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High-Speed Friction Welding as an Innovative Technology for Joining Solenoid Valve Elements Made of Steel Grades 11SMnPb37 and 11SMn37

Abstract: High-speed friction welding (HSFW) is a solid-state joining process involving the use of friction heat emitted during the technological process. The application of the HSFW technology enables the fast and repeatable making of joints characterised by favourable properties. The article presents tests concerning the development of the HSFW-based technology enabling the joining of solenoid valve elements made of two grades of free-cutting steel, i.e. 11SMnPb37 and 11SMn37. The article also discusses the course of technological tests, the making of a test rig, the determination of ranges of technological parameters and selected test results concerning welded joints.

Keywords: High-speed friction welding, HSFW

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Introduction

The satisfaction of automotive industry requirements necessitates the construction of a multitask processing station enabling the fabrication of solenoid valve elements and involving the use of an innovative dry welding and turning technology (i.e. high-speed friction welding – HSFW). The use of the above-named welding method (in the multitask processing station) to join solenoid valve elements is a successful alternative to the brazing process [1]. High-speed friction welding enables the fast, economically efficient and repeatable making of joints characterised by favourable functional properties [2, 3].

High-speed friction welding (HSFW) is a solid-state joining process involving the use of friction heat emitted during the technological process [4–6]. High-speed friction welding machines offered by the market enable the performance of the welding process at rotation rates reaching approximately 24 000 rpm [5]. The use of such high rotation rates significantly changes joining conditions in comparison with those characteristic of conventional friction welding technologies. Process parameters should be adjusted in relation to the type and dimensions of elements to be joined. Friction pressure, rotation rate and friction time are factors affecting the heating rate of the friction contact area, rates at which elements shorten, the width of the heat affected zone in the joint and, consequently, the quality of joints. It is possible to adjust proper welding parameters in relation to many types of materials made of carbon steels, alloy steels and non-ferrous metals. In doing so,

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it is necessary to take into account both the dimensions of elements to be welded and friction welding machine [5].

Particular features of the high-speed friction welding process make this technology usable in joining dissimilar materials or even materials significantly varying in terms of their physical properties. The HSFW process can be used to joint austenitic steel with carbon steel, free-cutting steel with stainless steel, carbon steel with aluminium, aluminium with copper as well as metals with non-metallic materials [5].

Collaboration between Zannini Poland and Sieć Badawcza Łukasiewicz – Instytut Spawalnictwa, connected with the implementation of an INNOMOTO competition research project and based on numerous tests of the HSFW process, resulted in the identification of technological conditions enabling the welding of solenoid valve elements made of two free-cutting steel grades, i.e. 11SMnPb37 and 11SMn37. The article presents technological test results, the design of the test design, identified ranges of technological parameters and selected test results concerning welded joints [1].

Test materials, welding station and technological tests

Tests concerning the applicability of the HSFW process to join solenoid valve elements involved elements having a diameter of 13 mm and made of free-cutting steel grades 11SMnPb37 and 11SMn37. Free-cutting steels, characterised by excellent machinability and used in high-volume production, can be processed using automatic CNC machines. The above-named steels, widely used in the production of bolts, nuts, washers, hydraulic hose terminals, solenoid valves etc., are difficult to weld and, as a result, are joined through brazing or pressure welding. The chemical composition of the test steels are presented in Table 1.

The HSFW tests were performed using an RSM 400 high-speed friction welding machine (Harms & Wende). The HSFW station with the solenoid valve elements is presented in Figure 1.

The initial parameters of the high-speed friction welding of elements made of free-cutting steel grades 11SMnPb37 and 11SMnPb37 were

Fig. 1. High-speed friction welding station used in the tests: a) RSM 400 HSFW machine (Harms & Wende) with welding parameter recording equipment and b) welded elements fixed in the clamps [1]

Table 1. Chemical composition of steel 11SMnPb37 and 11SMn37 [7]

Steel	Chemical composition, %						
	C	Pb	Si	Mn	P	S	Fe
11SMnPb37	0.08	0.25	≤0.05	1.20	0.07	0.37	bal.
11SMn37	0.09	-	0.03	1.28	0.04	0.35	bal.

