COMPARATIVE EVALUATION OF METHODS FOR DETERMINATION OF FRACTURE TOUGHNESS OF HAZ METAL OF LOW-ALLOY STEEL WELDED JOINTS

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The article presents results of experimental studies of fracture toughness of the HAZ metal of low-alloy steel welded joints with different schemes of formation of a notch. Currently available methods for preparation of specimens and results of testing them to crack tip opening displacement under three-point loading were evaluated.

Keywords: *manual arc welding, welded joints, fracture toughness, crack tip opening displacement fracture diagram, metallographic examinations, structure, test temperature*

At present, the special consideration in evaluation of performance of critical structures and constructions, pressure vessels and pipelines operating under severe conditions is given to resistance of welded joints to brittle fracture.

As shown in study [1], the key factors leading to formation of brittle fracture of a welded joint include stress concentration caused by a notch (dramatic change in cross section, technological defects of welds and base metal), tensile residual stresses at the notch root, decreased ductile properties in the above region, and low temperature.

Criterion of non-linear fracture mechanics, i.e. the value of crack tip opening displacement (CTOD) δ_c [2] finds an increasingly wide application, along with traditional criteria (impact toughness, fracture character), for evaluation of sensitivity of welded joints to brittle fracture. Quantitatively reflecting fracture resistance of materials and welded joints with crack-like defects of a technological and operational origin, this indicator makes it possible to find values of critical temperatures that separate regions of tough, quasi-brittle and brittle fractures for structural materials. This is of practical importance for the welded joints in view of the probability of local embrittlement of metal in the weld zone and, therefore, the need to limit working temperature ranges by a tough state [3].

Advantages of the crack opening displacement (COD) test method are covered in detail in studies [1–4]. Moreover, welded joints of some repaired structures inevitably contain stress raisers, which may affect not only formation of cold cracks, but also resistance to brittle fracture.

As a rule, embrittlement of metal in welding of structural steels takes place in a coarse-grained region of the heat-affected zone (HAZ). In this connection, evaluation of resistance of welded joints to brittle fracture is usually performed proceeding from the results of tests of the notched specimens within the said zone under three-point slow loading [5].

As proved by the world experience, when using the CTOD method for determination of permissible sizes of crack-like defects in the welded joints, the most reliable results are exhibited by the specimens with incomplete root face penetration (IRFP) in groove of a joint, which are made according to the Japanese procedure [6] (Figure 1, *a*). Welding of such specimens is performed in a special fixture (Figure 1, *b*), which limits angular deformations and allows free deformation to occur in a direction that is transverse to the weld. However, this procedure is labour-consuming. It is meant only for welding with stick electrodes, as it requires that the fusion interface of the multilayer weld be parallel to a slot gap.

Manufacture of specimens and method for making notches, according to study [7], allows using the CTOD procedure for other welding methods as well. In this case, specimens with a V-groove are advantageous over the other ones owing to simplicity and labour intensiveness of their manufacture.

To establish adequacy of the said procedures and correlation of the results, in this study the joints on steels X60 and 17G1S with different groove shapes (Figure 2) were welded under identical welding conditions by using stick electrodes. Chemical compositions of the steels are given in the Table.

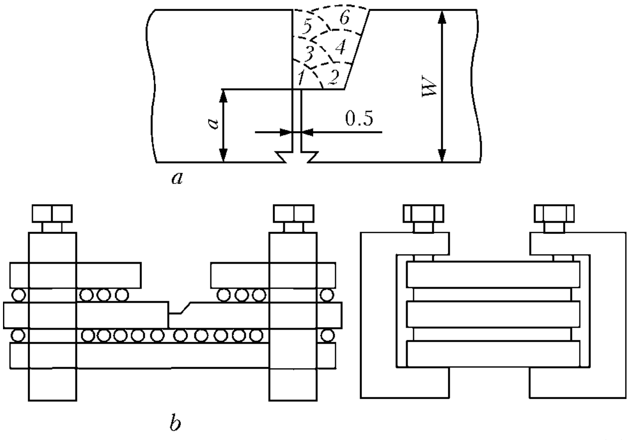

Figure 1. Schematics of welded specimen with IRFP in edge (*a*) and device for its welding (*b*): *1–6* — groove filling sequence

