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W. WIĘCKOWSKI[#], P. LACKI^{**}, J. ADAMUS^{**}**EXAMINATIONS OF STEEL OVERLAP JOINTS OBTAINED USING THE FRICTION STIR WELDING TECHNOLOGY**

The aim of the study was to analyse mechanical properties and microstructure of joints obtained using friction stir welding (FSW) technology. The focus of the study was on overlap linear FSW joints made of 1.4541 DIN 17441 steel sheets with thickness of 1.2 mm. Tools used during friction stir welding of steel joints were made of W-Re alloy. The joints were subjected to visual inspection and their load bearing capacity was evaluated by means of the tensile strength test with analysis of joint breaking mechanism. Furthermore, the joints were also tested during metallographic examinations. The analysis performed in the study revealed that all the samples of the FSW joints were broken outside the joint area in the base material of the upper sheet metal, which confirms its high tensile strength. Mean load capacity of the joints was 15.8 kN. Macroscopic and microscopic examinations of the joints did not reveal significant defects on the joint surface and in the cross-sections.

Keywords: friction stir welding, FSW, 1.4541 steel

1. Introduction

Friction stir welding (FSW) is becoming increasingly used for joining components in many industries, including the aircraft, maritime, rail, automotive and construction industries. Nowadays, it is successfully used for joining aluminium, magnesium and other metal materials with low melting points. Its commercial use for joining steel has not reached a similar high level, mainly due to high costs resulting from low durability of welding tools. Joining steel requires tools that can be used at elevated temperatures while maintaining high strength and hardness. By using expensive yet modern wear-resistant tool materials based on WC (tungsten carbide) and PCBN (polycrystalline cubic boron nitride), friction stir welding offers an alternative to conventional welding methods where weldability or properties of welded joints are at an inadequate level [1-6].

The research results in the field of friction stir welding of various steel grades presented in the literature provide information on the tools and parameters of the welding process critical from the standpoint of the quality of FSW joints (microstructure and mechanical properties) [7].

The authors of the study [8] examined FSW of hot-rolled AISI 1018 steel. The welding process was performed for different rotational speeds and linear velocities of the tool. As a result of investigation, in the steel weld, several zones with different structure were distinguished: stir zone (SZ) with small grains caused by dynamic recrystallization after intense plastic deformation and high temperature impact, not clearly

visible thermo-mechanically affected zone (TMAZ) with some deformations, but with no recrystallization due to insufficient temperature, and a heat-affected zone (HAZ). The changes in the joint microstructure depend on the welding parameters and have a significant impact on the mechanical properties after welding. Stainless steel is characterized by low thermal conductivity, so the stirring zone narrows, especially at high welding speeds [9].

The results of FSW of carbon steel with different carbon contents have been presented in studies [10-12]. The authors of these studies have discussed the relationships of the microstructure and joint strength with welding parameters.

The study [13] analysed the effect of tool material on the mechanical and microstructural properties of joints made of AISI 316L austenitic stainless steel. As reported in [14,15] high quality FSW joints without any defects were obtained for high-carbon steel. The effect of tool rotational speed, feed rate, axial force and angle of tool inclination on welding of austenitic stainless steel AISI 304 was analysed in the study [16]. With a specific set of welding parameters, the researchers obtained high quality joints with tensile strength exceeding the strength of base material. The study [17] examined the effect of welding speed for FSW 304L stainless steel on the FSW process. FSW welding of materials such as stainless steel requires that an adequate amount of heat has to be supplied to joint area, determining the number and type of defects in the joint, its mechanical properties, residual stresses in the joint and tool life.

The usefulness of the FSW technology for joining steels used in the automotive industry was presented in the paper [2].

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The authors attempted to identify FSW process parameters for steel with different tensile strength using a tungsten carbide (WC) tool. Research has shown that the higher the strength of the joined material, the narrower the range of parameters that allow for obtaining a joint with sufficiently high strength.

The results of the research on the opportunities for using FSW for joining GL-A36 steel in the shipbuilding industry were documented in [18]. The study analysed the effects of welding parameters on metallurgical characteristics and mechanical properties of welds obtained using a tantalum-based tool.

