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MICROSTRUCTURAL EVALUATION OF THE HIGH-FREQUENCY INDUCTION WELDED JOINTS OF LOW CARBON STEEL PIPES

ABSTRACT

The work presents the results of research on the structure of welded joints in the area of heat affected zone (HAZ). Based on precisely performed metallographic tests, the contribution of individual structural components in the area of welds of pipes welded with the induction method was assessed. The volume fraction of individual structural components in various areas of the heat affected zone, the size of the grain formed in the welding process, as well as its shape coefficients were determined. On the basis of metallographic observations, an attempt was made to describe the course of the pressure induction welding process, taking into account the structural changes, phase changes and the recovering and recrystallization processes taking place in this process.

Keywords: *welding joints; heat affected zone; structure changes; recovering; recrystallization*

INTRODUCTION

Welding processes are widely used in the production of various types of products made of steel [1–3] and non-ferrous alloys [4–6]. Belong to them, steel and aluminium structures, self-supporting constructions, casings, pipes and tubes, automotive, aerospace structures and many more. Line pipes with longitudinal or spiral welds are a special case of the welded product [7,8]. They are used in pipeline transportation systems in the petroleum and natural gas industries or used for the conveyance of water and other liquids. Pipes are manufactured in a wide range of outside diameters (10.3 mm – 2 134 mm), specified wall thickness (1.7 mm – 52 mm) and production length. Pipes are often covered with a protective coating or lining, both inside and outside. The connection is achieved using various methods of arc, resistance, laser or induction welding [9–14]. The properties of such a joint, by shaping its microstructure, are influenced by the conditions of its production. Conscious shaping of the microstructure of the joint requires understanding the mechanisms of its formation.

Induction high-frequency (IHF) welding consists in heating the contact surface of the metal parts to be joined until it reaches high plasticity or even a liquid state. The heat in this process is generated by the generation of eddy currents in the joined material, and the solid metal joining occurs as a result of applying additional pressure to the areas to be joined. The joining technologies used for production often require detailed mechanical and/or structural research of welded joints [15–17]. In the case of pipes for transportation systems in the petroleum and natural gas industries, the chemical composition is examined and mechanical tests are

performed. Destructive tests of welded joints are preceded by non-destructive tests to determine the places of surface and volume imperfections [9]. Improper selection of parameters or the characteristics of the material itself - its weldability - determines the occurrence of various imperfections [18,19]. The most common surface conditions, imperfections and defects in the welded joints of pipes are undercuts, arc burns, laminations, geometric deviations or hard spots [9].

In welded joints, made by IHF welding, four different zones can be distinguished, i.e., base material (BM), thermomechanically affected zone (TMAZ), heat affected zone (HAZ), and welding line (WL) [20–22]. A specific feature of this type of steel joining is the presence of a characteristic temperature field [20], as a result of which the distribution of individual zones takes the shape of an hourglass [18]. During the welding process of the pipes, the adjacent and heated, and thus plastic edges are deformed by the pressure, thus initiating the formation of a metallurgical connection by eliminating the boundary between them. Thus, in the finished weld, there is a mechanical and thermal interaction zone where the residual deformation associated with the welding process is preserved [21]. The HAZ is an area where structural changes occur as a result of the temperature, which makes it not homogeneous and can be divided into different subzones - coarse grain (CGHAZ), fine grain (FGHAZ), intercritical (ICHAZ) and subcritical (SCHAZ) heat-affected zone. The structure of HAZ and TMAZ is essential as it affects the functional properties of welded and welded structures and their resistance to fracture and the tendency of the joint to form cold cracks [23]. IHF welding has narrow welds and HAZ, welds that are more compact (narrow) than wider welds from many other welding processes. This is due to the lack of a casting structure in the induction welded joint and the minimization of deformation of the joined elements [21].

Currently, research is being carried out on the microstructure of welds obtained by welding with high-frequency currents and the influence of heat treatment on the microstructure of the welded joint. Udhayakumar & Mani [24] in HSLA steel, close to X100 grade, found the BM has very fine ferrite grains lesser than 10 μm , HAZ has the mix of polygonal ferrite and bainitic ferrite and the weld region has the mix of low carbon martensite, bainitic and polygonal ferrite. Zhang et al. [25] analysed ZQS700Z steel, where BM has a regular polygonal ferrite with a grain size of 5 μm . In HAZ observed granular bainite, bainite ferrite, and a small amount of polygonal ferrite and martensitic-austenitic islands. Yan et al. [21,22] analysed X65 steel, where they found that in all zones of the joint, the largest average grain sizes are in the WL and the average grain size in the WL varies along with the thickness of the pipes. Other studies indicate that the HAZ has a finer grain compared to the mechanical-thermal interaction zone. Santana et al. [26] analysed AISI 441 ferritic stainless steel, where they found an increase in grain size as it approached the WL.

Conscious shaping of the microstructure of the joint requires understanding the mechanisms of its formation. Descriptions of the microstructure of welded joints have been presented in many studies, however, no attempt has been made so far to quantify the microstructural changes that occur in the welded joint during its production. This work is an attempt to create a model of such changes based on both quantitative and qualitative microstructural documentation of the joints formed in the IHF process.