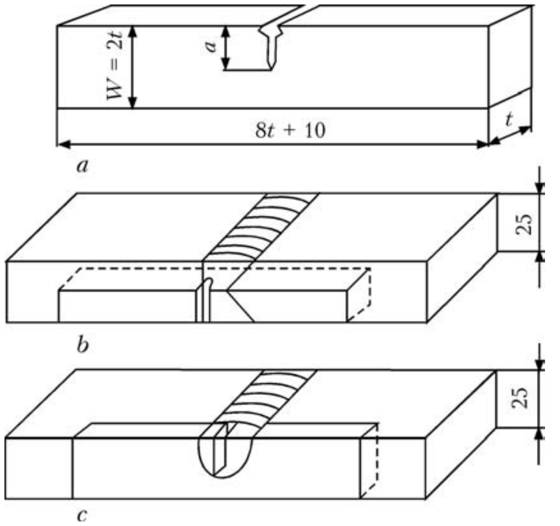

Figure 2. Schematics of specimens cut out from welded joints for CTOD with different shapes of notches

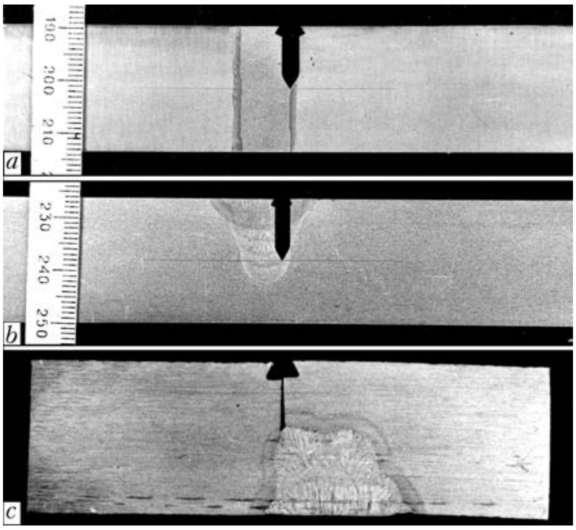

Figure 3. Macrosections with artifical (mechanical) and natural notches in HAZ: *1* — notch located parallel to fusion interface; *b* — notch made at angle to joining interface; *c* — natural notch with IRFP

Notches were made by the mechanical method in the said specimens at an angle normal and parallel to the fusion interface (Figure 2). In all the cases the tip of a notch with a curvature radius of 0.1 mm was located at a distance of 0–0.3 mm from the fusion interface. In addition, specimens with a natural stress raiser, i.e. IRFP in a groove of the welded joint, were also welded. In this case, a gap between the weld edges (Figure 1, *a*) was chosen according to recommendations [7].

Macrosections of welded specimens for the CTOD tests with different schemes of formation of a notch are shown in Figure 3. Specimens with IRFP were bend tested using the same procedure as specimens with mechanical notches according to the recommendations of British Standard BS5762–79 and procedure [8]. In this case, the COD tests were carried out at a controlled and relatively low speed of rise of a load, v_c, by simultaneously fixing it and COD with an X–Y recorder. The tests were ended when the uncontrolled crack propagation was achieved and fracture took place. A set of three specimens of each welded joint at the same temperature was used for the tests. Schematics and sizes of the specimens for evaluation of CTOD are shown in Figure 2, *a*. The CTOD tests are performed by plotting the load–COD diagram. As a rule, the curves obtained correspond to one of the fracture types shown in Figure 4 [9].

Special fixture was made for tests by the CTOD procedure (Figure 5). Main components of the fixture are a load-bearing clamp and clip with a movable load bearing base, this allowing testing of specimens over a wide range of thicknesses (5–30 mm) under three-point loading. Strain gages that monitor the level of loading were attached to the surface of side plates of the load bearing clamp at points of maximal bending stresses formed in loading of a specimen. This increases the sensitivity of a strain gage and provides proportionality on coordinate y in recording the load–COD diagram. Furthermore, placing of the strain gages outside the cooling environment allows extending their service life and improving reliability in multiple tests under low temperature conditions.

