FRACTURE TOUGHNESS OF WELDED JOINTS UNDER STATIC AND DYNAMIC LOADING

V.I. KIR'YAN

E.O. Paton Electric Welding Institute,
Academy of Sciences of Ukraine,
11 Bozhenko Str., 252650. Kiev, Ukraine

ABSTRACT

The *COD* criterion of non-linear fracture mechanics is used as a basis to assess the fracture resistance of welded joints on high-toughness low-alloyed steels of X70 grade with the crack tip located in various zones. The observed considerable scatter of fracture toughness (COD_c at the stage of the crack transition into the unstable state) of the welded joint zones near the fusion line is considered in connection with the crack propagation features. A criterion is proposed for assessment of the welded joint compliance to the requirements made. Studied is the effect of the loading rate varying in a broad range (10^{-5}...120 m / s).

KEYWORDS

Welded joint, fracture toughness, crack opening displacement, inhomogeneity of properties, static loading, dynamic loading, transition temperature, probability, requirements.

INTRODUCTION

In welded metal structures for even very critical applications (high pressure vessels, line gas and oil pipelines) it is not possible to completely eliminate the cracklike defects, despite the stringent requirements to their admissibility in specifications and codes. Therefore, in the assessment of the fitness for purpose of such structures one of the determinant governing properties at their fabrication stage is the fracture toughness of welded joints. The required level of fracture toughness should guarantee the reliable performance of the structure with inherent most probable defects the maximum sizes of which are determined by statistical analysis of defects formed in welding and detected by the used NDT methods of quality control.

The assessment of the fracture toughness of the actual welded joints on the basis of the fracture mechanics criteria meets with certain complications in the interpretation and practical use of the derived results. They are caused by the essential scatter of the fracture toughness of metal adjacent to the fusion line because of the structural and mechanical heterogeneity of the properties of various welded joint zones (see Otsuka et al, 1978; Toyoda and Satoh, 1984; Toyoda, 1989; Zemzin and Boikova, 1982). The higher the fracture resistance of the steel being welded, the greater is the scatter of fracture toughness of the welded joint zones near the fusion line.

The purpose of the present paper consists in determining the fracture resistance of welded joints on the high-toughness low-alloyed steels (KCV >130 J) with the crack tip located in various zones and selection of the criterion for assessment of the compliance of the welded joint fracture toughness to the specified requirements.

FRACTURE TOUGHNESS OF WELDED JOINTS UNDER STATIC LOADING

Studies were performed on 1420 mm dia. pipes of low-allolyed steels of X70 grade, whose composition and mechanical properties are given in Tables 1 and 2, respectively.

Table 1. Composition

Steel	Mass fraction x 10, %									
	C	Mn	Si	P	S	V	Ti	Nb	B	Ni	Mo
A	0.8	17	4.4	0.19	0.04	1.0	0.3	0.3		1.1	1.0
B	0.7	15	4.4	0.16	0.03	0.5	0.4	0.3	0.01	3.3	2.7

Table 2. Mechanical properties

Steel	$\sigma_{0.2}$ MPa	σ_b MPa	δ_5 %	ψ %	δ_i mm	KCV (J) at 293K	253K	233K	213K
A	601	663	19.2	34.4	0.20/0.21*	130	110/80*	79	70
B	570	665	20.2	35.0	0.22/0.22*	153	115/92*	109	82
*	The data for the weld metal								

Assessment of the critical *COD* (COD_c) with the crack tip located in various zones of the welded joint was carried out on the samples with BxB cross-section (B is the pipe wall thickness) tested under the conditions of three-point bending (Fig. 1). The *COD* value at various stages of fracture was calculated by the measured displacements of the crack edges in two cross-sections (V_1 is at 2...3 mm distance from the crack tip, V_2 is on the specimen surface) according to the $COD = (V_1\ a_2 - V_2\ a_1)\ /\ (a_2 - a_1)$ dependence. During testing the diagrams of the specimen deformation in time ($P, V_1, V_2 - \tau$) were recorded besides the $P - V_1$ and $P - V_2$ diagrams, it permitting to reliably record the pop-ins during crack initiation in the local brittle zones (LBZ) of the welded joint. The temperature dependences of the weld metal fracture toughness (WM, zone 1) and

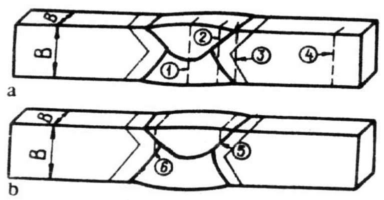


Fig.1. Studied zones of the welded joints (1-6) in case of fracture propaga-tion along the weld (a) and through the thickness (b).