In addition to welding parameters, proper choice of geometry and positioning of the tool in relation to the joined components has also a significant effect on the quality of FSW/FSSW joints. Incorrect shape of the working surface of the tool and poorly selected process parameters lead to the defects on the surface and inside the weld [19]. The study [20] examined the effects of the shape of the pin and shoulder of the FSW tool made of tungsten alloy on the type and size of defects occurring in the low-alloy steel joints.

The authors of the work [21] present the test results of FSW joints made of AISI 316L austenitic stainless steel welded at different tool rotational speeds and constant values of other process parameters. Microstructure analysis revealed that discontinuous dynamic recrystallization was the main recrystallization mechanism in the stir zone. The grain size of the stir zone was significantly influenced by both heat generation and material strain rate.

In [22] the results of FSW of ultrafine grained austenitic 304L stainless steel were presented.

After friction stir welding, different grain structures in different areas of the weld nugget were observed due to the asymmetry in the heat generation in the process. A banded structure was detected in the advancing side of the weld nugget. It was noted that the welding speed growth can reduce the final grain size of the weld nugget leading to higher hardness. It was observed that the hardness increases not only as a result of grain refinement but also due to the presence of sub-boundaries and a high density of dislocations.

Tests of mechanical properties of FSW joints of stainless steel using PCBN tool were presented in [23]. The authors manufactured FSW joints of higher strength than base material. Investigation of FSW joints made of super-austenitic stainless steel S32654 confirm that the grain refinement combining with high density dislocations and substructures improves the hardness and strength, but greatly reduces the plastic deformation capacity of joints [24].

In [25] the results of tests of FSW of 304 stainless steel using tungsten carbide tools with a tapered cylindrical (conical) pin were discussed. The analysed in the tensile tests' samples underwent fracture outside the weld region. Welding speed, shoulder diameter and tool rpm have the essential impact on UTS of the joints. The weld microstructure study performed in three distinct FSW zones showed: fine grain structure in stir zone, finer grains in the TMAZ and refined grain region in HAZ. The highest hardness was observed in the TMAZ on advancing side.

The results of investigations of stainless steels processed by friction stir welding were given in [26,27]. The microstructural evolution of AISI 201 stainless steel was studied by optical microscopy, scanning electron microscopy and transmission electron microscopy. The results showed that the final grain structure in the stir zone originated from recrystallization and the grain size and the content of δ -ferrite in SZ were closely related to the processing parameters [26]. Modification the microstructure in 316L austenitic stainless-steel using friction stir processing (FSP) caused a significant improvement in mechanical properties of the material in stir zone [27].

A significant problem during friction stir welding of steel is tool wear, which is most intensive when the tool plunges deeper into the welded material. In order to reduce the tool wear, it has been proposed to heat the plunge area initially, reduce the plunge feed rate, and drill the hole at the tool insertion point [8].

The evaluation of the wear of FSSW tools made of tungsten carbide WC-Co during steel joining was presented in the study [28]. The tools made of tungsten alloys used for testing showed significant wear, while the quality of the joints was significantly affected by tool geometry that changed as a result of wear. The particles of the worn tool material are transferred to the joint material. In some applications inclusions in FSW joints are acceptable, but in the other cases the tool debris embedded in the weld have an unfavourable impact on the joint properties and are unacceptable. The size and distribution of inclusions in the joint depend on the interactions between the material processed and tool material, tool geometry and welding parameters. The study [29] evaluated boron concentration in a steel FSW joint made using a tool made of polycrystalline boron nitride (PCBN).

The results of durability tests of three different tools based on tungsten and, respectively, lanthanum, rhenium and hafnium oxides with various ratios during the process of FSW welding of high strength steels were published in the study [30]. The authors of the study found that FSW tools containing hafnium (10%) and rhenium (20%) in the tungsten matrix have higher life compared to tools with W-1% La_2O_3 and W-(25%) Re.

The authors of the work [31] applied a specially designed water-cooled holder during friction stir welding in order to limit an unfavourable effect of high temperature on the machine, the tool and the welded materials. The research focused on the choice of tool material and type of coolant. The obtained results show the increase in possibility of friction stir welding of steel.

Important information about the efficiency of the process of joining metal materials by means of friction stir welding technology is provided by numerical models that analyse important process parameters, allowing to predict mechanical and functional properties of joints, changes in weld microstructure and tool life [32,33].

