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INFLUENCE OF METAL STRUCTURE OF PIPES ON MECHANICAL PROPERTIES OF FLASH-BUTT WELDED JOINTS

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Technology of flash-butt welding occupies a sufficient place in different industries, including welding of different purpose pipes. At a high quality of joints the discrepancies in values of properties are observed in a number of cases. The paper considers the causes of such discrepancies and their relationship with the initial structure of metal of pipes. It was revealed that the formation of areas with a structural heterogeneity in joints is predetermined by the structure and volume of segregation bands of nonmetallic inclusions in steel and is not related to the technological parameters of welding. In welding of advanced pipe steels, produced by a controllable rolling, the required mechanical properties of the joints are provided. 10 Ref., 1 Table, 8 Figures.

Keywords: *pipelines, flash-butt welding, quality of joints, nondestructive testing, standards, mechanical tests, bending tests, delaminations, cracks, nonmetallic inclusions, segregation bands, structural heterogeneity, rejection criteria*

Flash-butt welding (FBW) is successfully applied in different industries, including welding of different purpose pipes. The technologies and equipment for this welding method, developed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine, have found a wide application in the construction of different pipelines. The welding process is fully automatic. At the same time, the parameters are controlled, providing a high stability of joints quality. In addition, a nondestructive testing of welded joints is performed applying the modern ultrasonic testing systems (UST). While performing welding operations, mechanical tests of reference batches of specimens, cut out from welded circumferential joints, are periodically carried out. The tests are conducted according to the methods approved by regulatory documents provided by departmental and state standards. The departmental standards take into account the specific conditions of works in construction and maintenance of pipeline systems, the state ones cover broader fields of application of technologies and welding consumables.

In the recent decade a harmonization of departmental and state standards with international standards is carried out. During construction of land pipelines, the international standard API 1104 [1] is widely applied.

At the E.O. Paton Electric Welding Institute of the NAS of Ukraine a large experience in applying FBW technology in construction of land pipelines has been gained, including, in particular, the results of comprehensive mechanical tests of joints of circumferential welds of different steels, as well as nondestructive testing (UST, X-ray inspection) and in-process control of welding parameters [2].

The study of these data shows that the joints of pipes made by FBW are characterized by high and stable values as compared to the other methods applied for welding pipes in field conditions, that is confirmed by the publications of organizations applying FBW technology and equipment [3]. An analysis of the available data also shows that in welding of some batches of pipes a discrepancy between the results of mechanical tests and other types of testing is observed. In the absence of any defects, the discrepancies in values below the admissible limits were observed from the results of nondestructive and in-process control during tests of separate specimens for bending, which resulted in need for repeated tests.

The aim of the investigations was to determine the causes of arising such discrepancies and their influence on the structure and chemical composition of pipe steel.

For investigations the circumferential joints of pipes with a 1420 mm diameter of steel of strength class X60 with a 19 mm wall thickness and those of steel of strength class X70 with a 16 mm wall thickness were taken. Welding was performed in the machine K700 using the optimum modes adopted for the mentioned wall thicknesses of pipes in accordance with VSN 006–89 [4]. In total 18 butts of pipes, made

Mechanical properties of circumferential pipe butts (quantity of joints — 9)

Evaluation method	Strength class	Tensile strength, MPa	Fracture location	Bend tests	
				Bending angle, deg	Weld quality
Tests in accordance with GOST 6996–66	X60	541–563 555	Along base metal and weld	>70 (7 butts)	Norm
				<70 (2 butts)	Rejection
	X70	599–619 612	Along base metal	>70 (8 butts)	Norm
				<70 (1 butt)	Rejection
Tests in accordance with API 1104	X60	547–569 559	Along base metal	180	Norm
	X70	589–611 602		180	Same

of steel of each strength class, were investigated. The mechanical tests of welded joints of specimens of each steel were carried out in accordance with the international standard API 1104 [1], as well as with the interstate standard GOST 6996–66 [5].