Specimens of the said sizes were tested to three-point bending at a controlled loading speed (2 mm/min) and temperature of –30 to –110 °C using the hydraulic machine with a load of 300 kN, equipped with a strain intensifier, adjustable power unit and two-coordinate recording flat-bed potentiometer. A down to –70 °C temperature of the specimens was provided using a petrol solution of carbonic acid snow. Nitrogen vapours were used to cool specimens to a lower temperature. Temperature of the specimens was monitored with chromel-alumel thermocouples and millivoltmeter. Calibration temperature–stress diagram was preliminarily plotted, and temperature of the specimens was controlled during the tests on the basis of this diagram.

Three types of load–COD diagrams, i.e. A, C and E, were fixed during the tests (Figure 4). At a tem-

Chemical composition of steels under investigation

Steel grade	C	Mn	Si	Ni	S	P	V	Nb	Al	C_{eq}
X60	0.12	1.60	0.48	0.20	0.01	0.025	0.08	0.06	0.01	0.42
17G1S	0.18	1.48	0.39	0.10	0.03	0.022	–	–	–	0.43

Note. C_{eq} was determined by using the International Institute of Welding formula.

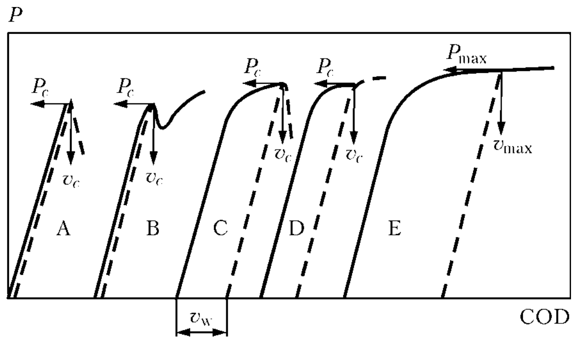

Figure 4. Types of load–COD diagrams: P_c — critical load

perature of −70 °C, specimens with an artificial notch fractured by the C and E type, and specimens with IRFP — by the A type. When temperature was decreased to −90 °C, the 17G1S steel specimens with a mechanical notch fractured by the A type, and the X60 specimens — by the C type. At −110 °C, all the specimens fractured by the A type.

At a temperature increased to −50 °C or higher, specimens with IRFP fractured by the C type. Curves of variation in δ_c for specimens of the investigated steels versus test temperature and type of notch in HAZ were plotted on the basis of minimal values of δ_c (Figure 6). It can be seen from the Figure that the scheme of making a notch by the mechanical method in the coarse-grained region of HAZ does not affect CTOD. Comparative evaluation of brittle fracture resistance of the HAZ metal can and must be performed on specimens made by the simplest and least labour-consuming procedure described in study [7], according to which it is possible to evaluate HAZ of any type of the welded joints produced by different welding methods. Specimens with IRFP have a much lower CTOD value than specimens with an artificial (mechanical) notch tested at a temperature of −70 °C, this value reaching that of the specimens with a notch at a higher (−40 °C) test temperature.

The X60 steel specimens with an artificial notch have a sufficiently high CTOD value (0.22–0.31 mm) within a range of −70 to −80 °C, whereas the 17G1S steel specimens have a much lower CTOD value, $\delta_c \approx$ $\approx$ 0.1 mm at −80 °C. At a temperature decreased to −110 °C, different steel specimens with an artificial notch have almost identical (minimal) CTOD values in HAZ of the welded joints. Using the material evaluation criteria ($\delta_c \approx 0.12$ mm) given in study [8], it can be assumed that the HAZ metal (coarse-grained region) of the X60 steel welded joints will have a brittle fracture at a temperature below −90 °C, and that of the 17G1S welded joints — at a higher temperature (−80 °C). Using the CTOD values obtained on specimens with IRFP, we can see that the temperature range of brittle fracture of the said zone regions is below −60 and −45 °C for steels X60 and 17G1S, respectively.