In the technical literature there is no information on FSW of 1.4541 steel or its substitutes. There is only the information on research of welded joints made using laser beam, MIG technology and gas tungsten arc welding (GTA), [34 -36]. FSW can be an alternative to conventional methods for joining stainless

steel sheets, which are widely used in aviation and automotive industry in production of fuel tanks, exhaust system components and structural parts operating at ambient temperature, [37,38].

The limited amount of information on FSW of 1.4541 steel inspired the authors of the present study to start explorations in the field of manufacturing and assessment of the properties of overlap joints made of austenitic 1.4541 stainless steel sheets.

2. Aim and Scope of the Study

The aim of the study was to perform and evaluate the quality of overlap joints obtained during friction stir welding. The joints with the length of 32.5 cm were made on 1.4541 steel sheets with the thickness of 1.2 mm (Fig. 1). Characterization of 1.4541 steel is shown in Table 1. 1.4541 steel can be applied up to 850°C. It has exceptional corrosion resistance to a variety of aggressive media, including hot petroleum products.

Welding parameters used during FSW of steel joints are shown in Table 2. Tools used during welding of the joints were made of W-25Re alloy. Tools made of tungsten-rhenium alloys show the increased resistance to fracture and wear compared to pure tungsten, thus they are among the most commonly used materials for FSW tools concerning materials with high melting point.

TABLE 1

Material data for 1.4541 steel according to DIN 17441

Material	Chemical composition, %				R_m	$R_{p0.2}$	A_5
	C	Cr	Ni	Other			
	%	%	%	%	MPa	MPa	%
STEEL: 1.4541 (according to DIN 17441)	<0.08	17.00- 19.00	9.00- 12.00	Ti 5x %C to 0.80	520- 720	220	40

The tool had a flat shoulder with a diameter of 12 mm and a cylindrical pin with a diameter of 6 mm and a height of 1.5 mm (Fig. 2). A FYD32 milling machine was used to obtain the joints. Machine workspace makes it possible to mount the fixing device, which aims at precise sticking of the joined sheet edges to each other and preventing them from shifting during the process.

TABLE 2

Parameters of the FSW process

Rotational speed n , rpm	Welding velocity, v , mm/min	Tool inclination angle α , °
900	280	2

After visual inspection, samples of FSW joints underwent strength tests and metallographic examinations. Joint strength

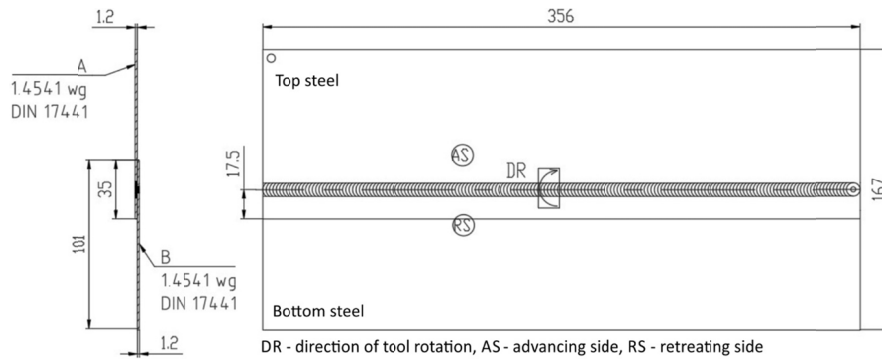


Fig. 1. Geometry of FSW joint

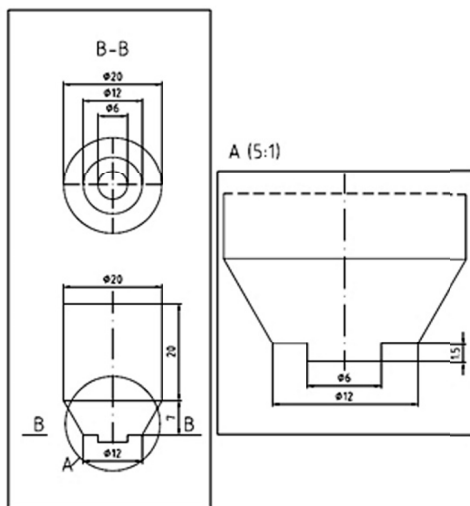


Fig. 2. Geometry of the W-25Re tool used for FSW steel joints

was determined by means of a static tensile test, followed by the analysis of the joint breaking mechanism. Strength tests were conducted by means of a Zwick Z050 testing machine. The tensile speed was of 2 mm/min. The load bearing capacity of the overlap joints was defined as the maximum force recorded during the tensile test. 11 samples were cut out from the FSW joints for the tensile tests. The samples were mounted in the jaws of the tensile machine in such a way that both tensile and shear forces occurred during the tests. The tensile tests were recorded using the ARAMIS Digital Correlation Image System. Based on the measured displacements in the weld area and its vicinity the plastic strain distributions on the surface of the samples were determined.