MATERIALS AND METHODS

The aim of the study was the qualitative and quantitative assessment of the microstructure in the area of the high-frequency induction welded joint (743 process acc. to ISO 4063) in pipes made of two steels: 12X and S235JR. The assessment of the microstructure was related to the

welding stage when the highest temperature was reached it means before cooling. Therefore for example, based on the microstructure, the morphology of austenite grain formed during heating when the joint was performed was assessed.

Observations of the microstructure and their documentation were made using the Axiover 200 MAT light microscope. The structure of the welded joints was revealed by etching them in 2% nital. The image of the microstructure obtained in the microscope was processed, i.e. the grain boundaries were reconstructed by outlining them and marking the identified structural components with appropriate colors. For this purpose, the vector graphics program Inkscape 0.92.4 was used. Then, for the digital images obtained in this way, stereological calculations in the field of quantitative metallography were performed using the Met-Ilo v9.11 program [27–29]. Volume fractions V_v of the defined areas of particular structures, mean surface areas of grains and subgrains were determined, and their shape factor was also calculated. At this work structure identification was based on the microstructural observation only and was not extended by XRD as these method could not distinguished particular structure constituents like martensite, bainite, ferrite and perlite as all of them have the same phase composition.

The tests were carried out on two steels, the chemical composition of which is presented in Table 1 and their mechanical properties in Table 2. 12X steel is a steel used mainly for welded or electrically welded pipes (with a spiral or longitudinal seam) of sheets and strips. It is characterized by a reduced content of carbon and manganese, which translates into higher plastic properties. 12X steel is classified as non-quenched steel and is considered a "higher quality" steel, i.e. it has a narrower range of carbon content and a reduced allowable amount of phosphorus and sulfur (0.040% each at most). S235JR steel is used in the construction of structures, machine components and general purpose devices. It is the low grade steel with a high content of impurities (mainly sulfur, silicon and phosphorus). Additionally, it is characterized by a fairly wide range of the carbon content. It is a steel which, is characterized by good weldability.

The pipes from which the test samples were taken were made in a multi-cage aggregate. Initially, the strip was formed into a slotted tube and then welded into a 42.4 mm x 3.05 mm (12X) and 33.7 mm x 2.15 mm (S235JR) tube. The induction welding method was used to create the weld, using a current with a frequency of 400 kHz. The current was induced in the open tube by means of an inductor wrapping the tube (Fig. 1.a).

Table 1. Chemical composition (% by weight) of the welded steels from which the pipes are made

Steel	C	Mn	Si	P	S	Cu	Cr	Ni	Al	Mo
12X	0.11	0.43	0.008	0.014	0.015	0.06	0.03	0.03	0.048	-
S235JR	0.11	0.34	0.008	0.014	0.01	0.04	0.03	0.02	0.047	0.003

Table 2. Mechanical properties of welded steels from which the pipes are made

Steel	R_{eH} , MPa	R_m , MPa	A, %	C_{EV}
12X	297	415	33.8	0.1888
S235JR	319	403	36.9	0.1795

Metallographic tests were carried out on the cross-sections of the welded joint, including all characteristic zones (Fig. 1.b). Detailed microscopic analysis was performed in the middle of the joint thickness in the area presented in Fig. 1.c.

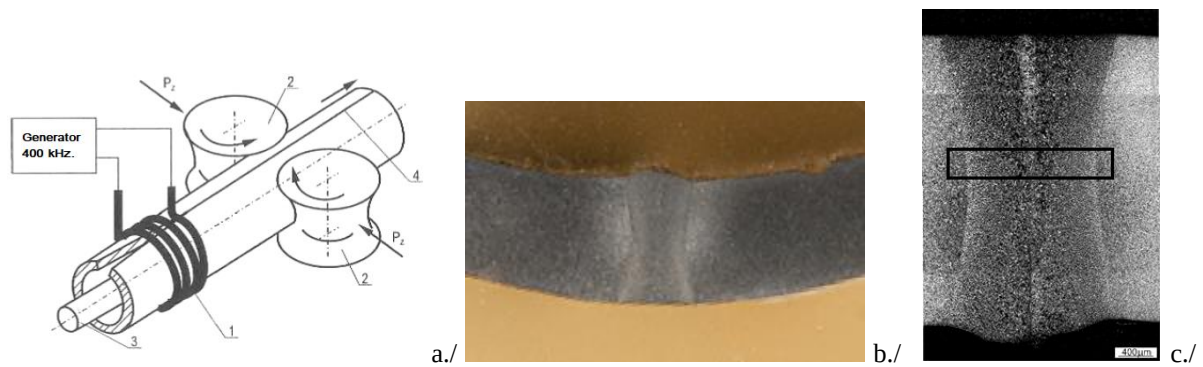


Fig. 1. a).Diagram presenting welding technology applied at the experiment. b).Macrostructure of the sample from the 12X pipe, etched with 2% nital, c).Microstructure in the area of the welded joint (the marked fragments show where the microstructure of individual zones of the welded joint was examined at higher magnification)

The microstructure of both pipes in the area of the parent material is characterized by a ferritic-pearlitic structure (Fig. 2) with different sizes of ferrite and pearlite grains.