Comparison of the temperature dependencies of δ_c in HAZ of the welded joints on steels X60 and 17G1S (tensile strength 540–600 MPa), derived on specimens with IRFP and artificial notch, showed that for steels of the investigated grades both dependencies corresponded to each other very well. However, the δ_c values of specimens with IRFP were much lower, and the threshold of brittle fracture of HAZ shifted towards the positive temperature by 30–35 °C, compared with specimens with an artificial notch in HAZ. This can be explained by the following reasons. Firstly, tip of a natural notch in specimens with IRFP is on the fusion line, therefore, it should be sharper compared with specimens with the artificial notch; secondly, concentration of plastic strains and residual stresses takes place at the notch tip during welding. Hence, it can be concluded that for an accurate and

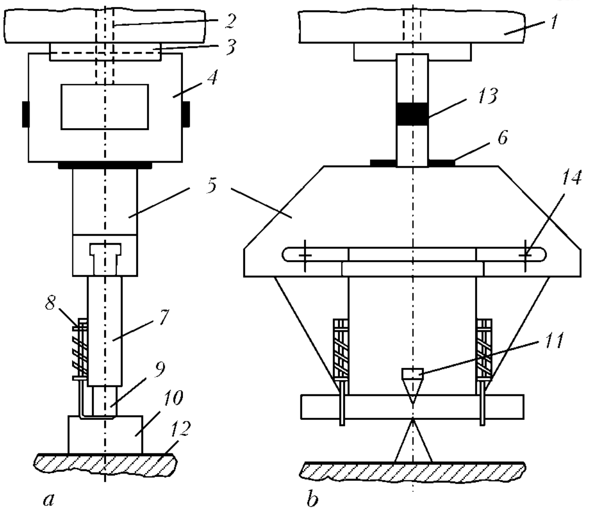

Figure 5. Schematic of fixture for testing specimens by the CTOD procedure: *1* — upper cross-arm; *2* — fixing rod; *3* — bearing foot; *4* — load-bearing clamp; *5* — clip with movable bearings; *6* — heat insulating gasket; *8* — hold-down; *9* — specimen; *10* — fixed bearing; *11* — COD sensor; *12* — testing machine platform; *13* — load sensor; *14* — retainer

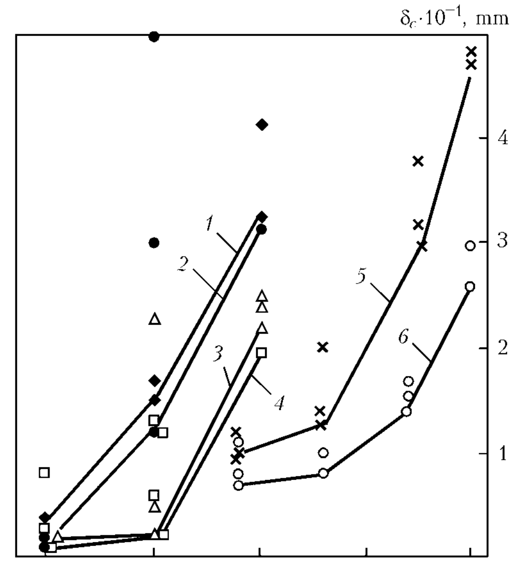

Figure 6. CTOD versus test temperature and notch type in HAZ of X60 (*1, 2, 5*) and 17G1S (*3, 4, 6*) steel specimens: *1, 3* — notch parallel to fusion interface; *2, 4* — notch normal to fusion interface; *5, 6* — specimens with IRFP