Three samples were cut out from the FSW joints for metallographic examinations. The micro- and macrostructures were taken on an Olympus GX41 microscope.

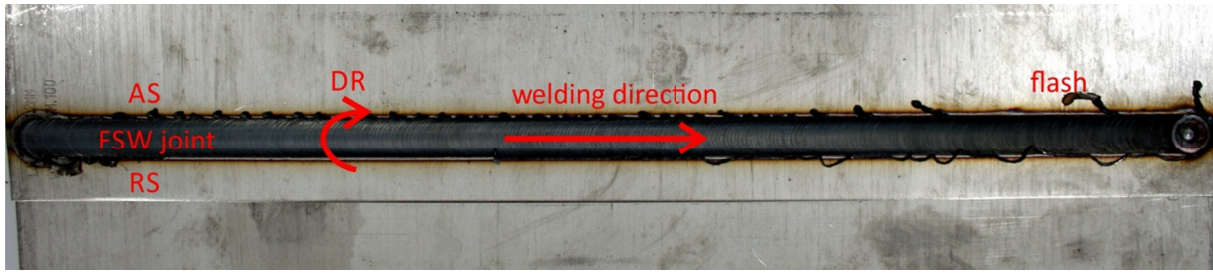


Fig. 3. FSW joint (1.4541 according to DIN 17441 1.2 mm + 1.4541 according to DIN 17441 1.2 mm)

Microhardness (HV 0.2) distribution measurements on the cross-sectional surface of the joint were made with increments of 0.5 mm using a Shimadzu microhardness tester.

3. Results

An example of an overlap joint made of 1.4541 steel sheets with a thickness of 1.2 mm obtained during friction stir welding is shown in Figure 3. No visible defects were found on the surface of the joints during the visual inspection. A constant weld face width was obtained, with no visible cavities or discontinuities.

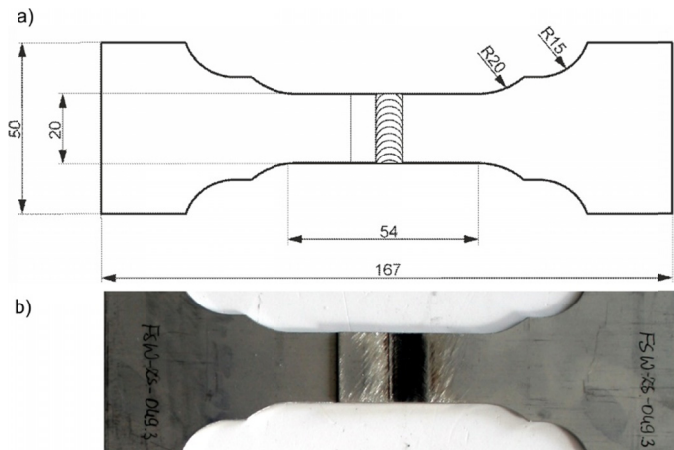


Fig. 4. Sample for tensile test: a) geometry, b) view of sample taken from the 1.4541-FSW steel joint