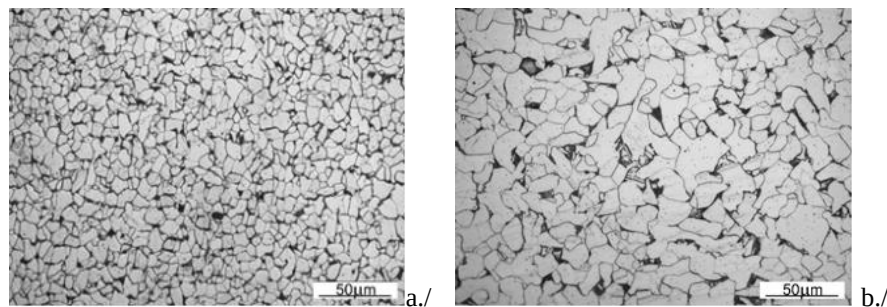


Fig. 2. Microstructure of the base material of the pipe: a) 12X, b) S235JR

EXPERIMENTAL RESULTS

The microstructure of the joint in the area of the weld

The characteristic areas of the welded joint were analyzed in terms of changes in the microstructure caused by heating and plastic deformation when making the joint. Based on the images of microstructures, the identification of their individual components was made. The individual components of the microstructure were distinguished and in the images of the models, appropriate colors were assigned to them as it is shown in Figure 3. These colors were used in the images of the microstructure, in charts and in tables presenting all the results of microstructure analysis.

	former austenite area
	dynamically recrystallized ferrite remaining in the microstructure
	ferrite remained in the microstructure after intensive recovery
	ferrite remained in the microstructure after intensive recovery with a visible division into subgrains
	ferrite grains with ingrown carbides (cementite) from pearlitic areas
	ferrite grains with ingrown carbides (cementite) from pearlitic areas with a visible division into subgrains
	pearlite
	original ferrite of base material

Fig. 3. Legend for marking individual structural components

The microstructure documentation for the characteristic areas starting from the welding line towards the parent (base) material for the joint of the 12X steel pipe is shown in Figure 4. It distinguishes seven zones from the welding line towards the base material. The microstructure documentation for the characteristic areas, starting from the welding line towards the base material for the joint of the S235JR steel pipe, is presented in Figure 5. It distinguishes five zones, from the welding line going towards the base material. Apart from microscopic images of individual zones, the drawings also show images of a computer model of the microstructure, which is the basis for quantitative metallographic analyzes.

In a 12X steel tube, the microstructure of zone I consists solely of austenite, which dominates the microstructure up to zone III, with progressively finer grains in each subsequent zone. The former austenite areas were not recognized directly at the weld structure. Austenite gave at the cooled down weld areas of poorly diffusion structure products like quasi martensitic and bainite structures with the shape defined by evident grain boundaries of former austenite [30]. From zone II, dynamically recrystallized ferrite grains remaining in the microstructure can be observed. The next appearing microstructure component is ferrite remaining in the microstructure after intensive recovery, a significant proportion of which can be seen from zone IV. In this zone, also ferrite grains with ingrown carbides (cementite) emerge from the pearlitic regions, which dominate in terms of volume fraction to zone V. In zone V, ferrite grains begin to appear with a visible division into subgrains with and without ingrown cementite. Zone VI consists almost entirely of subgrained ferrite grains. In this zone, one can also notice and distinguish the appearance of pearlitic areas remaining when heated, and the disappearance of dynamically recrystallized ferrite grains. In the last zone VII, unmodified ferrite grains from the parent material begin to appear.

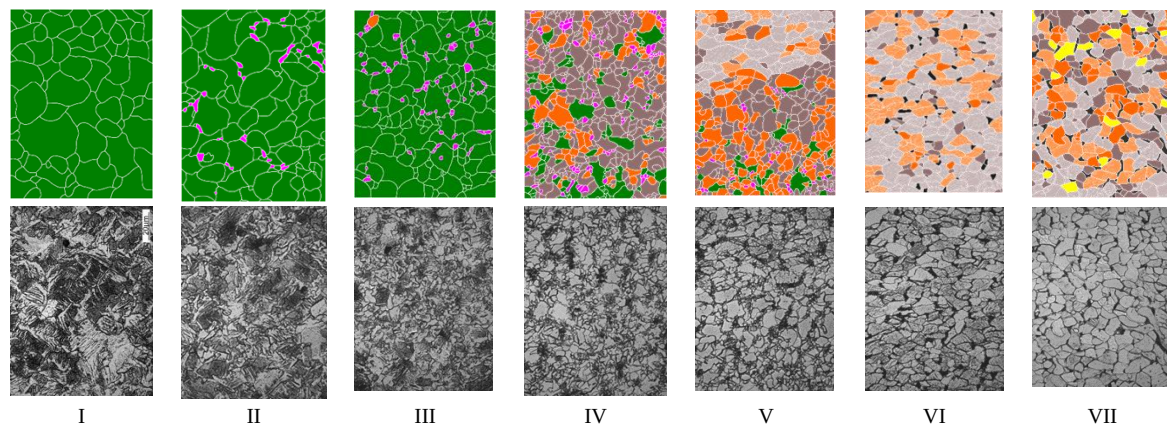


Fig. 4. Image of the microstructure model based on real microstructures divided into individual zones (I-VII) for a welded joint of a pipe made of 12X steel