Table 2. Sets of parameters used in the high-speed friction welding of the elements made of steel grades 11SMnPb37 and 11SMn37 [1]

Welding parameters	Set no. 1	Set no. 2	Set no. 3	Set no.4
Rotation rate; V_n, rpm	20 000	20 000	20 000	20 000
Friction pressure, F_t, bar	3.0	4.0	5.0	5.0
Upsetting pressure, F_s, bar	6.0	6.0	6.0	6.0
Friction time, t_t, s	4.0	4.0	4.0	6.0
Upsetting time, t_s, s	4.0	4.0	4.0	5.0

adjusted on the basis of results obtained in previous research works performed at Sieć Badawcza Łukasiewicz – Instytut Spawalnictwa and concerning the identification of technological welding conditions regarding various structural materials. The tests involving the high-speed friction welding of similar joints made of free-cutting steel grades 11SMnPb37 and 11SMn37 were performed using four various sets of parameters presented in Table 2. The edges of the solenoid valve elements were bevelled to reduce friction at the initial stage of the welding process. The manner of the preparation of the elements made of free-cutting steel 11SMnPb37 is prepared in Figure 2.

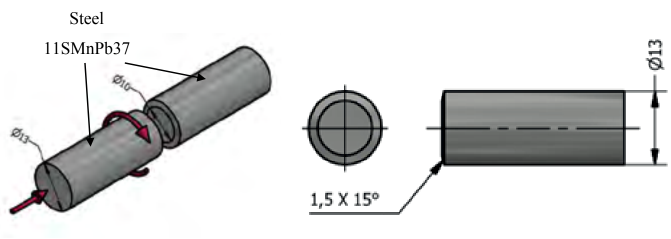

Fig. 2. Pre-weld preparation of elements made of steel 11SMnPb37 – bevelling of the edges [1]

The solenoid valve elements made of steel 11SMnPb37 and subjected to the HSFW process are presented in Figure 3. Figures 4 and 5 present exemplary HSFW joints of the solenoid valve elements made of steel grades 11SMnPb37 and 11SMn37.

Tensile tests

All of the HSFW joints of solenoid valve elements made of steel grades 11SMnPb37 and 11SMn37 were subjected to tensile tests [8]. The test results (i.e. average values determined in

Fig. 3. High-speed friction welding of the elements made of steel 11SMnPb37 [1]

Fig. 4. Welded joint made of steel 11SMnPb37; welding parameters in accordance with Table 2 (set no. 1): rotation rate Vn = 20 000 rpm, friction pressure Ft = 3.0 bars, upsetting pressure Fs = 6.0 bars, friction time tt = 4.0 s and upsetting time ts = 4.0 s [1]

Fig. 5. Welded joint made of steel 11SMn37; welding parameters in accordance with Table 2 (set no. 2): rotation rate Vn = 20 000 rpm, friction pressure Ft = 4.0 bars, upsetting pressure Fs = 6.0 bars, friction time tt = 4.0 s and upsetting time ts = 4.0 s [1]

relation to five specimens) are presented in Figure 6.

