ASSESSMENT OF DEFORMABILITY OF PIPE STEEL JOINTS MADE BY AUTOMATIC CONTINUOUS FLASH-BUTT WELDING

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Peculiarities of formation of high quality flash-butt welded joints on pipes are analyzed. Factors affecting the results of impact tests of standard specimens are considered. Toughness properties of metal in the welding zone have been studied by using different impact test methods. It is shown that metal of as-welded joint made at optimum parameters has sufficiently high resistance to impact loads. Conditions for performing flash-butt welding and inspection of the joints providing high operating reliability of pipelines have been determined.

Keywords: *flash-butt welding, pipelines, joint quality, impact testing methods, joint zone, impact toughness, operating reliability*

One of the important tasks in construction of pipeline systems is ensuring their operating reliability. It is solved by specifying a number of technical and technological requirements pertaining both to welding performance, and to the properties of site (circumferential) butt joints. Mechanical properties of the latter are represented by values of strength and ductility, and they should meet the requirements of standards [1, 2]. In addition, in order to prevent fractures in butt joint operation because of the most characteristic defects, inherent to the applied welding process, also specified are the requirements to the value of joint metal impact toughness representing the energy consumed in fracture of a standard sample.

Over the recent decades the method of impact testing of samples with a sharp mechanical notch (KCV) of depth h = 2 mm with radius r = 0.25 mm at the bottom, has become the dominant method that was due to a high probability of formation of sharp stress raisers in welds, including crack-like ones. Nowadays such a testing procedure and established values of impact toughness are extended to all the welded joints, irrespective of the process of their welding. In keeping with the requirements of [1], average value of impact toughness of metal of welded joints on pipes of strength class X52–X70 at −20 °C testing temperature should be not less than 34.4, and minimum value should be 29.4 J/cm^2. These KCV values were determined allowing for the inevitable and admissible defects for joints made by electric arc welding processes. These defects include external crack-like defects (one- and two-sided lacks-of-penetration — lacks-of-fusion) of up to 1 mm depth and up to 30 mm length, weld root concavity (shrinkage of down to 2 mm depth and length of up to 1/6 of welded butt joint perimeter), as well as internal lacks-of-penetration both between the layers and around the contour of the edges. In addition, in electric arc welding there is a high probability of appearance of various kinds of cracks, which are not allowed in welded joints. Their detection, however, by industrial NDT methods presents certain difficulties in a number of cases.

Transfer of the testing procedure and the above standard KCV requirements to welded joints made by other welding methods, is not always justified by far. In the case of absence of the above defects in the weld, ensuring KCV values on the level of 34.4 J/cm^2 for all the zones of the joints should be recognized as unpractical as such requirements make pipeline construction more complicated and lead to excessive consumption of material means. API-1104 standard is advanced in this respect [2]. It does not specify the impact toughness values; they are indicated by the customer in the form of special requirements that are defined allowing for specific conditions of pipeline construction and operation. Such an approach is directed to simultaneous solution of the two main tasks: lowering of failure probability of the pipelines in operation with the most probable defects in circumferential butt joints, characteristic for the applied welding process, and minimization of construction costs.

Many years of experience of operation of various diameter welded pipelines, including high-capacity gas- and oil pipelines of 1420 mm diameter, shows the high reliability of circumferential welds, made by automatic flash-butt welding. Mechanical properties of these joints meet all the requirements of the standards, in keeping with which large-scale construction of the main and industrial pipelines is performed, except for individual cases when special requirements are made to the value of impact toughness (mainly in welding large diameter pipelines operating at below zero temperatures).

Compared to electric arc fusion welding, flash-butt welding has principal differences in joint formation, which need comprehensive analysis, and should be taken into account at substantiation of the procedure of fitness-for-purpose assessment of welded joints of pipes made by flash-butt welding.