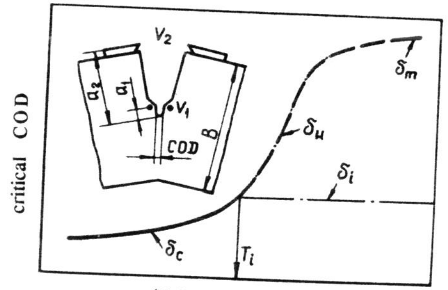


Fig. 2. Nature of temperature dependence of the fracture toughness of WM (zone 1) and BM (zone 4).

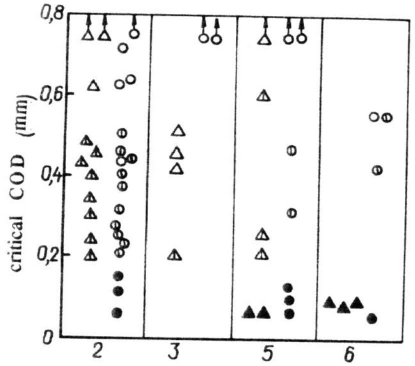
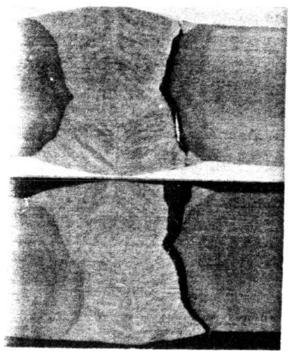


Fig. 3. Welded joint fracture toughness with the crack tip location in the zones 2, 3, 5 and 6 (T = 253 K): ●,◑,O - Steel A; ▲, ◭ ,Δ - steel B; ●,▲ - δ_c ; ◑,◭ - δ_u; O,Δ - δ_m

base metal (BM, zone 4) including the stages of brittle, quasibrittle and tough state are qualitatively identical and are schematically shown in Fig. 2. Designation of the critical *COD* by the δ_c , δ_i , δ_u and δ_m symbols corresponds to the British standard BS 5762:79. The downward arrow indicates the temperature of transition from the quasi-brittle fracture to the tough initiation of a crack T_i . The fracture toughness of other welded joint zones (2, 5, 6) adjacent to the fusion line, depends on many factors. Besides the frcture toughness levels and temperatures of transition to the T_i tough state of individual zones through which the crack front passes, which are determined by the welding method and conditions, the welded joint fracture resistance is essentially affected also by the orientation of the crack plane relative to the fusion line. When the crack front is in one of the mentioned zones, the welded joint fracture toughness at the stage of the crack transition to the unstable state varies in a broad range (Fig. 3). Thus, for instance, for zone 2 (steel A) COD_c = 0.06...0.83 mm. Such a scatter of fracture toughness is connected with the different crack propagation paths and resulting different ratios of the dimensions of the areas of brittle, quasi-brittle and tough fracture modes. The lowest values of COD_c correspond to the fracture initiation in the local brittle zone (LBZ) of the welded joint, crossed by the crack front, and its propagation along the fusion line (Fig. 4, a). When the crack propagates in the WM and the heat-affected zone (HAZ) areas, different kinds of fracture (brittle, tough, mixed) can occur when *COD* values δ_c, δ_u and δ_m are reached.

The scatter of the welded joint fracture toughness with the crack front located in the zones 5 and 6 (see Fig. 1 and 3) is also connected with the change of the fracture trajectory, and

a



b

Fig. 4. Fracture propagation along the fusion line: a - zone 2, b - zone 5.

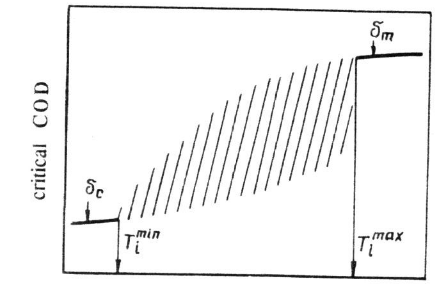


Fig. 5. Temperature dependence of welded joint fracture toughness.

the minimum COD_c values are achieved in case of crack propagation along the fusion line (Fig. 4, b). An important factor here is the distance from the crack plane to the point of crossing of the fusion lines of the first and second weld.