The analysis of the test results concerning the tensile strength of the HSFW joints made of steel 11SMnPb37 and 11SMn37 revealed that an increase in friction pressure Ft, the extension

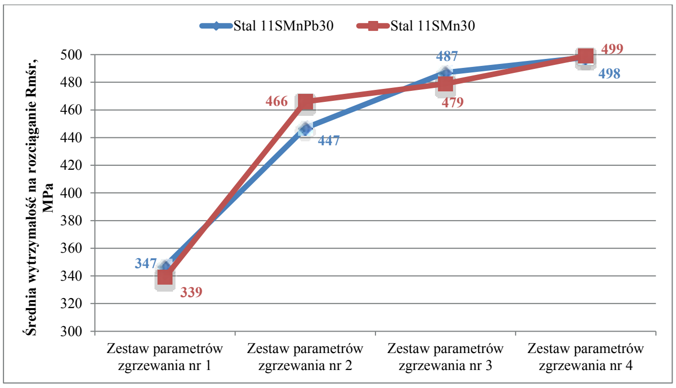

Fig. 6. Average tensile strength of the HSFW joints made of steel 11SMnPb37 and 11SMn37 – in relation to welding process parameters according to Table 2 [1]

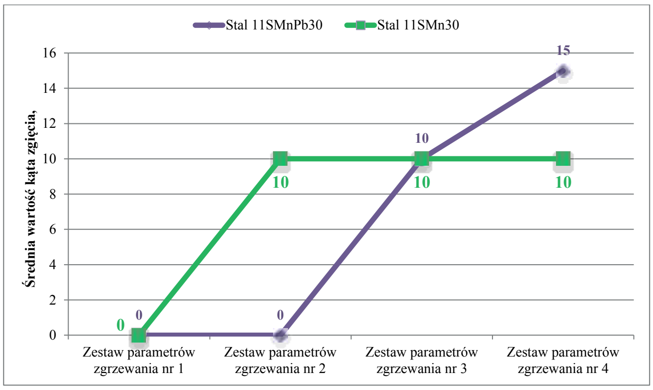

Fig. 8. Average bend angle value of the HSFW joints made of steel 11SMnPb37 and 11SMn37 – in relation to welding process parameters [1]

of friction time tt and an increase in upsetting time ts led to an increase in the tensile strength of the joints. The highest average tensile strength (amounting to 499 MPa) was obtained in relation to the parameters of set no. 4, i.e. rotation rate Vn = 20 000 rpm, friction pressure Ft = 5.0 bars, upsetting pressure Fs = 6.0 bars, friction time tt = 6.0 s and upsetting time ts = 5.0 s. In turn, the lowest tensile strength value (339 MPa) was obtained in relation to the parameters of set no. 1, i.e. rotation rate Vn = 20 000 rpm, friction pressure Ft = 3.0 bars, upsetting pressure Fs = 6.0 bars, friction time tt = 4.0 s and upsetting time ts = 4.0 s. During the tensile tests, all of the joints ruptured in the weld. The fracture of the HSFW joint made of steel 11SMnPb37 (after the tensile tests) is presented in Figure 7.

Fig. 7. Exemplary fracture of the HSFW joint made of steel 11SMnPb37 (after the tensile tests) [1]

Bend tests

After the technological welding tests, all of the joints made of steel grades 11SMnPb37 and 11SMn37 and welded using parameters presented in Table 2 were subjected to bend tests [9]. The average bend angle values are presented in Figure 8. Before the performance of the bend tests it was assumed that the minimum bend angle critical for the usability of the joint amounted to 10°.

The analysis of the bend test results concerning the HSFW joints made of steel 11SMnPb37 and 11SMn37 revealed that an increase in friction pressure as well as the extension of welding time and friction time resulted in an increase in the average bend angle of the welded joints. During the technological tests involving the joints made of steel 11SMnPb37 using the welding process parameters of set no. 4 (rotation rate Vn = 20 000 rpm, friction pressure Ft = 5.0 bars, upsetting pressure Fs = 6.0 bars, friction time tt = 6.0 s and upsetting time ts = 5.0 s), the average bend angle value amounted to 15°. In turn, as regards the joints made of steel 11SMnPb37 using the welding process parameters of sets nos. 1 and 2, it was not possible to obtain a required bend angle of 10°.

Macro and microscopic metallographic tests

Selected HSFW joints made of steel 11SMnPb37, using the welding process parameters of set no.