In each batch, a half of the specimens were tested according to the standard API 1104, and the second one — according to GOST 6996–66. The results of mechanical tests of welded joints are shown in Table. The mechanical properties of the pipe metal had the following values of the standard tensile strength: the pipes of strength class X60 — 540 MPa, the pipes of strength class X70 — 588 MPa. Here the chemical composition of the metal of two batches of pipes is presented. Steel of strength class X60, wt.%: 0.18 C; 0.42 Si, 1.50 Mn; 0.018 S; 0.014 P; 0,04 Ni; 0.02 Cr; 0.04 Cu. Steel of strength class X70, wt. %: 0.07 C; 0.31 Si; 1.53 Mn; 0.004 S; 0.017 P; 0.27 Ni; 0.002 Cr.

The metallographic examinations were carried out in the light microscope «Neophot-32», the analyses of chemical composition of fractures surface of joints were made in the Auger microprobe JAMP 9500F of JEOL Company (Japan).

Figure 1 shows macrosections of joints of steels of strength class X60 and X70. With the same width of heat-affected zone (HAZ), the macrostructure of joints is different, which is determined by the structure of base metal of pipes. In both batches the structure of base metal has banding. The pipes metal of steels of strength class X60 (Figure 2, *a*) has, as compared to the pipe metal of strength class X70, a higher point of banding 5 according to GOST 5640. The banding of steel of strength class X70 (Figure 2, *b*) corresponds to the point 2. By the content of nonmetallic inclusions the steels are differed more significantly. In steel of strength class X60, the content of nonmetallic inclusions in the bands of rolled metal is higher and estimated by the point 4 in accordance with GOST 1778. The chains of nonmetallic inclusions form the continuous lines (Figure 2, *c*). In steel of strength class X70 these are the separate small inclusions having not higher than 3 points (Figure 2, *d*). According to the chemical composition, the inclusions in both steels represent sulfides, oxides and silicates. According to the chemical composition of metal (Table), the sulfur content in pipe steel of strength class X60 is 3 times higher than in steel of strength class X70. This gives grounds to assume that in the segregation bands of strength class X60 the manganese sulfides prevail. The structure of metal along the line of joints and of the regions adjacent to it is coarse-grained (Figure 3, *a*). The forming structure of joint line represents a polyhedral ferrite. In the region of coarse grains, the microstructure represents a lamellar ferrite with an ordered second phase. The size of the primary austenite grains reaches No.2 and No.3 in accordance with GOST 5639–82 for joints of pipes of strength class X60 (Figure 3, *a*) and No.3 and No.4 for joints of pipes of strength class X70 (Figure 3, *b*).

In the pipes metal of strength class X70 there are no stitch nonmetallic inclusions (Figure 2, *d*). This can be explained by a more advanced technology for production of such steels by the method of a controllable rolling.

The table shows the results of mechanical tests of welded joints made in accordance with the require-

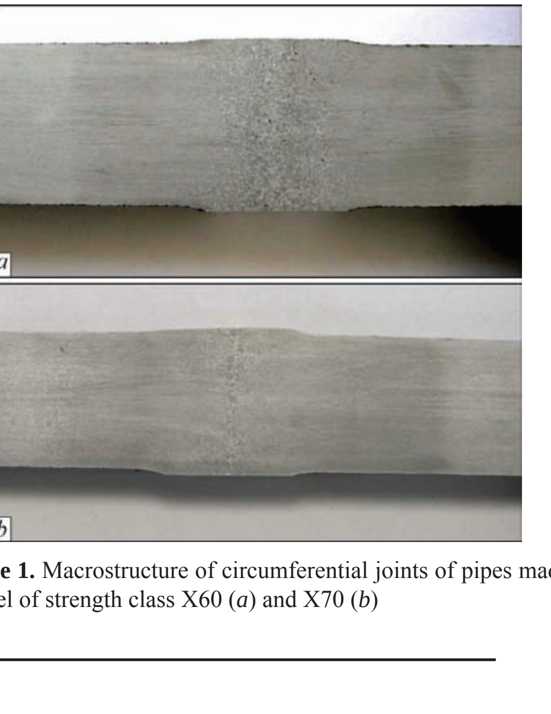

Figure 1. Macrostructure of circumferential joints of pipes made of steel of strength class X60 (*a*) and X70 (*b*)