Flash-butt welding is one of pressure welding processes in which there is no molten metal in the joint zone (weld), thus eliminating all the prerequisites for formation of such hazardous defects as cracks. In performance of welding in the optimum mode other defects are also absent in the joint zone (JZ), which could detract from joint performance. Such a welding mode is determined by statistical treatment of mechanical testing data obtained during investigation of weldability of each typesize of pipes under the condition that inadmissible welding defects are completely absent in the joints. Mechanical properties should correspond to the requirements of standards, made of pipe welded joints. Assessment of welding quality is performed by breaking welded butt joints through JZ [3]. From admissible defects in flash-butt welding, only local clusters of nonmetallic inclusions can be present in individual JZ regions with maximum area of 20–30 mm^2 [4, 5], but as they do not influence the static strength of the joints [6] they should not be regarded as defects. Considering the structural condition, such nonmetallic inclusions should be regarded as one of the kinds of structural inhomogeneity, presence of which is admissible in the pipe metal. In some works such JZ regions are called «mat spots» [7, 8]. Maintenance of the specified parameters of optimum welding mode in flash-butt welding is ensured by a computerized system of control and monitoring without intervention of welding operator. This is the determinant factor in ensuring the high operating reliability of more than 70,000 km of various pipelines, including more than 10,000 km of pipelines of 1420 mm diameter welded by flash-butt process [9, 10], that have been operating unfailingly for more than 30 years under different natural conditions, including artic regions of West Siberia (Figure 1). Average value of impact toughness of these joints, determined at testing of standard samples with a sharp mechanical notch, the tip of which is located in JZ center, is equal to 30–40 J/cm^2 in the scatter band of KCV values in the range of 14.3–56.3 J/cm^2 (20 °C testing temperature). Such values of impact toughness of JZ metal are largely due to mechanical inhomogeneity that forms as a result of varying degrees of metal strengthening in the welding zone. The magnitude of plastic deformation at the final stage of welding, i.e. upsetting, varies, depending on the temperature gradient in pipe welding zone (on both sides of JZ). As a result, the joint metal in its cross-section differs essentially by hardness, and, therefore, also mechanical properties ($\sigma_{0.2}$, σ_t). JZ has the smallest hardness value. Hardness of adjacent regions of the welding zone is higher than that of the pipe metal. In welding of pipes produced now from low-carbon low-

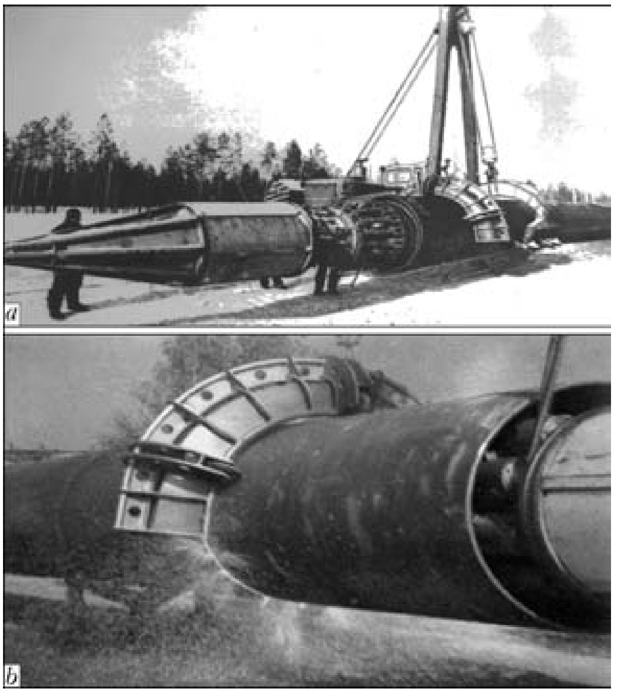

Figure 1. «Sever-1» welding complex in the construction route of 1420 mm diameter pipeline in West Siberia: *a* — position of welding machine in the pipeline before feeding the next pipe to be welded on; *b* — welding operation

alloyed steels, the width of JZ region can be within 0.5–5 mm, depending on the welding mode. Difference in hardness, and, therefore, strength of this region, compared to the adjacent regions of the zone of thermomechanical strengthening can be up to 30 %, and in welding of pipes from carbon steels it can be higher. The length of individual regions of the welding zone depends on the initial metal properties determined by its production technology, and welding mode.