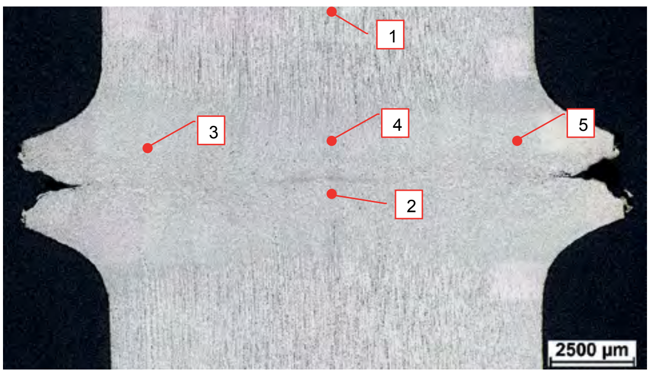

Fig. 9. Macrostructure of the HSFW joint made of steel 11SMnPb37; main view of the joint with areas subjected to microscopic observation; mag. 10x [1]

3 (Table 2), were subjected to macro and microscopic metallographic tests [10]. The macrostructure of the HSFW joint is presented in Figure 9, whereas the microstructure of selected areas of the welded joint along with related description is presented in Figures 10–14.

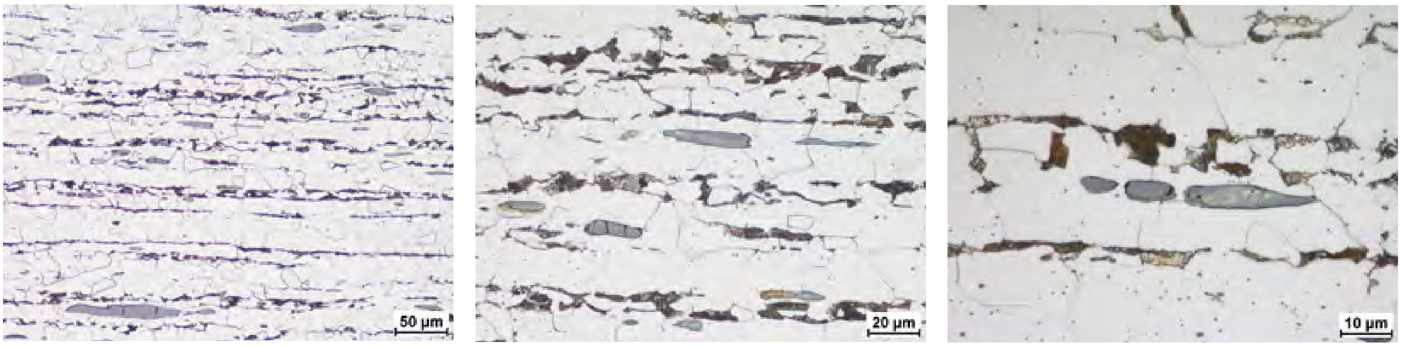

Fig. 10. Microstructure of the welded joint; structure of the base material – steel 11SMnPb37; ferrite + banded pearlite + visible banded non-metallic inclusions; mag.: a) 200x, b) 500x, c) 1000x [1] (Area 1, Fig 9)