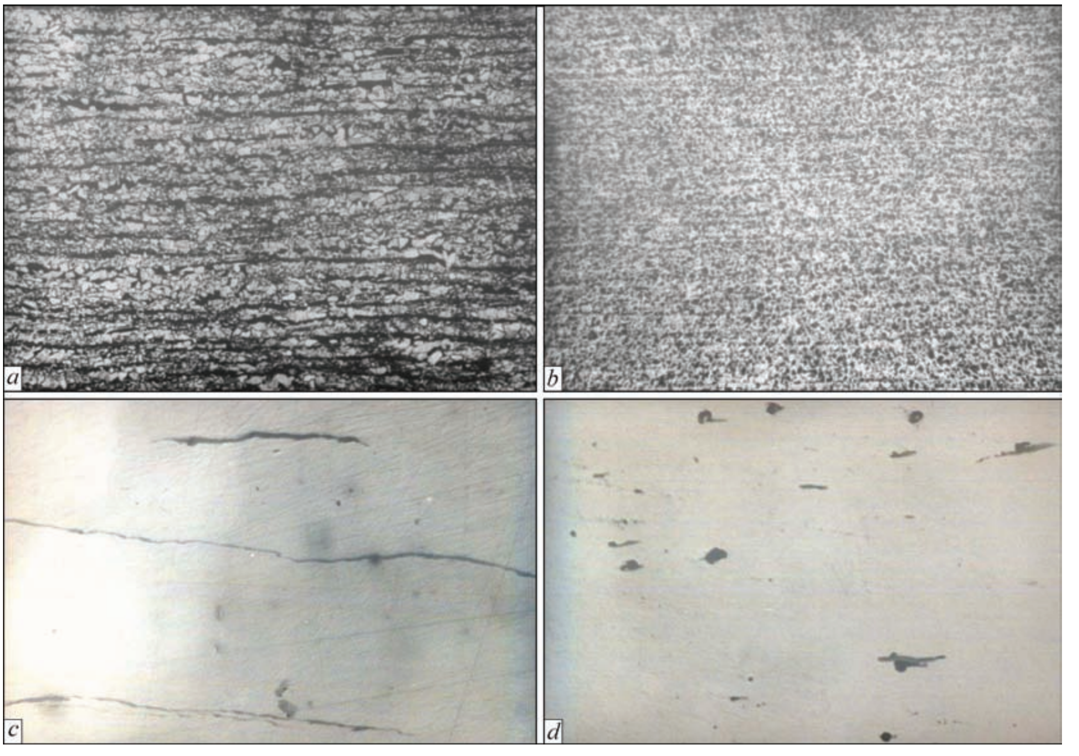

Figure 2. Microstructure (×100) of pipes base metal of steels of strength class X60 (*a*) and X70 (*b*); *c* — chains of nonmetallic inclusions in steel of class X60 (×500); *d* — separate small nonmetallic inclusions in steel of class X70 (×500)

ments of API 1104 and the interstate standard GOST 6996–66. The main difference between GOST 6996–66 and API 1104 is more severe testing of welded joints specimens on bending. The comparison of test results shows that in tensile tests the tensile strength of joints of pipes is at the level corresponding to the values of base metal of the mentioned steels. The results of bending tests of welded joints of all batches of specimens according to method of API 1104 also correspond to the requirements of this standard. During bending tests of batches of specimens according to the methods of GOST 6996–66 the separate discrepancies in values below the admissible level were observed. This is connected with arising of crack-like openings (Figure 4, *a*) and delaminations of outer layers of specimens (Figure 4, *b*), subjected to tension during bending. In most cases, the crack and subsequent delamination began in the places where segregation bands escaped to the surface and the fracture of specimen occurred after reduction in the cross-sectional area of the specimen, if its bending is continued. The origination of initial crack occurred on separate sections of the surface, subjected to tension, depending on the width of segregation band, escaping to the surface of the specimen after its treatment and removal of the weld reinforcement, i.e. flash.