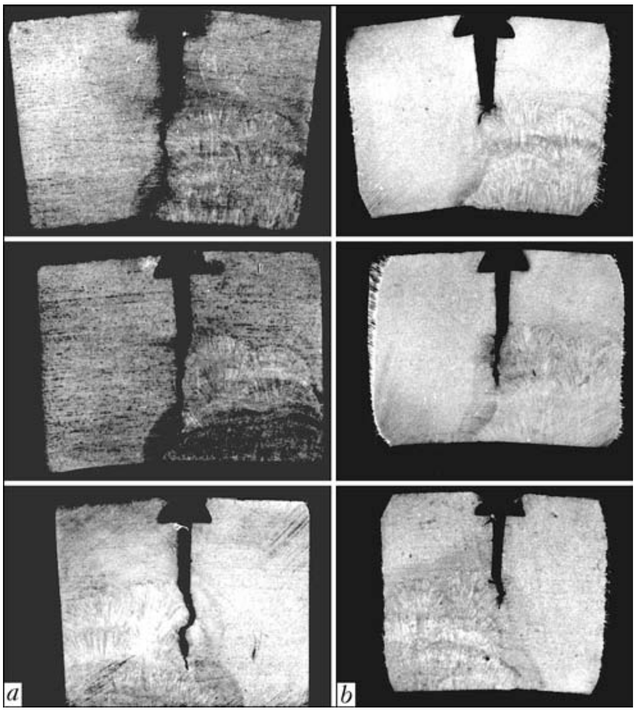

Figure 7. Character of fractures of 17G1S (*a*) and X60 (*b*) steel specimens

reliable evaluation of resistance of a welded joint to brittle fracture the notch tip should be located in a coarse-grained region of HAZ. However, such a notch is hard to make by the mechanical method. Specimens with IRFP make it possible to simply and reliably obtain the required characteristics, as in this case the natural notch tip is located exactly on the fusion interface. The δ_c values of specimens with IRFP can be used to determine permissible sizes of crack-like defects in the welded joints by the calculation method, according to [10]. At the same time, as shown by investigations, satisfactory results in determination of fracture toughness can be obtained by carefully marking and accurately making an artificial notch in the required region of HAZ. However, it should be noted that the temperature range of tough fracture widens towards decrease in temperature by 30–35 °C.

The δ_c criterion, whose values are 0.20–0.25 mm (the latter value applies to welds), has been used abroad for quite a long time in design critical structures to establish requirements to toughness of metal and welded joints. Imposing higher requirements to welded joints is attributable to the probability of appearance of additional factors, such as a higher probability of formation of defects in the joints, compared to base metal [11].

Considering the above specification levels of crack resistance of the welded joints, it can be concluded that the range of tough fracture of the HAZ metal on steel X60 is above −45 °C, and that on steel 17G1S — above −30 °C. As the lowest temperature for northern gas pipelines [12] is only −15 °C (for oil pipelines even higher), the said steels can be recommended for manufacture of repair sleeves and split welded T-joints [13, 14]. At the same time, steel X60 allows reducing the probability of brittle fracture of the welded joints, which seems to be related to metallurgical peculiarities of melting and rolling.

Sections were cut out to investigate the character of crack propagation and microstructure of individual regions of the welded joints on specimens with IRFP. As indicated by analysis, cracks propagate mostly along the fusion interface in a coarse-grained region (Figure 7, *a*), and in some cases they initiate in the coarse-grained region and propagate to the weld metal. It should be noted that cases of propagation of cracks into the weld metal of both 17G1S and X60 steel welded joints were fixed at the lowest test temperature (−75 °C). Apparently, this is related to substantial embrittlement of the weld metal and metal of the coarse-grained region. Moreover, cracks in specimens of steel 17G1S propagate to a lower depth than in specimens of steel X60. Figure 8 shows a typical picture of crack propagations in specimens of steel 17G1S with IRFP. Investigations of structure of the welded joint metal showed the following. Structure of the base metal was ferritic-pearlitic in all the cases. Hardness of steel 17G1S was *HV* 190, and hardness of steel X60 was *HV* 170. The weld metal of a welded joint was a cast mixture of hypoeutectoid ferrite, pearlite and regions of bainite. Structure of the HAZ metal in the overheated region (coarse-grained) on steel X60 was bainitic-pearlitic with hypoeutectoid ferrite precipitated mostly along the grain boundaries, and that on steel 17G1S consisted mainly of upper bainite, acicular ferrite and an insignificant portion of pearlite and hypoeutectoid ferrite.

Investigations of the character of propagation of cracks showed that the latter propagated primarily