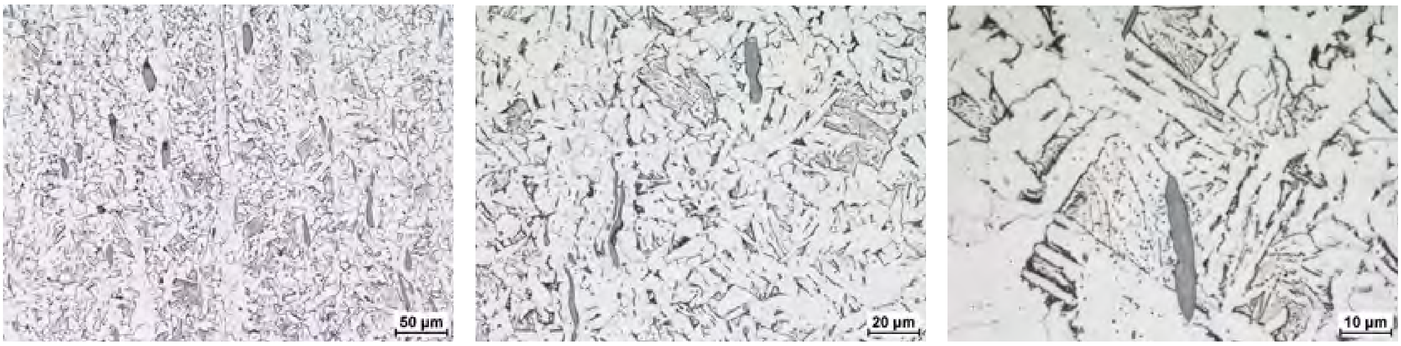

Fig. 11. Microstructure of the welded joint; HAZ structure; bainite + ferrite + slight amount of pearlite + banded non-metallic inclusions; mag.: a) 200x, b) 500x, c) 1000x [1] (Area 2, Fig 9)

Fig. 12. Microstructure of the welded joint; structure in the weld area near the weld collar; mixture of bainite and ferrite; visible non-metallic inclusions; mag.: a) 200x, b) 500x, c) 1000x [1] (Area 3, Fig 9)

Fig. 13. Microstructure of the welded joint; structure in the weld area in the centre of the joint; mixture of bainite, ferrite and small amounts of pearlite; visible non-metallic inclusions; mag.: a) 200x, b) 500x, c) 1000x [1] (Area 4, Fig 9)

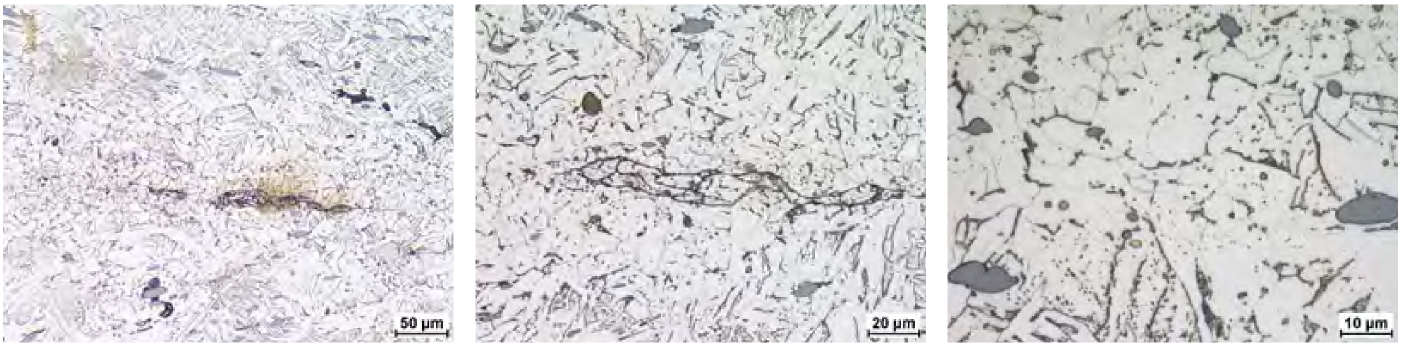

Fig. 14. Microstructure of the welded joint; structure in the weld area near the weld collar; mixture of bainite, ferrite and traces of pearlite; visible non-metallic inclusions. mag.: a) 200x, b) 500x, c) 1000x [1] (Area 5, Fig. 9)

The macro and microscopic metallographic tests of the HSFW joints also involved elements made of 11SMn37 using the welding process parameters of set no. 3. The macrostructure of a selected joint is presented in Figure 15. The microstructure of selected areas of the welded joint along with related description is presented in Figures 16–20.