Generalizing the derived results, the temperature dependence of fracture toughness of the welded joint zones near the fusion line can be schematically represented in the form shown in Fig. 5. At temperature below T_i^{min} the welded joint fails in the brittle or quasibrittle mode irrespective of the tip location and crack plane orientation, and its fracture toughness is determined by the value δ_c. In a broad temperature range of $T_i^{min} ... T_i^{max}$ (COD_c scatter zone) the critical COD can take the values δ_c, δ_u or δ_m, depending on the change of the failure mode. At the temperature above T_i^{max} the welded joint fracture mode is completely tough, and is characterized by the values δ_i and δ_m. The T_i^{min} and T_i^{max} vales depend on the minimum and maximum transtion temperatures of metal of individual zones of the welded joint.

ASSESSMENT OF THE WELDED JOINT FRACTURE TOUGHNESS COMPLIANCE TO THE SPECIFIED REQUIREMENTS

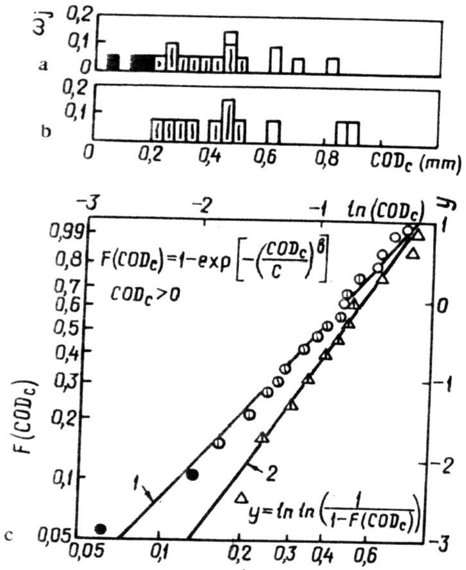


Fig. 6. Experimental histograms (a,b) and COD_c distribution functions (c): 1 - steel A, 2 - steel B.

The welded structures of the considered class of high-toughnes structural steels are used, as a rule, in the temperature range of $T_i^{min} ... T_i^{max}$. It is accounted for by its considerable extension because of the considerable difference in the transiton temperatures T_i for BM (<213K) and LBZ metal (>253K). The selection of the zones and orientation of the initial crack plane for determination of the welded joint fracture toughness to forecast its load-carrying capacity in service should be based on the data on the stress-strain state, defectiveness of welds and LBZ. Among the considered HAZ zones 2, 5 and 6, zone 2 should be singled out, in which the crackfront crosses the WM and HAZ, it allowing to perform an intgral assessment of the welded joint fracture toughness allowing for the entire range of the critical COD change (δ_c, δ_u, δ_m). The present investigations and the earlier work by Satoh and Toyoda (1984) has shown that the critical COD is a random value, characterized by the Weibull probability distribution

$$F(COD_c) = 1 - \exp[-(COD_c/C)^b], \quad COD_c > 0 . \tag{1}$$

Fig. 6 gives an experimental histogram (dependence of $w_j = n_i / n$ frequency on the critical COD, where n_i is the number of times the critical COD falls into the jth interval of partition, n is the number of specimens tested) and emphirical function of distribution (of a point) in comparison with the calculated one (straight lines 1 and 2) for zone 2 at the temperature of 253 K.

As the increase of the critical COD (δ_c, δ_u, δ_m) is accompanied by the change of the fracture mode from the brittle to the completely tough one, it is proposed to use the $COD_c > COD^*$ inequality fulfilled with the probability P as the criterion of the welded joint fracture toughness compliance to the specified requirements. The levels of probability P and of the required fracture toughness COD^* are determined proceeding from the service conditions, posibility of welded joint quality control, degree of structure criticality, consequences of fracture, etc. Proceeding from (1) the probability with which the welded joint fracture toughness COD_c exceeds COD^* is determined from the expression:

$$P = \exp[-(COD^*/C)^b], \tag{2}$$

$$COD^* = C[-\ln(P)]^{1/b}. \tag{3}$$

For the experimental data in Fig. 6 represented by the curves 1 (b = 0.62; c = 0.458) and 2 (b = 2.07; c = 0.545), with the probability 0.9 the critical COD is greater than 0.11 and 0.18 mm, respectively. It is rational to use such a probabilistic approach in practical studies when selecting steels, welding consumables and welding conditions, as well as in the fabrication of structures for periodical control of the welded joint quality.