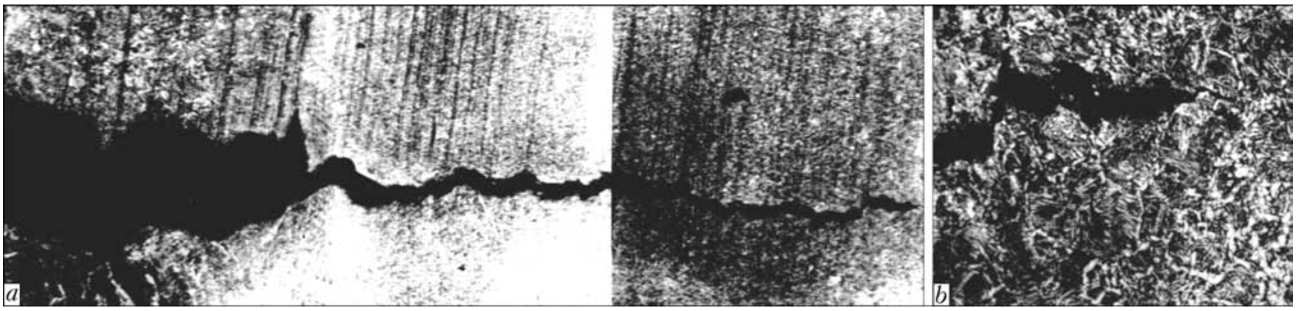

Figure 8. Panoramic view of typical propagation of cracks in 17G1S specimen with IRFP (*a* — ×63), and fragments of crack in its arrest region (*b* — ×200)

through the regions of upper bainite and acicular ferrite, and in rare cases — through the regions of hypoeutectoid ferrite. As a rule, the cracks stopped in the zones of locations of tough components.

At the same time, investigations were carried out to study peculiarities of fracture of the HAZ metal in specimens with an artificial notch by the common procedure using electron microscopes JEM-120 and JEM-200CX.

The X60 steel specimens tested at a temperature of −70 °C were characterised by a tough type of fracture. The fracture surface was mainly of a cellular type with a high degree of plastic flow prior to the fracture. Fracture centres initiated in a region of coarse phase precipitates. The regions of tough fracture, having a lower degree of plastic flow prior to the fracture (flatter facets), and regions of intergranular fracture could also be seen. The intergranular character of fracture is indicative of embrittlement in some regions of the grain boundaries. Fracture of a 17G1S steel specimen also had a tough character. However, boundaries of the tearing facets indicate to a lower degree of plastic flow prior to the fracture. Brittle fracture zones (lath pattern) were also detected. However, their share was insignificant.

Fractures of the 17G1S steel specimens at a test temperature of −90 °C were mostly of a tough character with flat facets or facets with a higher plastic flow prior to the fracture. Regions of a quasi-tough and brittle fracture were detected. Similar tests of specimens of the X60 steel welded joints showed that their fracture surface in HAZ had a tougher character of fracture, compared to the 17G1S steel welded joints, which is in agreement with data of mechanical tests of specimens of the investigated grades of steels. Tough fracture with a substantial plastic flow prior to the fracture took place both in the bulk and along the boundaries of grains.

Fractographic examinations of fractures of the 17G1S steel specimens at a temperature of −110 °C showed that fracture was mostly of a brittle character with clearly defined lath pattern and tearing ridges. It should be noted that intercrystalline fracture most often takes place at the above temperature. The fracture character of the X60 steel specimens was the same as that of the 17G1S steel specimens tested at the same temperature. Fractures occurring because of brittle cleavage and an insignificant share of the quasi-tough fracture regions were also detected. Given that fractures in HAZ of the welded joints on the investigated steels at a test temperature of −110 °C were identical, it can be concluded that the effect of alloying elements on fracture toughness is levelled at a low test temperature.

Fractures of specimens with mechanical notches made normal and parallel to the fusion interface were also investigated. Based on the results of fractographic examinations, the character of fracture of the welded joints was found to be identical even with different schemes used to make a notch in the coarse-grained region of HAZ. It was established that the δ_c values do not depend upon the method for making of a mechanical notch, and are considered reliable if the notch tip is at a distance of no more than 0.3 mm from the fusion interafce.

Metallographic examinations fully confirmed the CTOD test results. Temperature dependencies of δ_c of the HAZ metal of welded joints on the steels investigated, derived on specimens with IRFP and artificial (mechanical) notch, were in good agreement with each other. In this case, resistance of metal in the coarse-grained region of HAZ was higher for steel X60, compared with steel 17G1S.

Therefore, the simplest and least labour-consuming procedure for making a mechanical notch in HAZ is that at an angle to the fusion interface, which allows evaluation of brittle fracture resistance of the HAZ metal of the welded joints made over a wide range of welding heat inputs, compared with the deposited and base metal.

The CTOD values in testing of specimens with IRFP and mechanical notch show good correlation. However, in the first case the brittle fracture threshold shifted towards a positive temperature by 30–35 °C. This should be taken into account in defining a temperature range of brittle fracture of the HAZ metal by the results of testing of specimens with a mechanical notch.

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