As shown by testing of standard samples for static tension and bending, as well as of large-scale samples and pipe segments, mechanical inhomogeneity, on the whole, does not have a negative impact on the strength and ductility of welded joints [6, 11]. In this case, a narrow section of the JZ with lowered mechanical properties is plastically deformed due to contact strengthening together with the adjacent sections of the thermomechanical strengthening zone. Unlike that, at determination of impact toughness by the standard procedure (KCV) development of the fracture process is localized within a narrow section of JZ metal, located between the regions of the thermomechanical strengthening zone with higher strength properties, due to high values of concentration (α_σ = 3.45) and stress gradient. As a result, in connection with a small metal volume involved in the process of plastic deformation at impact, the energy consumption for sample fracture essentially decreases compared to homogeneous material [4, 5]. This is indicated by the shown in Figure 2, *a* fracture surface of such a sample without any noticeable side shrinkages and low value of impact toughness.

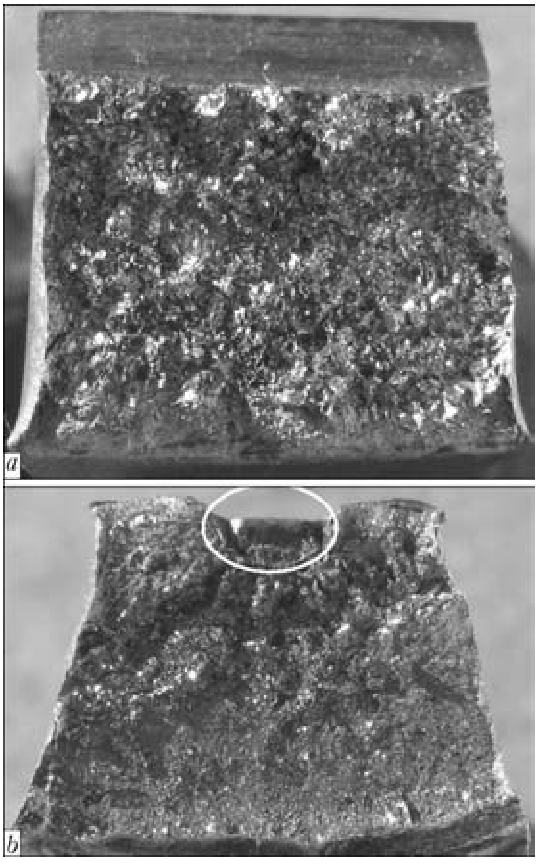

Figure 2. Fracture surface of impact samples of welded joints after their testing in as-welded condition with a standard mechanical notch, KCV = 32 J/cm^2 (a) and without an artificial notch with structural inhomogeneity (marked by an oval), KD = 161 J (b)

At the same time, the nature of fracture of impact samples of flash-butt welded joints without artificial mechanical stress raiser in the JZ, but with the characteristic for flash-butt welding admissible defects differs in principle from the one described above.

Fractures of samples with such defects located at their surface had the form of a trapezoid, because of considerable shrinkage of their side faces (Figure 2, b) that essentially increased the energy consumption for fracture which is denoted as KD according to [5]. Results of testing impact samples of a standard size (10 × 10 × 55 mm) without notches with structural inhomogeneity of various dimensions in the JZ by KD parameters turned out to be as follows: at 4.4 × × 2.5 mm — 247.2 J; 4.0 × 3.5 mm — 261.6 J; 4.7 × × 2.0 mm — 161.2 J, where the first value corresponds to the linear size of the defect on the impact sample surface, and the second value is the same, but in-depth of the sample.

Sections of structural inhomogeneity in the JZ located at some distance from the sample surface, practically do not affect the results of testing at impact loading. Such samples did not fail.

Thus, impact testing of standard samples with a sharp notch in JZ does not reproduce the pattern of deformation and fracture of a welded joint with admissible defects that may occur at flash-butt welding.

