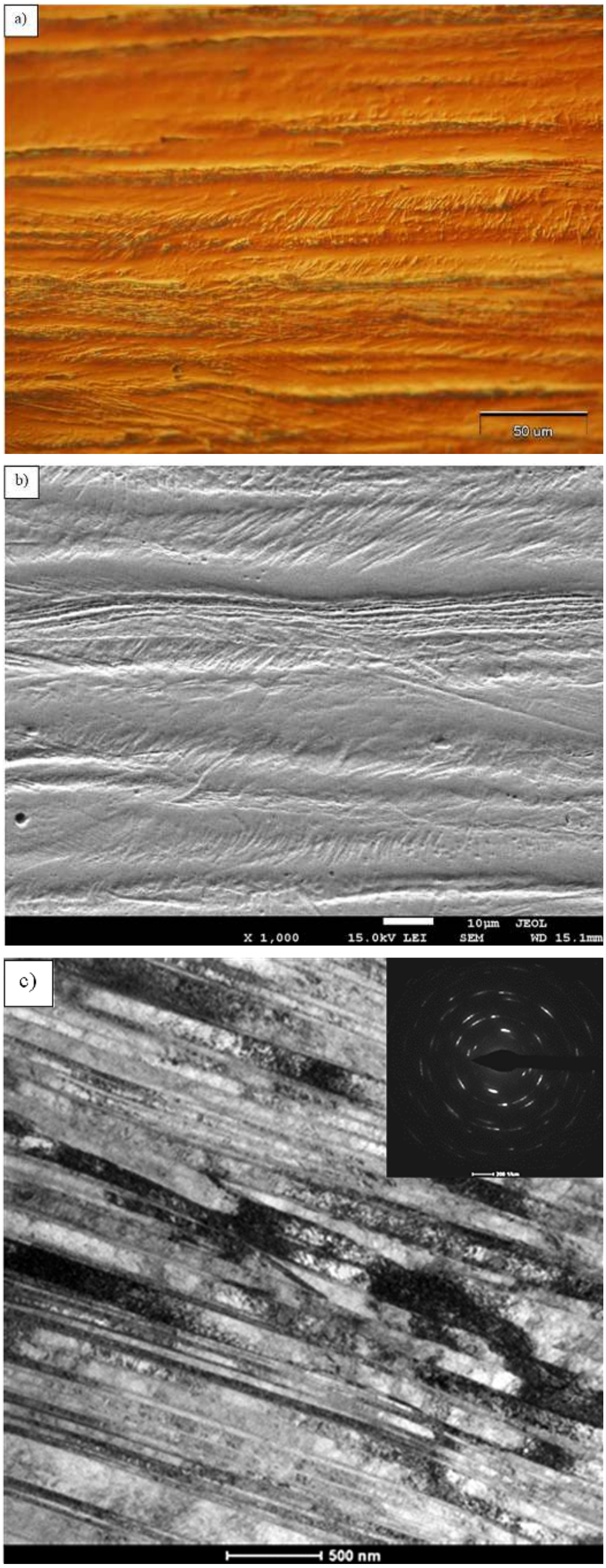

Fig. 4. Microstructure of 316L steel after one-pass hydrostatic extrusion, longitudinal cross-section: a) Optic micrography (Olympus IX70) in Nomarski interference contrast (DIC), magnification ×500, b) SEM in the LEI mode of sample (scanning electron microscope JEOL JSM-7600F), c) Bright field TEM images with corresponding SAED patterns

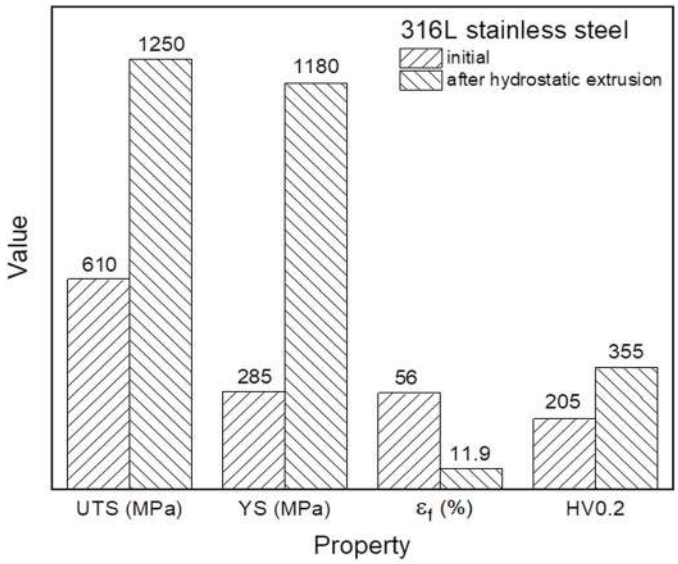

Fig. 5. Comparison of the mechanical properties of 316L stainless steel initial material and after cold hydrostatic extrusion with true strain of $\varepsilon = 1.23$ in one pass