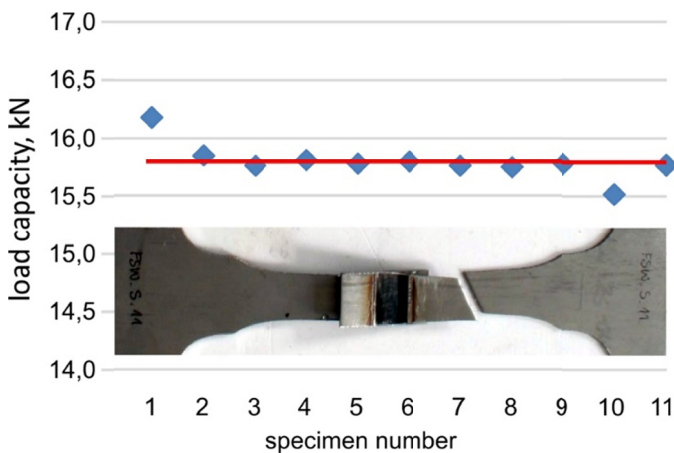


Fig. 5. Comparison of load bearing capacity of 1.4541 FSW steel joints

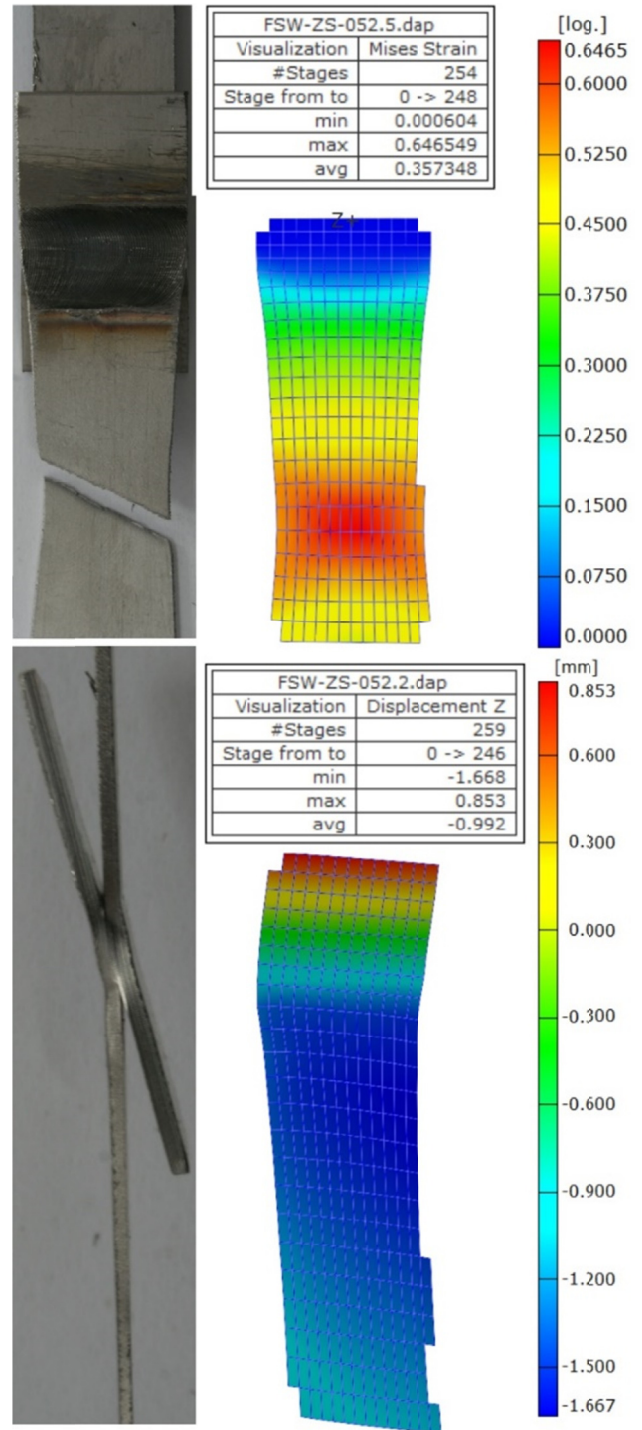


Fig. 6. Mechanism of breaking of 1.4541 FSW steel joints in the tensile test and distribution of deformations and displacements on the surface of upper and lower sheet metals

A small flash formed along the weld face was observed both on the retreating side (RS) and on the advancing side (AS).

Figure 4 shows an example of a sample for strength tests from the FSW steel joint. The tests were performed for 11 samples with the surface ground along the edge of the weld face to remove the flash protruding over the surface of the upper sheet.

The results of strength tests for FSW steel joints are presented in Figure 5. Analysis of the mechanism of destruction of the tested FSW joints showed that all samples taken from the FSW steel joints were destroyed outside the weld by breaking the base material. Therefore, load-bearing capacity of the joints was limited by the strength of the sheet material and was on the average level of 15.8 kN.