Values of fracture energy for samples with admissible defects (without an artificial notch) are much higher than those of samples from sound joints with a standard notch as a result of involvement of thermomechanical strengthening zone regions adjacent to JZ, into plastic deformation, which has a determinant role in the fracture process. This is indicative of the fact that impact toughness values of flash-butt welded joints with a sharp notch through the JZ are largely determined not by the properties of the joint metal, but by the stressed state induced in it. Thus, impact toughness values obtained on samples with a standard notch through the JZ, inadequately represent fracture resistance of a welded joint with admissible flash-butt welding defects, and, therefore, they cannot be a reliable characteristic of its fitness-for-purpose.

Proceeding from the above, an unambiguously positive reply can be given to one of the main questions: are the obtained values of KCV impact toughness of the metal of flash-butt welded joints in as-welded condition indeed sufficient to ensure reliable performance of pipelines under the conditions of service. It should be also taken into account that KCV values correlate with fracture mechanics characteristics (K_{1c}, δ_c). Their required level for prevention of welded joint fracture is directly related to the type and dimensions of the most probable defects, characteristic of the accepted welding process, including crack-like defects, the maximum dimensions of which are determined by the resolution of the used inspection techniques. Therefore, absence of hazardous defects in the metal of flash-butt welded joints guarantees their integrity at lower impact toughness values compared to the welding processes, in which cast metal forms in the welding zone. This is confirmed by many years of commercial operation of flash-butt welded pipelines.

Considering the known fact that «brittleness is not a property of a structural material and is determined not only by its structural state, but also by an essential influence of structural-technological factors ...» [12], in assessment of impact toughness of flash-butt welded joints it is important to create such a stress-strain state in the tested sample that the nature of its deformation and fracture corresponded to samples with admissible defects. Here, the main testing condition is ensuring simultaneous plastic deformation of the metal of JZ and thermomechanical strengthening zone. Such a task can be solved by reducing the depth of the mechanical notch down to zero (samples without an artificial stress raiser), changing their number and location in the welded joint.

In publications there is an example of localization of plastic deformation and fracture in the specified narrow volume of the tested impact sample by making two additional notches in the plane of location of the main notch on the side faces adjacent to it. Additional notches are similar to the main one in shape and size [13].

In [14], noting the practical absence of defects in flash-butt welded joints, it is proposed to lower stress concentration in standard *KCV* samples at the expense of reducing the notch depth. Testing conducted at PWI at the temperature of 20 and −20 °C of flash-butt welded joints on large-diameter pipes from steels of different strength grades, at different absolute values of notch depth h with radius $r = 0.25$ mm in standard samples, confirmed the potential of such an approach. With reduction of the depth of mechanical notch to $h = 1$ mm impact toughness values increase more than 2 times compared to a notch with $h = 2$ mm. Increase of the values occurs as a result of increase of the volume of metal involved in plastic deformation.

To determine the level of toughness properties of metal of flash-butt welded joints, it is necessary to eliminate JZ constraint by the adjacent large volumes of stronger metal of thermomechanically strengthened zone in the standard sample. With this purpose additional «straightening grooves» with geometrical parameters of the standard notch, located parallel to the notch through the JZ, were made in the high-hardness regions of thermomechanically strengthened zone.

Figure 3, *a* shows a schematic of making samples of flash-butt welded joints of 10 × 10 × 55 mm size with a standard notch through the JZ and two additional grooves. Such grooves are made in parallel to the notch through the JZ at distance $k = h$ (where k is the distance between the axes of the central and additional notches) on both sides from its center. In such a sample, in keeping with Neuber theory [15] stress concentration is mutually lowered, compared with one central notch, and practically equal conditions of plastic deformation of the metal of JZ and thermomechanically strengthened zone are created.