In the S235JR steel joint, zone I also consists only of austenite grains, which dominates the microstructure up to and including zone III, reducing the grain size more and more. From the second zone, one can observe in the microstructure dynamically recrystallized ferrite remaining in the microstructure. In zone III, ferrite remaining in the microstructure after intensive recover and ferrite grains with ingrown carbides (cementite) from pearlitic areas begin to mark their share in the microstructure. Zone IV is the last zone in which austenite grains contribute. However, ferrite grains begin to appear, which are characterized by division into subgrains (with and without cementite). Zone V is mainly ferrite remaining in the microstructure.

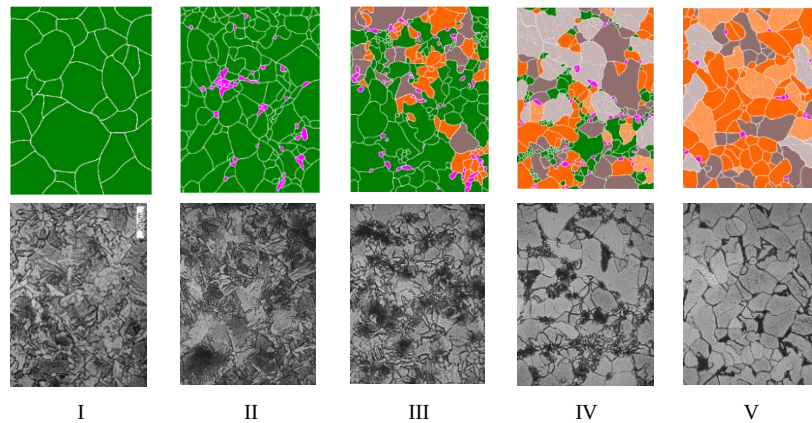


Fig. 5. Image of the microstructure model based on real microstructures divided into individual zones (I-V) for a welded joint of a pipe made of S235JR steel

Share of structural components in the welded joint

Based on the images of the microstructure models presented in Figures 4 and 5, analyzes of the volume fraction V_v of individual structural components were performed for individual zones of welded joints of pipes made of 12X steel made of S235JR steel, and their grain sizes and coefficients determining their shape were determined. The results of these analyzes are presented in Tables 3 and 4. Figures 6 and 7 present the results in a graphic form. The volume fraction V_v refers to the microstructure of the joint when it reached its highest temperature during induction welding, i.e. before cooling.

Table 3. Volume fraction V_v of the defined areas for individual zones of the 12X steel pipe joint as well as the grain size of the identified structure and shape factors

Zone	Structure parameters	former austenite	recrystallized ferrite	recovered ferrite.	recovered ferrite in subgrains	ferrite + cementite	ferrite in subgrains + cementite.	perlite	original ferrite
I	Volume fr [%]	100.0	-	-	-	-	-	-	-
	Grain size [μm^2]	182.9	-	-	-	-	-	-	-
	Grain shape	0.75	-	-	-	-	-	-	-
II	Volume fr [%]	97.8	2.2	-	-	-	-	-	-
	Grain size [μm^2]	115.9	7.2	-	-	-	-	-	-
	Grain shape	0.70	0.83	-	-	-	-	-	-
III	Volume fr [%]	96.4	3.2	0.4	-	-	-	-	-
	Grain size [μm^2]	73.3	4.4	47.3	-	-	-	-	-
	Grain shape	0.72	0.91	0.92	-	-	-	-	-
IV	Volume fr [%]	18.6	4.7	16.4	-	-	60.3	-	-
	Grain size [μm^2]	19.7	4.5	23.6	-	-	20.8	-	-
	Grain shape	0.79	0.90	0.76	-	-	0.77	-	-
V	Volume fr [%]	5.8	1.2	30.0	5.6	22.6	34.8	-	-
	Grain size [μm^2]	18.5	3.5	23.5	35.8	70.7	19.7	-	-
	Grain shape	0.71	0.93	0.78	0.70	0.64	0.77	-	-
VI	Volume fr [%]	-	-	3.4	28.3	58.4	6.2	3.7	-
	Grain size [μm^2]	-	-	21.8	50.8	55.8	14.8	7.3	-
	Grain shape	-	-	0.75	0.68	0.68	0.75	0.77	-
VII	Volume fr [%]	-	-	13.3	20.4	34.9	20.8	6.0	4.6
	Grain size [μm^2]	-	-	27.2	61.0	59.5	25.9	6.5	39.8
	Grain shape	-	-	0.79	0.71	0.70	0.78	0.65	0.76