As is seen from Figure 5, *a* [6], the bending angle of fibers and segregation interlayers has a maximum

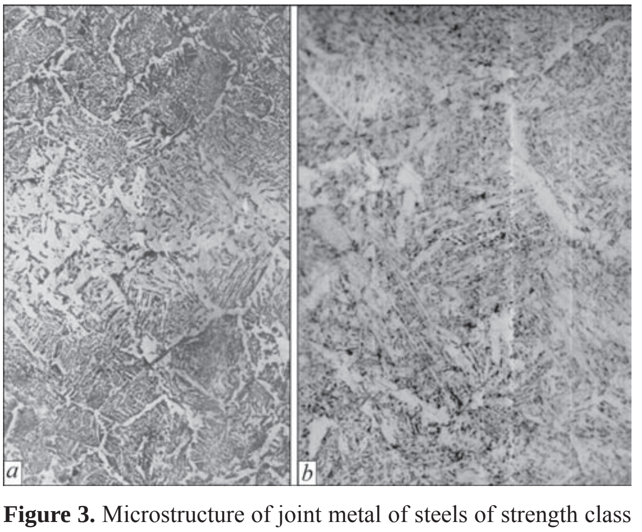

Figure 3. Microstructure of joint metal of steels of strength class X60 (*a*, ×100) and X70 (*b*, ×200)

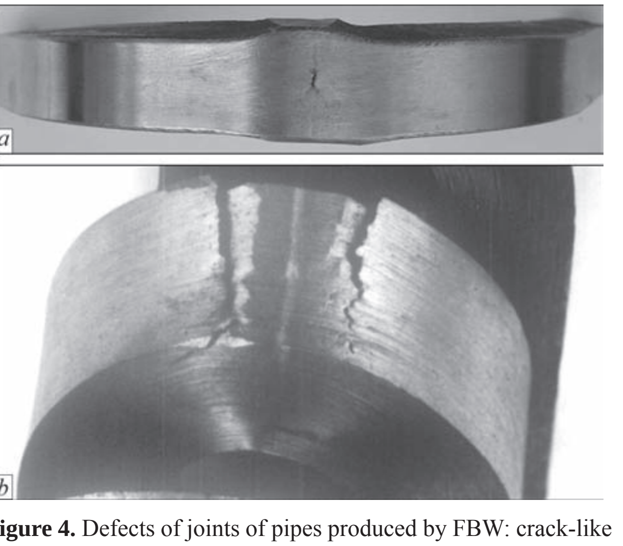

Figure 4. Defects of joints of pipes produced by FBW: crack-like opening (*a*); delamination of outer layer (*b*)

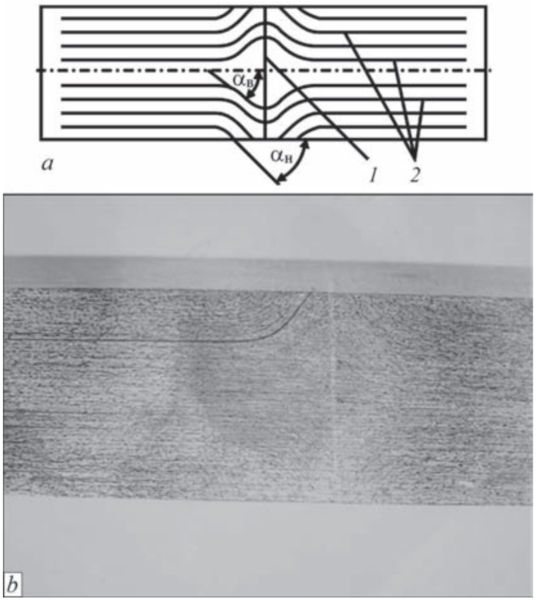

Figure 5. Scheme of welded joint (*a*) and location of escape of segregation band to the surface of pipe wall (*b*): *1* — joint line; *2* — bands of rolled metal; $\alpha_н$ is the angle of bending the bands of rolled metal near the surface; $\alpha_в$ is the angle of bending the bands of rolled metal in the middle of the joint

value at the weld center and decreases as the fibers moved away from the center to the sheet surface. At the same time, the maximum compression deformation of heated near-contact layers of metal is observed in the weld center, and as the bands move away from the center, they undergo compression with bending, the outer layers experience tensile stresses acting on segregation interlayers and reducing their density. In most cases, the tears and cracks in the zone of tension of surface layers occur at the places where segregation layers escape to the surface of welded specimens at the distance of 2–3 mm from the weld center (Figure 5, *b*). This is predetermined by the increase in the thickness of segregations as a result of «opening» of the segregation layer during its deformation, as well as by the lower mechanical properties of sections with nonmetallic inclusions.