2.2. Friction welding process and characteristic of friction welded joint

The conducted initial tests of friction welding of ultrafine grained 316L steel have shown that the degree of heat affected zone being defected depends on the velocity of heating in the first phase of the friction stage of this process. The test was carried out on high speed friction welding machine Harms Wende HWM RSM200 and the value of heat input by friction welding was controlled by rotational speed of spindle [24]. Figure 6 shows the method of fixing samples in the machine. One of them was placed in a rotary spindle, which in Figure 6 was marked with the letter A, while the other was locked in a fixed holder – B. The article presents the results for which the highest strength properties of the joint were obtained (corresponding to the rotation speed of spindle 12000 rpm).

The structure of the friction welded joint, were examined by optical microscopy Olympus IX70 in differential interfer-

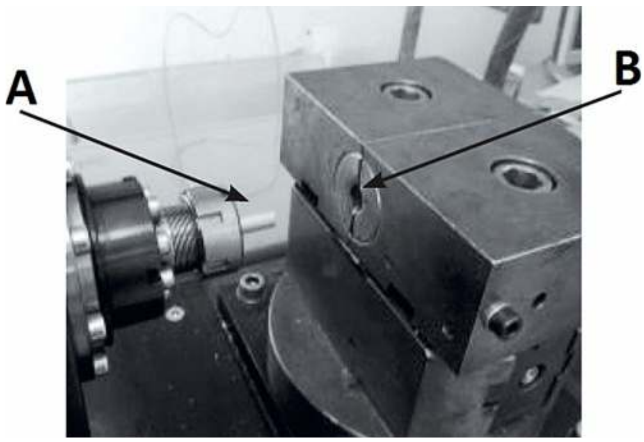

Fig. 6. Method of fixing welded samples, rotary spindle – A, fixed handle – B

ence contrast (DIC) and by transmission electron microscopy JEOL JEM 1200 EX. SEM-investigations were conducted with the scanning electron microscope JEOL JSM-7600F equipped with Schottky field emission gun. The SEM conditions for the alloy element distribution measurements by EDS were set to an acceleration voltage of 20 kV and a working distance of 15 mm. The friction welded samples were examined on their transverse section, polished and etched.

3. Results and discussion

3.1. Metallographic examinations

The first metallographic tests performed on the optical microscope showed that the individual joint zones differ in their microstructure, Figure 7. The friction welded joint is characterized by a relatively narrow heat affected zone (zone of recrystallization) with a width of approximately 0.8 mm, Figure 8. A comparable width of HAZ over the entire radius of the connector indicates the correct ratio of rotational speed and welding time. The microstructure of the material adhering to the joint differs from the material after hydrostatic extrusion, but the bandwidth of degradation of the structure is relatively small.

3.1.1. SEM and TEM

SEM-investigation confirmed the changes of the original structure of UFG 316L in the obtained joint, Figure 9. In the low-temperature HAZ, the material structure remains streaked (hydrostatic extrusion effect), however, the upsetting phase in friction welding process caused a change in the band's arrangement – along the weld. In the friction weld, Figure 9b, the loss of the band structure and the strong grain refinement caused by defragmentation of the grains by their mutual abrasion can be noticed.