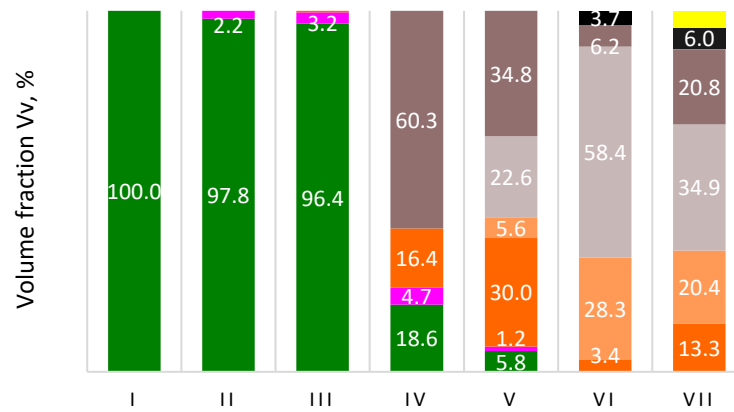


Fig. 6. Volume fraction V_v of areas defined in Fig. 4 for individual zones of the 12X steel pipe joint

The quantitative assessment of the content of individual structural components defined for the heating state during the production of the joint corresponds and confirms the qualitative assessment. It can be observed that the fully austenitized area was present only in zone I. In zone II, there are remnants of ferrite unconverted into austenite. Whereas in zone III, apart from the above-mentioned austenite and the remaining fully recrystallized ferrite, ferritic areas were distinguished, the morphology of which indicates that the recrystallization process is blocked by intensive dynamic recovery. The number of such ferritic regions is increased in zone IV, as is the proportion of fully recrystallized ferrite grains. However, ferrite grains dominate in zone IV with visible ingrown carbides. It proves that the A_{c1s} temperature was exceeded in this area, but without exceeding the A_{c3} temperature. A similar temperature range should be indicated for zone V, whereby this temperature is approaching the A_{c1f} temperature. In this zone, small proportions of former perlite areas of the former perlite, which were austenitized during the weld, can be observed. The dominant in this microstructure are recovered ferrite, both with and without carbides growing into it. The new structural components are areas indicating the extent of dynamic recovery, causing the division of the grains deformed during the bonding process into subgrains. These are areas with and without visible carbides ingrown into them. In zone VI, it should be assumed that the A_{c1s} temperature has not been exceeded. Therefore, the occurrence of pearlitic areas can be distinguished in this zone. The dominant areas of grains are visible, which underwent dynamic recovery after deformation causing division into subgrains. We can also distinguish areas that do not show such an effect, the recovery of which had to be based only on the annihilation of linear defects. In zone VII, it is possible to distinguish areas where the morphology of the structural components corresponds to the native material. However, still most of the microstructural components show morphological features indicating the occurrence of dynamic recovery processes in a different range of changes induced by them.

The quantitative description of the morphology of the welded joint made on the S235JR steel pipe indicates that the material at the point of welding (zone I) was fully austenitized during the joint production. In zone II, the distinguishing feature is the presence of a small amount of ferrite grains, which indicate that the temperature in this place did not exceed the A_{c3} temperature, but was very close to it. The morphological features of the remaining ferrite grains indicate that they were fully recrystallized. In zone III, the temperature to which the material was heated was between A_{c1f} and A_{c3} . It is possible to distinguish areas of ferrite whose morphology is indicative of plastic deformation, but the microstructure corresponds to the level of intensive dynamic recovery blocking the recrystallization process and division into subgrains

(thus corresponds to the range of dislocation annihilation at the initial stage of their formation as a result of plastic deformation). There are of course areas of recrystallized ferrite. In zone IV, it is possible to distinguish areas of grains where division into subgrains took place as a result of the recovery process. There is also some area that indicates austenitization during the making of the joint. So this is the heating temperature range between A_{c1s} and A_{c3} (probably close to the A_{c1f} temperature). Zone V no longer shows features related to the austenitic transformation. However, the features that indicate health processes are dominant. They are related to carbon diffusion and the formation of ferritic-pearlitic grain structures.

Table 4. Volume fraction V_v of the defined areas for individual zones of a welded joint of a pipe made of S235JR steel and the grain size of the identified structure and shape factors