As the carried out investigations show, the anisotropy of mechanical properties is characteristic for base metal of pipes made of steel of strength class X60 with a diameter of 1420 mm produced in the 1990s. During the rupture tests of specimens, cut out along the rolled metal and in the direction perpendicular to the rolled surface, the ratio $\sigma_{r.s}/\sigma_t$ in certain cases was $K = \sigma_{r.s}/\sigma_t = 0.8$, where σ_t is the strength of pipe metal along the rolled surface, $\sigma_{r.s}$ is the strength of pipe metal across the rolled surface. The low *KCV* values of impact toughness of base metal of these pipes, tested across the thickness of the wall with a notch located in the direction of rolling, were also observed. At a room temperature, the minimum *KCV* values were

Figure 6. Appearance of specimen with a crack along the welding line

32.3 J/cm^2, and at the temperature of minus 20 °C they decreased to 14.5 J/cm^2.

In some specimens of welded joints, during bending tests the cracks of small length along the welding line were observed (Figure 6). At the same time the bending angle of the specimens was 180° and the state of weld as to the presence of cracks and their admissible size corresponded to the requirements of API 1104. At the same time, such specimens did not meet the requirements of GOST 6996–66. During visual inspection of such specimens, after bringing them to a complete fracture by additional bending, the areas on the fracture surface were found, where on the background of crystalline fracture the areas were present differed from the rest of the fracture surface by an undeveloped relief and the dark coloring (Figure 7). Such defects in practice of flash-butt welding were defined as «dead spots» (DS) [7]. The degree of influence of DS on the values of bending tests is determined by their area and location on the joint plane. If DS is located in the area subjected to tension, then the values of tests can decrease even at a small area

Figure 7. DS at the fracture surface

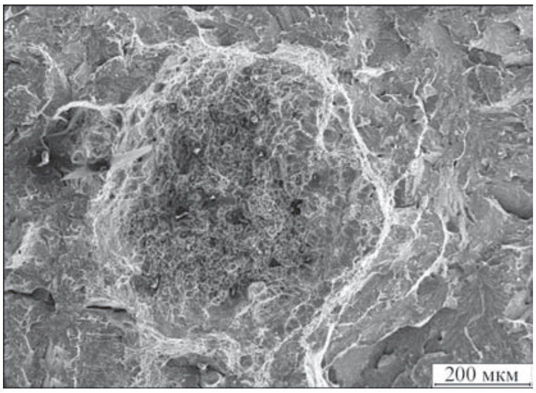

Figure 8. Microstructure of fracture surface of the joint in DS region

of DS (16–20 mm^2). In tensile tests, the presence of DS with the area of 30–50 mm^2 does not influence the test results. When the microstructure of DS was examined in a scanning electron microscope, it was revealed that it bears a pit character (Figure 8). In the pits the numerous small nonmetallic inclusions were observed. As to their composition, these inclusions do not differ from nonmetallic inclusions on the base of Mn, Si, S, and Fe, included in the composition of pipe steel of strength class X60. These data allow making a conclusion that DS formation is influenced by nonmetallic inclusions, which are contained in the base metal of pipes. Considering different probabilities of getting them into welded joint from segregation bands, it can be assumed that the region of segregation band during its deformation can be located along the joint plane. This assumption is acceptable if we admit that the bending angle of segregation bands under deformation is close to 90°. The similar formation of structure during the process of deformation of rolled products was considered in the work [8] as-applied to friction welding of pipes. It was shown that decrease in ductile properties is predetermined by orientation of segregation bands parallel to the welding plane. As can be seen from the scheme of a welded joint (Figure 5, *a*) made by FBW, the bending angle even in the weld center does not exceed 30°. Therefore, during deformation an insignificant part of the «material» of segregation band can get to the joint and its influence on weld formation will not be significant.

More probable is the formation of DS from the melt of a liquid metal, constantly renewed at the ends of parts during flashing [9]. In the work [10], performed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine, it was shown that the cavity in the ends, simulating nonmetallic inclusions in the metal and filled with the «material» of segregation band, i.e. nonmetallic inclusions, leads to the formation of joints with a defect of the DS type on this surface area.