As a result of stretching, the free ends of the joined sheets were deflected from the sample axis. The mechanism of joint breaking is shown in Figure 6.

The microstructure of FSW steel joints made of 1.4541 steel sheets is shown in Figure 7. A stir zone (SZ) can be noticed in

the area of the weld, with small grain size due to the dynamic recrystallization following the intensive plastic deformation and the effect of high temperature. The material stir zone reaches below the contact line of the joined metal sheets (stir depth is ca. 1.77 mm). The width of the weld measured at the level of the contact surface of the joined sheets was approximately 9 mm. Macroscopic and microscopic examinations of the FSW joints did not reveal significant defects in the joint structure. A slight thinning of the upper sheet material was observed at the weld face.

The microstructure of the SZ consists of equiaxial grains, which are not uniform in size. In the central part, just under the surface of the weld face, grain growth after the process of dynamic recrystallization was observed. It is due to a longer influence of the heat coming from the tool shoulder. The welding parameters and the tool geometry determine the amount of heat input.

Around the SZ there is the thermo-mechanically affected zone in which the material undergoes the action of the tool

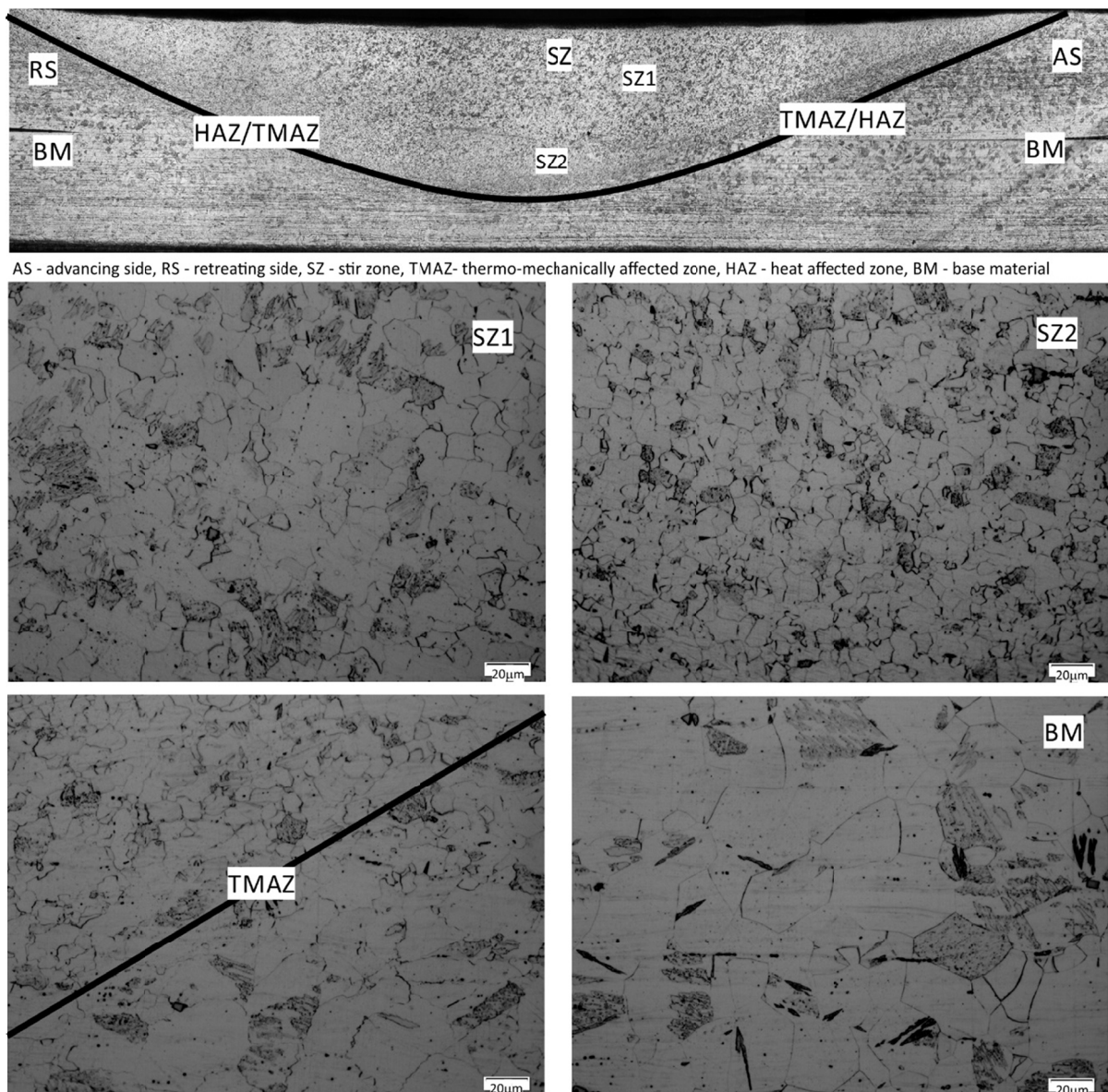


Fig. 7. Microstructure of 1.4541 FSW steel joints

both in mechanical and heat terms. This is where the boundary between the non-recrystallized material and the weld nugget is located, which is particularly visible on the advanced side (AS) due to the formation of shear bands. In the middle part of the TMAZ fine equiaxial austenite grains are observed. Moving to the outside of TMAZ the grains become more elongated due to not enough heat for dynamic recrystallization.

Figure 8 shows the results of HV0.2 microhardness tests on the cross-section of the FSW steel joint. The finer grains in the area of the weld, in comparison to the base material, affects the hardening of the weld material. An increase in microhardness in the cross-section of the weld was observed in relation to the micro-hardness of the base material. Furthermore, the microhardness increased more in the thermo-mechanically affected zone (TMAZ) both on the advancing and retreating sides.