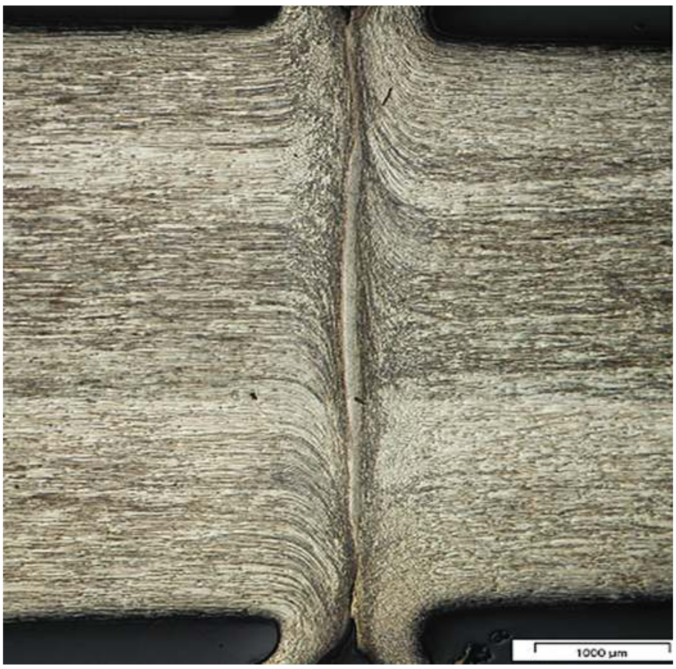

Fig. 7. Microstructure of friction welded joint of 316L UFG steel, etched

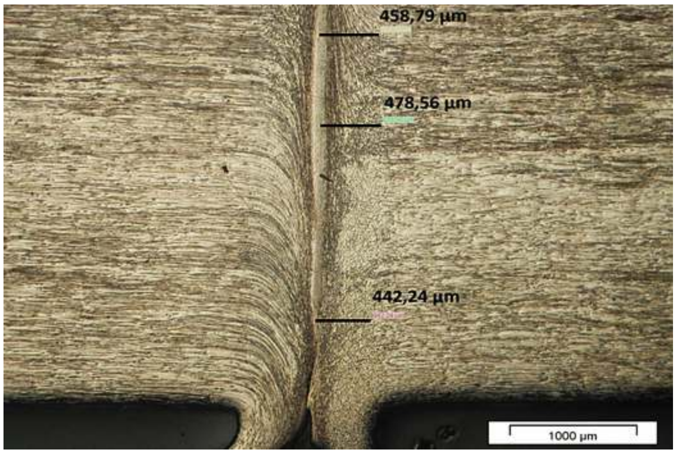

Fig. 8. HAZ measurements in friction welded joint of 316L UFG steel, etched

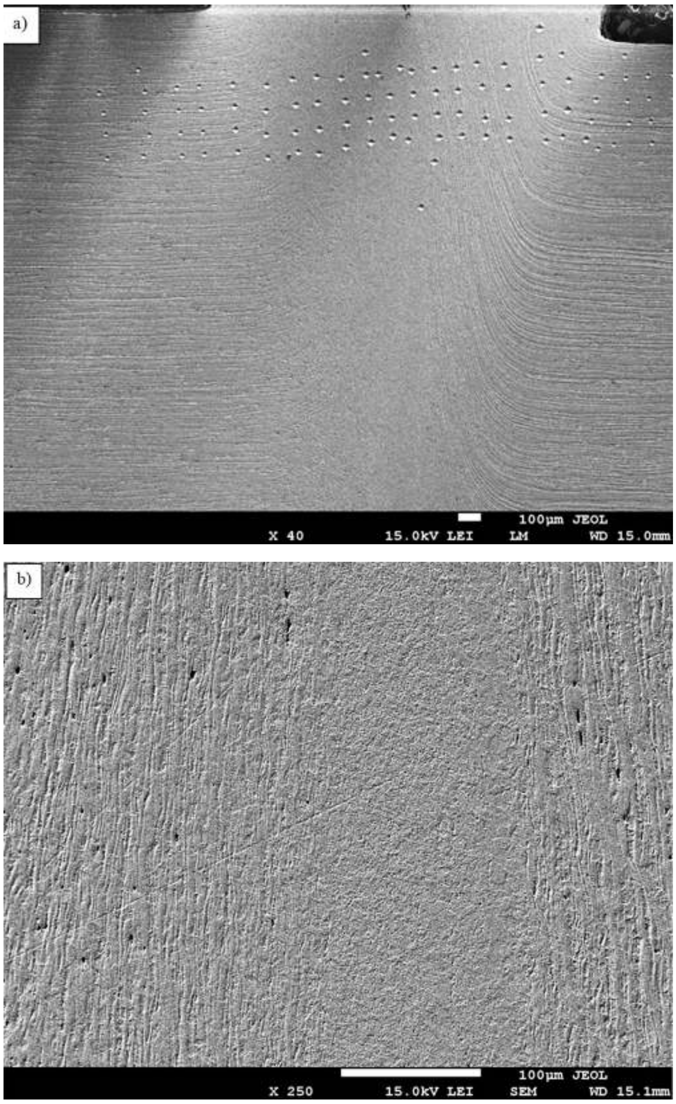

Fig. 9. SEM in the LEI mode of the transverse section of the friction welded joint sample, a) mag. ×40, b) mag. ×250

EDS (Energy Dispersive X-ray Spectroscopy) analysis showed that the temperature values occurring during the friction welding process and the process itself didn't cause chemical segregation in the welded joint, Figure 10.