The similar phenomenon is possible if segregation band has a sufficiently large volume. Its «material», interacting with the melt, which is formed at the ends of the welded parts in the process of flashing before upsetting, enriches it in separate areas and creating the conditions for DS formation in such a way.

At small sizes of DS of up to 15 mm^2, a significant influence on the values of mechanical properties of welded joints during tests for bending and tension is not observed. At a larger area of DS, the values of bending tests are reduced. It should be noted that in the tests of joints of steel of strength class X70, the DS occurred extremely rare, and their dimensions did not exceed 15 mm^2. In welded joints of steel of strength class X60, the probability of DS arising is significantly higher, their area reached 30 mm^2. This confirms the relationship between the appearance of MP and the content of nonmetallic inclusions in steel. In the base metal of X60 class steel, the largest segregation bands are observed, which contain Mn sulfides, forming brittle interlayers in the metal. The content of sulfur in this steel is almost 3 times higher than its level in the steel of strength class X70.

From the comparison of mechanical tests values of welded joints specimens of steels of strength class X60 and X70 for bending in accordance with the standards API 1104 and GOST 6996–66 it is seen that all discrepancies below the normative values belong to the specimens tests of steel of strength class X60 in accordance with GOST 6996–66. This is predetermined by the accepted scheme of cutting specimens out of a welded joint. During tests in accordance with GOST 6996–66, the tension in bending belongs to the fibers adjacent to the outer or inner surface of the pipe, the degree of their elongation at the same bending radius increases with increase in thickness of specimen. In the tests according to API 1104, the thickness of bent specimen remains constant, and the width is proportional to the thickness of pipe wall. All the fibers, regardless the varied bending angle of the welded joint specimen, are subjected to the same tension. Therefore, the results of tests according to the API 1104 standard more objectively reflect the ductile properties of the metal at different regions both in the joint plane as well as in the weld as a whole. The given data confirm the rationality of the application of API 1104 standard in evaluation of the level of mechanical properties of the joints produced by FBW regardless of the wall thickness of pipes.

During evaluation of the joints quality from the results of mechanical bending tests, it is necessary to take into account the peculiarities of steel structure of pipes being welded, the presence of a large number of segregation inclusions, especially sulfides in the base metal, which can cause delaminations in specimens during tests.

The appearance of separate cracks and delaminations in specimens during bending tests and reduction in values below the required level can not be the grounds for negative conclusion throughout the whole reference batch. The repeated tests make it possible to reveal whether crack (or delamination) is single on the surface of a specimen or it is found on specimens cut out in other joint sections.

The presence of separate cracks, as is given in the considered case, is not a rejection feature, even if the bending angle was lower than the normative requirements. The appearance of cracks along the entire width of the specimen or on the specimen(s) adjacent to it (them) indicates the need for adjustment of FBW modes. During bending tests of welded butts specimens of steel pipes of strength class X60 and X70 with a thickness of more than 10 mm, the presence of DS in the fractures with up to 15 mm^2 area should not to be considered as a rejection feature and grounds for adjustment of the welding mode parameters.

The carried out investigations allow making the following generalizations: during FBW of pipes in the welded joint zone the regions with structural heterogeneity are formed which can become the sources for development of delaminations and cracks during bending test of specimens; the formation of such areas is determined by the structure and volume of segregation bands of nonmetallic inclusions in steel and is not related to technological parameters of welding; in welding of advanced pipe steels of strength class X70–X80, characterizing by higher requirements to purity, the presence of regions of structural heterogeneity in welds practically does not influence the results of mechanical tests; during bend testing of large batches of specimens the fracture-like openings in the weld center were observed in some of them, which was caused by the formation of structural heterogeneity in these areas, characterized as «dead spots». It was revealed that their chemical composition is close to the composition of nonmetallic inclusions of segregation bands of base metal. The probability of «dead spots» arising is higher in welding of steels, characterized by an increased content of nonmetallic inclusions. If their area does not exceed 15 mm^2, they do not influence the results of mechanical tests of the investigated batches of specimens of steels of strength class X60 and X70; the comparison of test results of welded joints of FBW pipes of different steels shows that the test procedure, as described in API 1104 standard, allows a more objective evaluation of the properties of joints of pipes having a different composition of steels and wall thickness.

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