Fig. 15. Macrostructure of the HSFW joint made of steel 11SMn37; main view of the joint with areas subjected to microscopic observation; mag. 10x [1]

Conclusions

The above-presented technological tests and their results justified the formulation of the following conclusions:

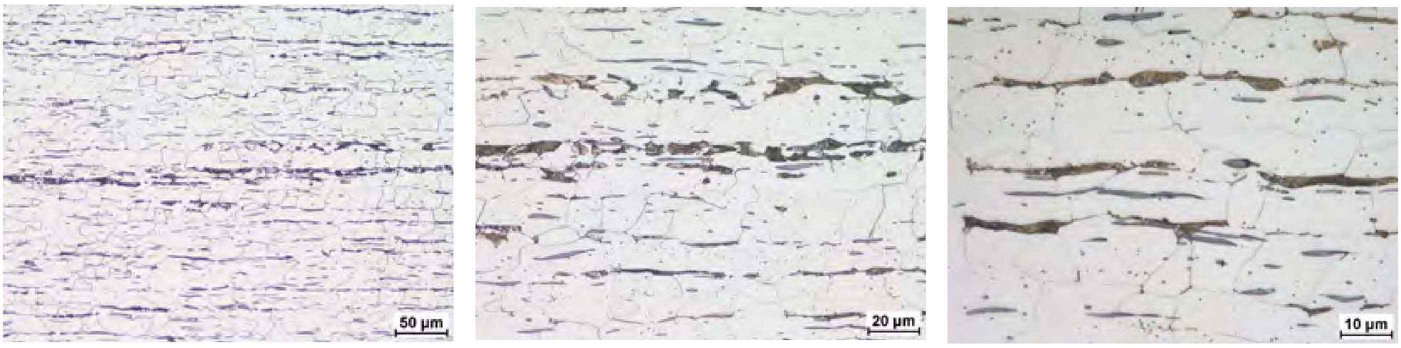

Fig. 16. Microstructure of the welded joint; structure of the base material – steel 11SMn37; ferrite + banded pearlite + numerous banded non-metallic inclusions; mag.: a) 200x, b) 500x, c) 1000x [1] (Area 1, Fig 15)

Fig. 17. Microstructure of the welded joint; structure in the HAZ area; ferrite + bainite + small amounts of pearlite + banded non-metallic inclusions; mag.: a) 200x, b) 500x, c) 1000x [1] (Area 2, Fig 15)

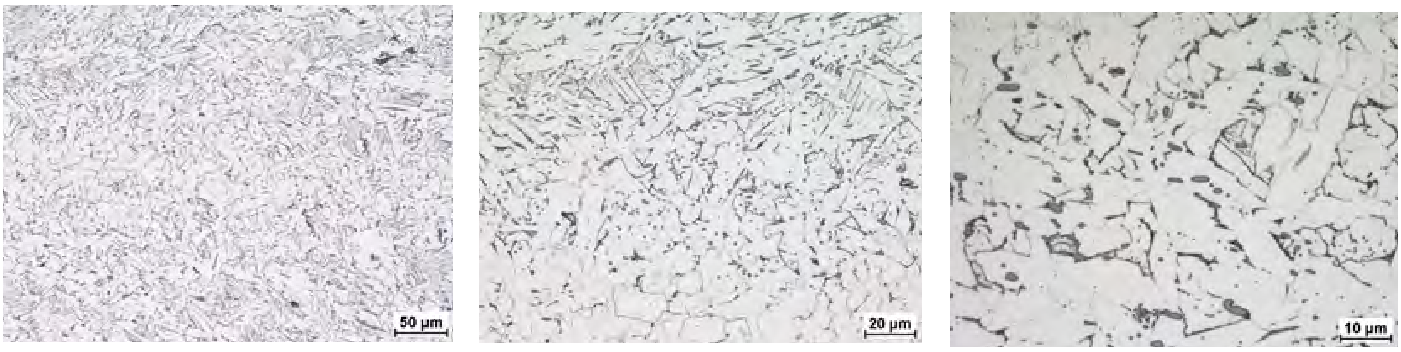

Fig. 18. Microstructure of the welded joint; structure in the weld area near the weld collar; mixture of bainite, ferrite and traces of pearlite; visible non-metallic inclusions; mag.: a) 200x, b) 500x, c) 1000x [1] (Area 3, Fig. 15)