Figure 11 shows the TEM microstructure of the transition zone of friction welded joint. In the HAZ grain growth >100 nm was observed, but their elongated shape remained. However, in the friction weld, the original material structure after hydrostatic extrusion was completely lost, Figure 11b.

3.2. Mechanical properties of the friction welded joint

The microhardness was measured on a transverse section using the LEITZ MINILOAD 8375 microhardness tester with the indenter load of 100 G. Four series of measurements were carried out, in two areas of the friction welded joint – the first at the outer surface of the sample, the next in the axis of the rods. The research methodology was as follows: the measurements were started from the central part of the friction welded joint, and then a measurement was made symmetrically every 0.1 mm until the results indicating the end of the HAZ were obtained.

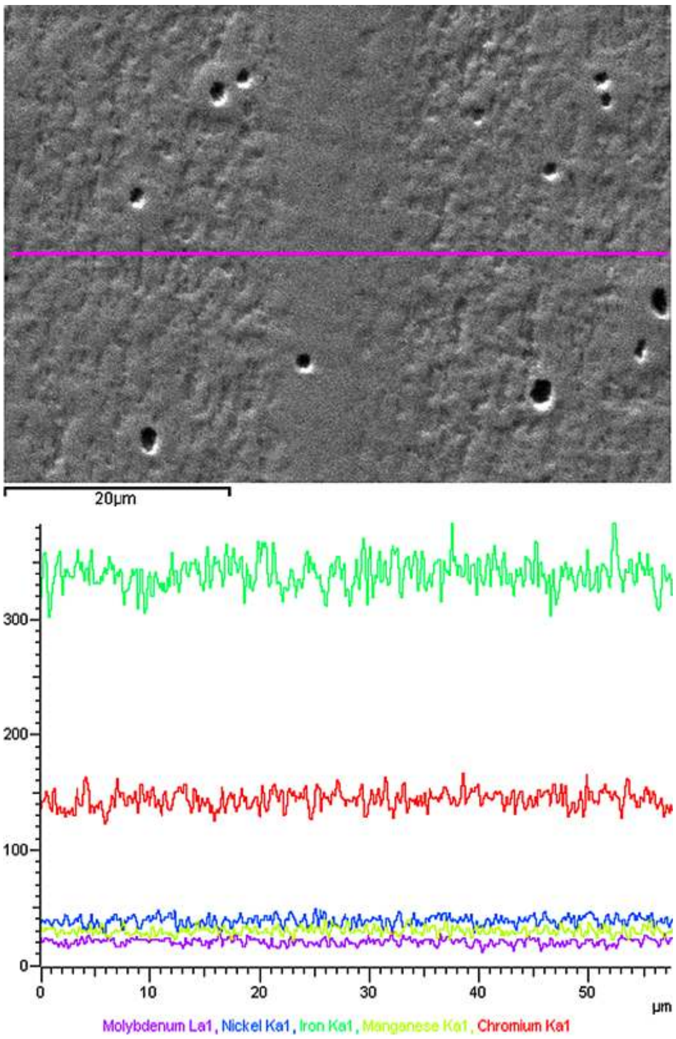

Fig. 10. Energy Dispersive X-ray Spectroscopy analysis of friction welded joint

The graph in Figure 12 shows the average of four measurements with standard deviation (t-student distribution with 95% confidence level).

The graph illustrates the width of the heat affected zone and indicates the degree of degradation (by recrystallization) of a specific ultra-fine grained structure. Hardness in the basic material was in range of 280÷300 HV0.1. In both areas, the distribution of microhardness is diversified and lower values were noted in the HAZ, mainly in the area of the axis of the sample. In the friction welding zone the same microhardness was measured for both areas – 200 HV0.1, it is the effect of defragmentation of the grains by their mutual abrasion.

The softening of metal in the heat affected zone confirmed the results of tensile strength tests. The tests were investigated in a Zwick/Roell Z250 kN static tensile machine at room temperature with a constant strain rate of 0.008 s^{-1}. Figure 13 shows the course of the sample cracking after tensile strength tests. The sample cracked in the HAZ.