Strefa	Parametry struktury	former austenite	recrystallized ferrite	recovered ferrite.	recovered ferrite in subgrains	ferrite + cementite	ferrite in subgrains + cementite.
I	Volume fr [%]	100.0	-	-	-	-	-
	Grain size [μm^2]	402.0	-	-	-	-	-
	Grain shape	0.73	-	-	-	-	-
II	Volume fr [%]	97.1	2.9	-	-	-	-
	Grain size [μm^2]	67.2	7.5	-	-	-	-
	Grain shape	0.73	0.81	-	-	-	-
III	Volume fr [%]	66.4	2.7	15.7	-	-	15.2
	Grain size [μm^2]	47.9	5.3	29.1	-	-	76.1
	Grain shape	0.77	0.87	0.75	-	-	0.68
IV	Volume fr [%]	15.4	1.9	21.0	4.9	31.5	25.4
	Grain size [μm^2]	11.2	4.2	45.2	88.3	273.4	74.7
	Grain shape	0.87	0.89	0.72	0.65	0.63	0.62
V	Volume fr [%]	-	0.8	42.8	21.5	13.0	21.9
	Grain size [μm^2]	-	6.8	79.0	204.6	407.6	75.0
	Grain shape	-	0.81	0.71	0.68	0.52	0.71

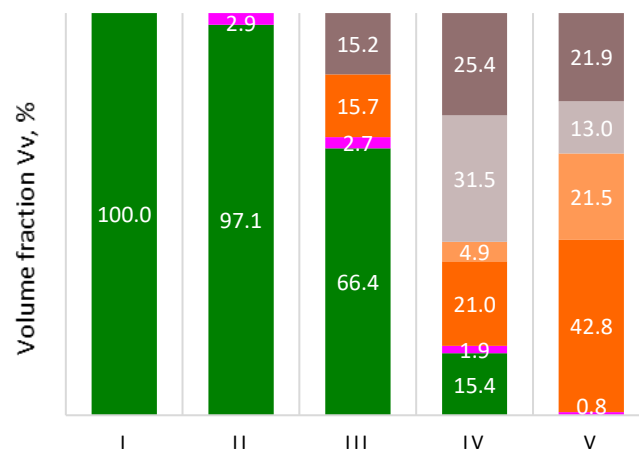


Fig. 7. Volume fraction V_v of areas defined in Fig. 5 for individual zones of a welded joint of S235JR steel pipe

Grain size assessment

Table 3 presents also the results of grain size measurements for individual zones of welded joints of pipes made of 12X steel and Table 4 of S235JR steel. These results are presented graphically in Figures 8 and 9.

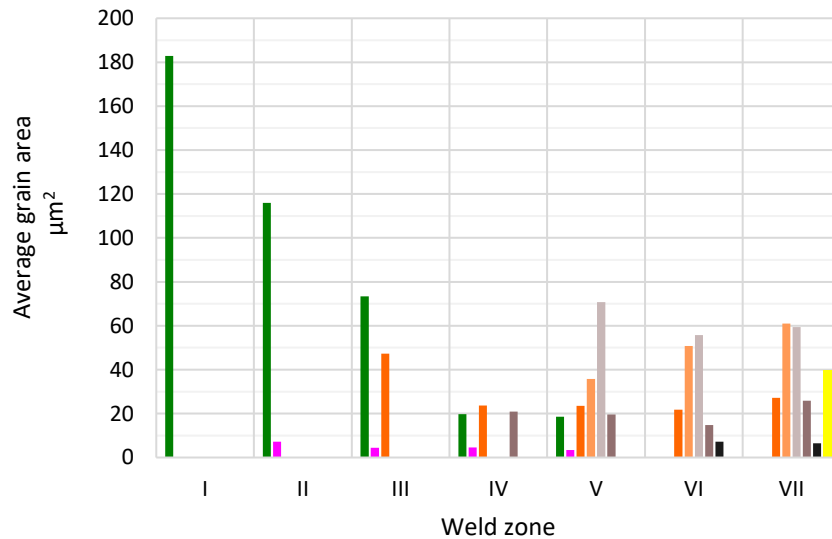


Fig. 8. Average grain surface area for individual zones of the 12X steel pipe joint, μm^2

In order to assess the heating temperature range during the production of the joint, the grain size analysis of individual microstructural components can be used. This is due to the fact that grain growth is mainly influenced by temperature, and only to a much lesser extent by the annealing time.

Analyzing the changes in the austenite grain size in the weld made of 12X steel, presented in Table 3 and Figure 8, it can be stated that the austenitizing temperature has decreased from zone I to zone V. Already the transition from zone I to II indicates a clearly lower heating temperature. The retention of small amounts of ferrite in the microstructure also contributed to blocking the growth of austenite grains. The increase in the share of ferritic areas with decreasing temperature causes further blocking of grain growth. Confirmation that the defined areas as recrystallized ferrite have been properly marked is the small grain size in these areas. It is slightly reduced from zone II to zone V. In zone III, the size of ferrite grains defined as subject to intensive recovery is confirmed by their larger size than that of recrystallized ferrite grains. It decreases towards zone IV and then slowly increases up to zone VII. From zone V to zone VII, the size of the ferrite grains that have broken down into subgrains increases. On the other hand, the size of the grains that have been divided is reduced, but are characterized by a ferritic morphology with cementite precipitates. The size of ferrite grains with cementite carbides growing into them, which have not been divided into subgrains, is at a similar level (from zone IV to zone VII). In zones VI and VII, small pearlite grains were defined, while in zone VII, the size of the ferrite grain, characteristic for the native material, is visible. In the above analysis, it should be taken into account that the grain size was determined on the cross-section of the pipe, which, as a result of welding, may lead to an apparent increase in grain size caused by plastic deformation when making the joint. Therefore, the ferrite grains assessed for zone VII as unchanged as a result of making the joint obtained a size smaller than the ferrite grains defined as those that underwent healing processes caused by plastic deformation at high temperature.