Fig. 19. Microstructure of the welded joint; structure in the weld area in the centre of the joint; mixture of bainite, ferrite and small amounts of pearlite; visible numerous non-metallic inclusions; mag.: a) 200x, b) 500x, c) 1000x [1] (Area 4, Fig. 15)

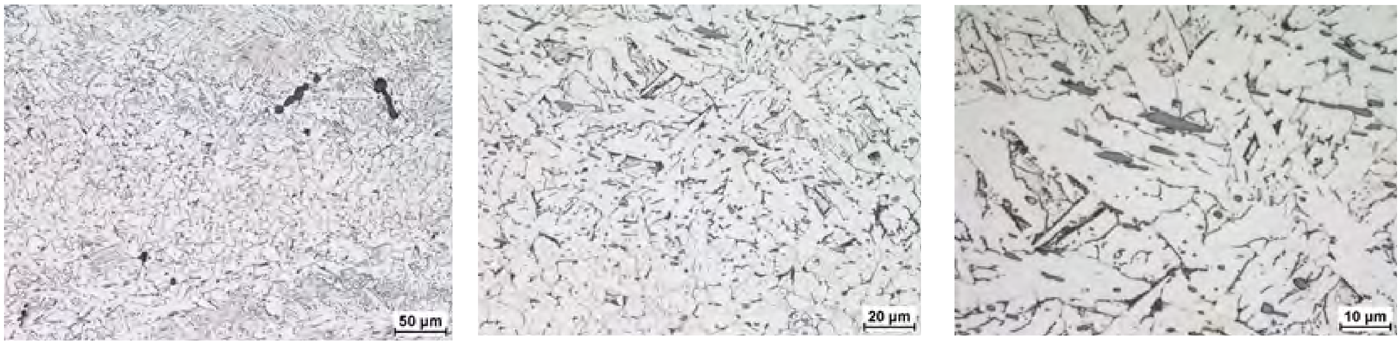

Fig. 20. Microstructure of the welded joint; structure in the weld area near the weld collar; mixture of bainite, ferrite and small amounts of pearlite; visible non-metallic inclusions; mag.: a) 200x, b) 500x, c) 1000x [1] (Area 5, Fig. 15)

– high-speed friction welding technology (HSFW) is currently the most effective technology enabling the joining of solenoid valve elements made of free-cutting streel grades 11SMnPb37 and 11SMn37. Joints made using the above-named method are characterised by favourable properties. The aforesaid steel grades are characterised by very limited weldability and good brazeability, yet the automation of the brazing process is significantly more difficult;
– test results revealed that the parameters of the HSFW process were adjusted properly. The joints were characterised by high and repeatable quality;
– HSFW technology proved better for the welding of elements made of steel grade 11SMnPb37 than those made of steel 11SMn37. Joints made of steel 11SMnPb37 reached greater bend angles during bend tests. The tensile strength values of the joints made of steel 11SMnPb37 and those made of 11SMn37 were very similar.

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obróbczego o wysokim poziomie równowagi środowiskowej do produkcji elementów elektrozaworów dla branży motoryzacyjnej. Opracowanie technologii zgrzewania tarciowego HSFW/FSW elementów elektrozaworów wykonanych ze stali w gatunku AlSi304, 11SMnPb37 oraz 11SMn37. Praca badawcza B-303/20 (Bb-127). Łukasiewicz – Instytut Spawalnictwa 2020.
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