For friction welded joints the ultimate tensile strength UTS = 840 MPa, yield stress YS = 750 MPa, were recorded, these are mean values of four tests with standard deviation. Compared to UFG 316L steel, the friction welded joint has a lower ultimate tensile strength by ~30% and yield stress by ~35%, Table 3. The samples cracked in the zone adjacent to the weld which indicates that a higher friction weld strength was obtained.

TABLE 3

Comparison of the mechanical properties of 316L stainless steel initial material, after cold hydrostatic extrusion and after friction welding

Material	YS [MPa], $\bar{x}$ (s)	UTS [MPa], $\bar{x}$ (s)	Hardness	Elongation ε_f [%]
Initial	285 (8.12)	610 (6.23)	205 HV0.2	65
After Hydrostatic Extrusion	1180 (7.15)	1250 (6.12)	355 HV0.2	11.9
After Friction Welding (HAZ)	750 (32.23)	840 (22.35)	180 < HV0.1 < 300	—

4. Conclusions

Presented solid state rotary welding method (RFW) allows to obtain continuous and sound joints. However, for UFG metals, it is always associated with the reduction of the mechanical properties in the joint area. A properly formed cycle of welding allows to reduce the degradation of properties that are the effect after the SPD process. Although the process was demonstrated feasible, the process parameters must be carefully selected in order to produce sound joints. In particular, from the preliminary results presented, the suitable parameters is in narrow range with respect to the one which can be used for the same, microstructural alloy. HV results show a reduction of hardness in the HAZ area, due to the heat conferred resulting in grain growth phenomena which partially eliminate the advantages of the UFG. It was observed that despite the high temperature close

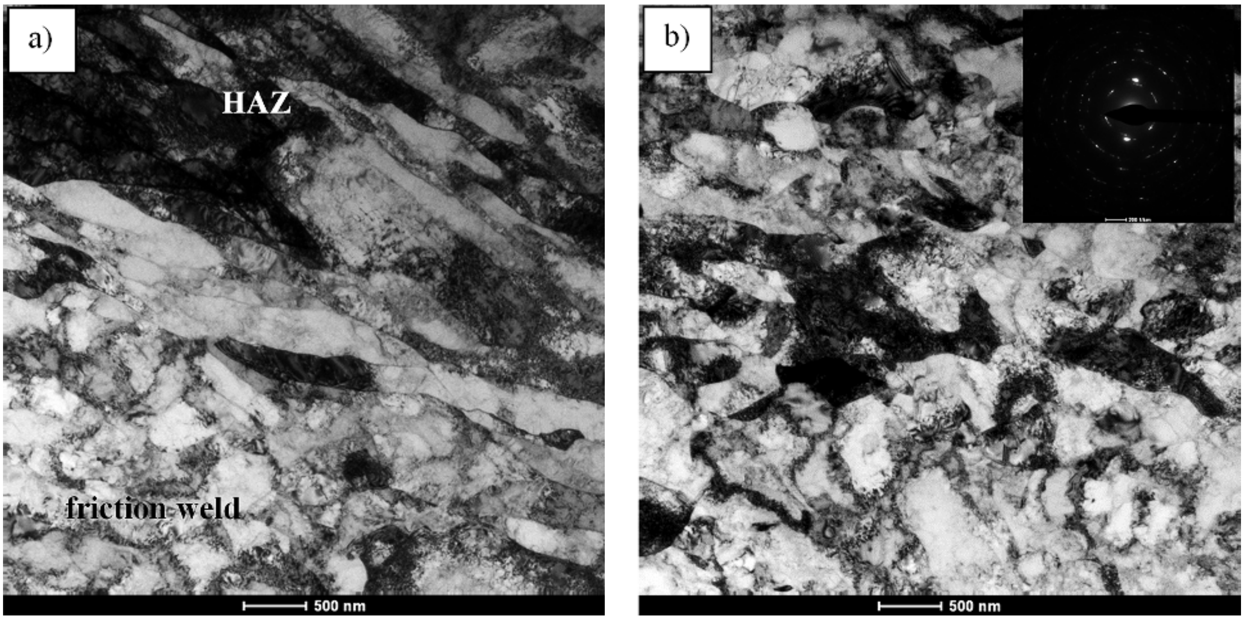

Fig. 11. TEM micrographs from transverse section a) of the transition zone of friction welded joint, b) of friction weld, with SAD pattern