By analogy with accepted designations of impact energy and impact toughness, representing the concentrator type *KV*, *KCV*, we will introduce *K*3*V* and *KC*3*V* symbols for the proposed sample with three notches. Figure 4, *a* shows a typical nature of fracture in impact testing of samples with three notches from sound flash-butt welded joints, the characteristics of which meet the requirements of standards, and Figure 4, *b* shows defective joints, not meeting these requirements. Fracture energy of impact samples (with three notches 2 mm deep with 0.25 mm radius) of welded joints of pipe steel of X70 strength grade in as-welded condition, is as follows:

• in sound joints made in the optimal mode, at $T_{test} = 20$ °C $K3V = \frac{114.6\text{–}254.3}{177}$ J, at $T_{test} = -20$ °C $K3V = \frac{112.8\text{–}214.4}{130}$ J;

• in defective joints made with mode violation (inadmissible defects found in fractures), at $T_{test} =$ $= 20$ °C $K3V = \frac{4.8\text{–}21.0}{11.5}$ J. At testing of sound flash-butt welded joints it is established that the welding

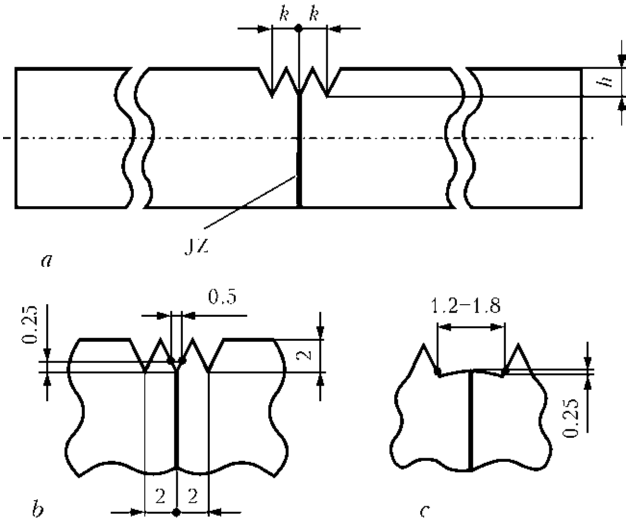

Figure 3. Schematic of *KC*3*V* impact sample: *a* — notch location; *b* — region of a sample with notches before testing; *c* — central notch after testing

zone, including JZ and thermomechanical strengthening zone, on the whole, has a high deformation ability, and, hence, high values of impact toughness. Here JZ was subjected to considerable plastic deformation at tension. While before testing the distance between the notch edges at its tip in accordance with its notch radius was equal to 0.5 mm ($2r = 2 \times 0.25$), after testing it increased 2.4–3.6 times (see Figure 3, *b* and *c*). These data are indicative of considerable ductility of JZ metal and its sufficiently high resistance not only to initiation, but also to propagation of cracks. In some samples micro- and macrocracks appeared at the bottom of the central notch through JZ (Figure 5), but they did not propagate any further. Final fracture of the sample in the shear mode was brought about by cracks initiating in the tips of the two side notches (see Figure 4, *a*).

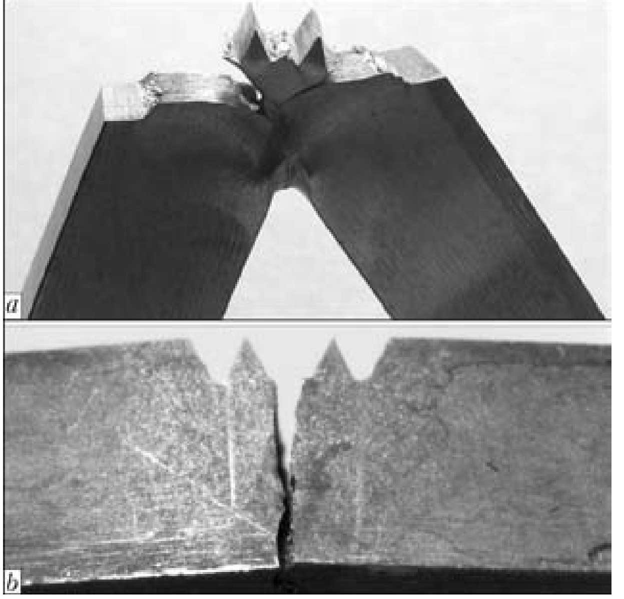

Figure 4. Typical nature of fracture of *KC*3*V* samples cut out of joints made in the optimum mode (sound joint) (*a*) and in modes with violation of the main parameters (defective joints) (*b*)