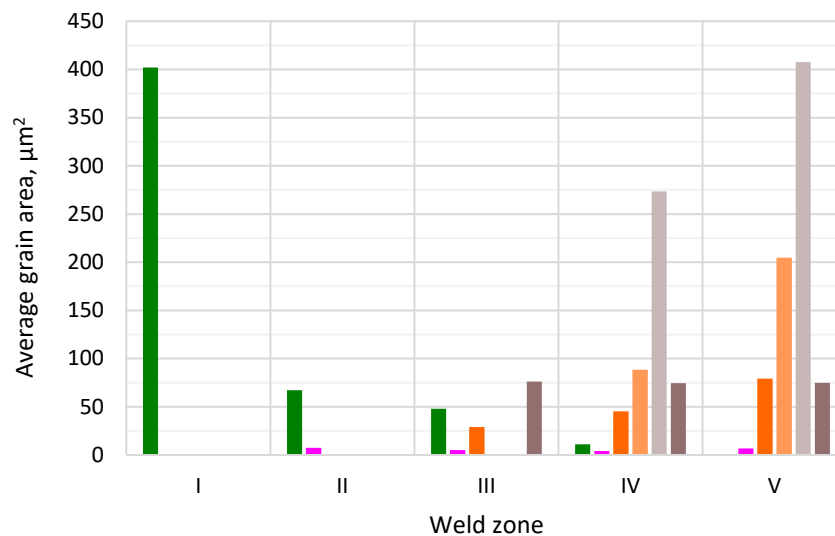


Fig. 9. Average grain surface area for individual zones of the pipe joint made of S235JR steel, μm^2

In the weld made of S235JR steel, a decrease in the austenite grain size is observed from zone I to zone IV (Table 4 and Figure 9). It results from the decreasing heating temperature when the joint is made and the blocking of grain growth by the ferritic areas remaining in the microstructure. Already a small share of the ferrite remaining in the microstructure in zone II caused a very large decrease in the size of the austenite grain in relation to zone I. The areas of ferrite defined as recrystallized are characterized by a similar grain size in zones II to V. However, in the range from zone III to zone V it occurs increase in the size of the ferrite grain, which has undergone intensive recovery processes. A similar increase in grain size between zones IV and V occurs in the case of ferritic areas and ferrite with carbides characterized by a visible division into subgrains. The grain size was practically not changed by ferrite grains with ingrown carbides that were not divided into subgrains. It is interesting to obtain the size of the ferrite grain with ingrown carbides, which was divided into subgrains, at the austenite grain size level in zone I. This may result from the incorrect assignment of several grains that were divided into subgrains as one ferrite grain and may indicate such a low temperature performing a weld (zone I) that the material has undergone austenitization at this point, but also dynamic recrystallization without the growth of recrystallized grain. It should be noted, however, that for area V the analyzed structural component was assessed only for two distinguished grains, which may be related to a large error in such an assessment.

Tables 3 and 4 also summarize the average surface areas and grain shape factors for individual zones of the welded joint of a 12X and S235JR steel pipe. Shape factor is important due to the possibility of distinguishing on the basis of its value the processes related to the formation of new grains and plastic deformation of these grains. The austenite grain shape factor indicates the recrystallization process, but also the deformation of austenite as a result of making the joint, which is caused by the pressure applied. It can be observed that at lower temperatures (e.g. zone IV), austenite grains are formed without deforming it. The highest shape factor is characteristic for the recrystallized ferrite grains remaining in the microstructure during the joint production. Strongly recovered ferrite has the most spheroidal shape at the highest temperature of its formation (zone III). The lowest shape factors, i.e. the lowest nodularity, are characteristic for the areas that underwent the healing process in terms of subgrain formation.

Their greater plastic deformation is visible in the areas of higher temperature of the formation of such structures, which results in a lower shape factor.

In the case of making a joint in a pipe made of S235JR steel, it is visible that the closer to the welding line, the more deformed the austenite grain is. The highest shape factor characterizes the recrystallized ferrite grain remaining in the microstructure during heating. The greatest effects of grain plastic deformation, i.e. the smallest shape factor, are characteristic of the areas where the recovery processes resulted in the formation of subgrains. These are grains more deformed than grains in which recovery was so intense that the linear defects were annihilated before the formation of subgrains.

Subgrains size assessment

The study also assessed the size of ferrite subgrains and their shapes (Tables 5 and 6). This analysis was performed on the basis of the developed metallographic models, an example of which is shown in Figure 10. The purpose of this assessment was to analyze the extent of the occurrence of dynamic recovery leading to their formation. The size of subgrains for purely ferritic areas and ferritic areas with cementite precipitates was compiled only for the areas where such grains were present.