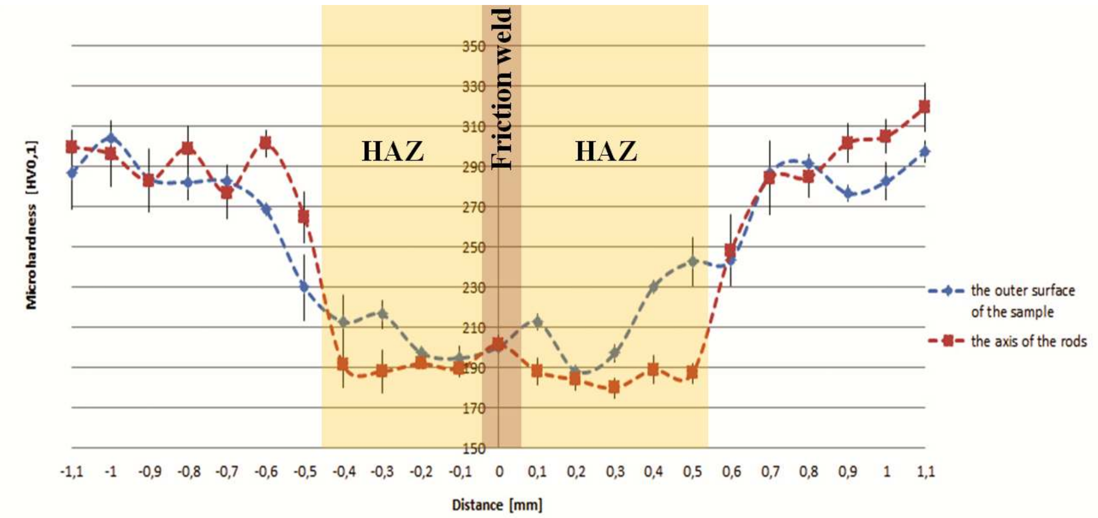

Fig. 12. Linear distribution of microhardness in friction welded joint of 316L UFG steel

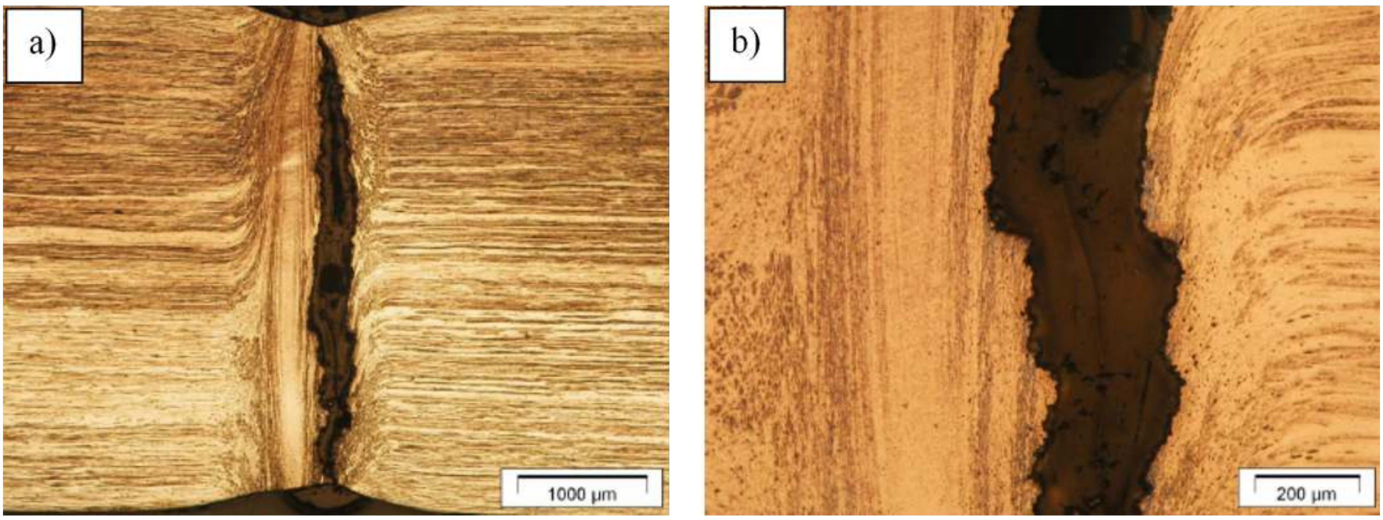

Fig. 13. Optic micrograph of fracture of sample after tensile strength tests, a) mag. ×50, a) mag. ×100

to the friction welding line, the combined recrystallization effect with the grain refinement (by its shearing) on the friction surface results in a limitation of recrystallization effect (local increase of hardness).

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