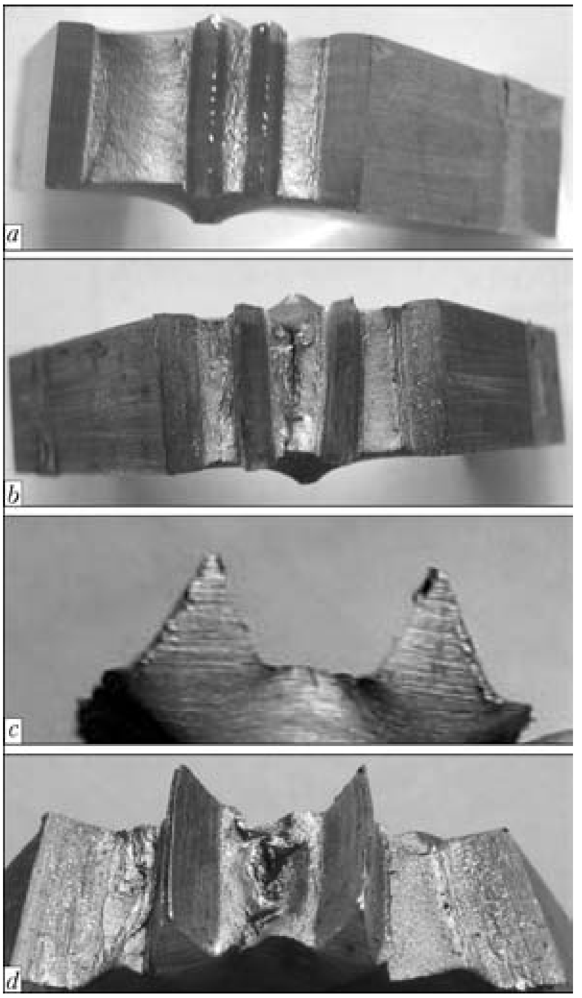

Figure 5. Nature of deformation of the zone of central notch of $KC3V$ samples with micro- (a, c) and macrocracks (b, d); a, b — top view; c, d — side view

It is important that the proposed testing type allows revealing, alongside the NDT methods [16, 17], butt joints with inadmissible defects in the JZ. Such samples fail only through the central notch with low values of $K3V$ fracture energy (see Figure 4, b).

At testing samples of a standard size with three notches from a sound joint of steel of strength grade X70 (samples from welded sectors of pipes supplied by Khartsyzsk plant, with impact toughness of pipe metal of more than 300 J/cm^2 at 20 °C) in as-welded condition had the energy consumed in fracture ($K3V$) on average equal to 177 J at 20 °C temperature, and to 130 J at −20 °C. Standard impact samples (with one notch) of the same joints at 20 °C temperature had KV of about 30 J, on average.

CONCLUSIONS

1. Values of impact toughness obtained on standard samples with a sharp notch KCV through JZ in as-welded condition, do not represent the true fracture resistance of welded joints of pipes made by flash-butt welding, with the characteristic admissible defects. In this case, one of the factors determining KCV level, are not the properties of the welding zone metal proper, but its mechanical heterogeneity.

2. Conducted investigations with application of the procedure of impact testing of samples with three parallel notches changing the stress-strain state in the welding zone, showed that the metal of flash-butt welded joint, on the whole, and all its zones (JZ and thermomechanical strengthening zone) in as-welded condition have a sufficiently high resistance to impact loading.

3. Investigation results account for the confirmed by practical experience high operational reliability of welded pipelines. There is every ground to eliminate the requirements of application of postweld heat treatment of flash-butt welded joints, which is recommended to increase the impact toughness values.

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