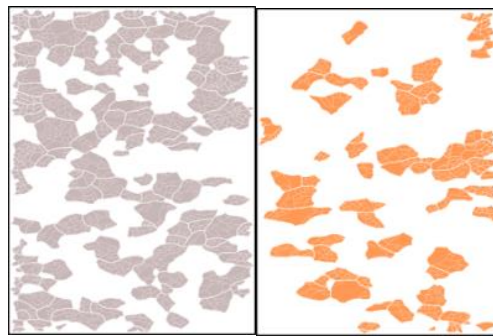


Fig. 10. Image of zone VI microstructure model for a pipe weld made of 12X steel

Table 5. Microstructure parameters for the joint zones of a pipe made of steel 12X

Zone	Structure parameters	recovered ferrite.	recovered ferrite in subgrains
V	Volume fr [%]	5.6	22.6
	Grain size [μm^2]	5.5	6.6
	Grain shape	0.83	0.78
VI	Volume fr [%]	28.3	58.4
	Grain size [μm^2]	4.4	4.1
	Grain shape	0.80	0.79
VII	Volume fr [%]	20.4	34.9
	Grain size [μm^2]	10.0	8.1
	Grain shape	0.71	0.74

It can be observed that the phenomenon of subgrain formation is not simply dependent on the temperature range and load at the time of making the joint. The subgrain size decreases between zones V and VI and then increases between VI and VII. This may result from opposing tendencies towards the initiation of division and the range of linear defects' displacement. At higher temperatures, there are fewer not annihilated line defects, but they can move more freely

creating narrow-angle boundaries. At lower temperatures, the annihilation of defects is weaker, but the range of their movement is also shorter. In the case of 12X steels, carbides appear to hinder the dislocation movement process that is expected to result in the formation of narrow-angle boundaries. However, they also seem to block the annihilation of linear defects of opposite sign.

Table 6. Microstructure parameters for individual zones of the joint of a pipe made of S235JR steel

Zone	Structure parameters	recovered ferrite.	recovered ferrite in subgrains
IV	Volume fr [%]	4.9	31.5
	Grain size [μm^2]	10.2	22.9
	Grain shape	0.77	0.75
V	Volume fr [%]	21.5	13.0
	Grain size [μm^2]	44.8	44.2
	Grain shape	0.65	0.61

In the case of the pipe made of S235JR steel, an increase in the size of subgrains between zones IV and V can be found, indicating the effect of the decreasing temperature, initiating the formation of subgrains in the process of dynamic recovery. It can therefore be concluded that the higher the temperature, the more subgrains will be formed, and therefore their size will be smaller. It can also be observed that at the stage of subgrain formation, when this process is intense (zone IV), the presence of carbides in the ferrite structure makes it difficult to divide the grain into zones with different activated slip systems favoring the rotation of crystallographic orientations, which are the cause of the formation of narrow-angle boundaries. This effect is diminished as the temperature decreases (zone V).

The average aspect ratio of the subgrains for purely ferritic areas and ferritic areas with cementite precipitates presented in Tables 5 and 6 shows that in both cases there is a tendency to increase the elongation of the subgrains with a decrease in the temperature of their formation. This is a natural consequence of the smaller range of movement of linear defects to the formation of narrow-angle boundaries.

SUMMARY AND CONCLUSIONS

For both steels, a similar sequence of microstructural changes was observed. These changes are similar in terms of quality, but differences can be observed in the quantitative nature of these changes. However, the comparison of both joints of both steels on the basis of the results obtained in this study is difficult due to the authoritative selection of the areas for analysis. This is because in this work a strictly defined range of observation distances of microstructures from the joint zone was not used. Such research can be the basis for the concept of further analysis of the described phenomenon.

In the case of a joint made of 12X steel, there is a smaller growth of austenite grain in the area of the welding line than in the case of S235JR steel. In further areas, however, the austenite grain of the S235JR steel is smaller than that of the 12X steel. The areas of recrystallized ferrite in both tested materials have a similar grain size. The initial higher grain size in the S235JR steel compared to the 12X steel results in a larger ferrite grain, which underwent the process of division into subgrains, bringing the grain size even closer to the austenite grain size. Therefore, it can be concluded that in both materials, the processes of microstructure changes as a result

of making the joint are of a similar nature, and the quantitative differences result mainly from the initial grain size difference.

The research presented in this paper is the first attempt to analyze the inverse quantitative assessment of microstructural changes that are taking place during the production of a welded joint. The obtained results indicate the general correctness of the applied inference. The applied research concept and the concept of microstructure interpretation allow for the formulation of the following conclusions:

1. Welding joints when they are performed are made with a fully austenitic microstructure in the area of the welding line.
2. Leaving a small amount of the recrystallized ferrite in the microstructure results in the reduction of the austenite grain size.
3. In welding joints there is a zone where the recovery processes lead to the formation of a subgrain structure.
4. The morphology of the formed subgrain microstructure depends on the temperature (distance from the joint).
5. The lower the temperature of subgrain structure formation, the larger and more elongated the subgrains are.

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