Changes in the hardness value in the narrow TMAZ depend on the transient features of the microstructure. In the outside zone of the weld there is a hardened zone due to the cold plastic deformation. In the weld nugget the increase in hardness results from the grain boundary hardening due to the dynamic recrystallization in accordance to the Hall-Petch relationship.

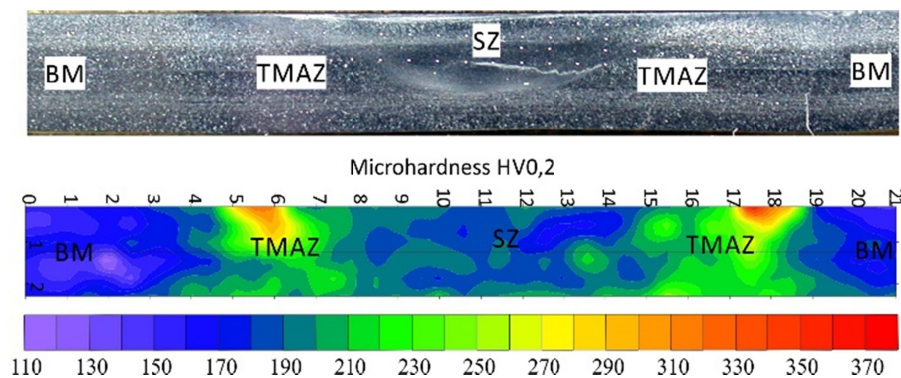


Fig. 8. Distribution of microhadness in the cross-section of the 1.4541 FSW steel joint



Fig. 9. Working surface of worn FSW tool (tool material: W-25Re)

Based on the hardness distribution in the cross-section of the tested joints no clear softened zone in the HAZ was observed.

Inspection of the working surface of the W-25Re tool after performing the joint with a length of several meters revealed its significant wear, excluding the tool from further use (see Fig. 9). In order to ensure invariable conditions of the welding process to obtain joints without defects, the tool required frequent regeneration.

4. Conclusion

Based on the performed research the following conclusions can be drawn:

1. FSW technology allows for obtaining good quality overlap joints of 1.4541 steel with strength which exceeds the base material strength.
2. The weld microstructure is nonuniform. The stir zone consists of fine equiaxial recrystallised grains, which become more elongated moving to the outside of TMAZ due to not enough heat for dynamic recrystallization.

3. The increase in microhardness observed in the thermo-mechanically affected zone (TMAZ) both on the advancing and retreating sides results from cold plastic deformation. The increase in hardness in stir zone results from the grain boundary hardening due to dynamic recrystallization.
4. Durability of W-25Re tool in the FSW process of 1.4541 steel is affected by the geometry of its working surfaces and welding parameters and above all, by combining the tool material with the welded material.

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