WELDED JOINT FRACTURE TOUGHNESS UNDER SINGLE DYNAMIC LOADING

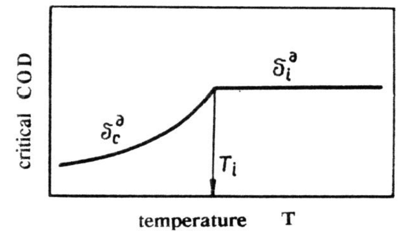


Fig. 7. Typical temperature dependence of fracture toughness at the crack initiation stage under single dynamic loading.

Besides other factors the metal high-rate deformation process itself can produce a rather essential effect on metal fracture resistance. Here, the level of fracture toughness is predetermined by the change (depending on the loading rate) of the metal mechanical properties in the crack initiation region and of the conditions of plastic deformation development in the micro- and macrovolumes. Therefore, it is important that the dynamic tests of laboratory specimens conducted to determine the fracture toughness simulate the metal performance conditions in actual structures, connected with high-rate deformation. The rate of COD ($\dot{\delta}$) change and the associated with it a rate of local plastic deformation on the blunted crack tip contour $\dot{\varepsilon}$ can be used as the reliable parameters determining the conditions of material deformation in the crack intiation region. The procedure of determining the critical COD value at the stage of brittle, quasi-brittle and tough fracture initiation, calculation of the $\dot{\delta}$ and $\dot{\varepsilon}$ rates, as well as the results of studying the dynamic fracture toughness are given in the works by Kir'yan, 1985, Kir'yan and Shamanovskii, 1988; Kir'yan et al., 1993.

Under the conditions of single application of dynamic loading the fractographic features of fracture of the welded joint zones near the fusion line are identical to those at static testing. However, in this case it is reliable to use the fracture toughness at the crack initiation stage δ_c^d and δ_i^d (Fig. 7) as the controlling parameter determining the load-carrying capacity of the welded joint. The quasibrittle to tough fracture transition temperature T_i is one of the material pro-perties which are the most sensitive to loading rate, it being of principal importance for solving practical tasks. In the semi-logarithmic system of coordinates there exists a linear dependence between the transition temperature T_i and rate parameters $\dot{\delta}$, $\dot{\varepsilon}$.

In the tough state ($T > T_i$) the metal resistance to crack initiation δ_i^d is practically insensitive to loading rate.

CONCLUSION

The considerable scatter of fracture toughness (COD_c at the stage of the crack transition into the unstable state) of welded joint zones near the fusion line is connected with the different paths of the crack propagation and the resulting different ratios of the sizes of areas of the brittle, quasibrittle and tough fractures. The lowest values of the critical *COD* are achieved with the fracture initiation in the local brittle zone crossed by the crack front and its propagation along the fusion line. Such a scatter of COD_c (δ_c , δ_u and δ_m) accompanied by the change of the failure mode occurs in a broad temperature range of $T_i^{min}...T_i^{max}$, notwithstanding the sufficiently high and not so essentialy different values of the base metal and weld metal fracture toughness. Its extension is determined by the minimum and maximum transition temperatures of the metal of individual zones of the welded joint. Studies have shown that the changes of critical *COD* are governed by the Weibull exponential law of probability distribution.

It is proposed to assess the compliance of the welded joint fracture toughness COD_c to the specified COD^* requirements by the results of determining the critical *COD* of the zone adjacent to the fusion line, proceeding from the $COD_c > COD^*$ inequality fulfilled with the specified propability *P*.

Under the single dynamic application of load it is reliable to use the fracture toughness at the crack initiation stage as the controlled parameter determining the load-carrying capacity of the welded joint. The quasibrittle to brittle fracture transition temperature T_i is linearly connected with the loading rate logarithm. The metal resistance to tough fracture initiation δ_i^d is insensitive to the deformation rate.

REFERENCES

Kir'yan V.I. (1985). Calculation of local plastic deformation in the tip of the cracklike defect. Avtomat. svarka, N 4, P.6-9.

Kir'yan V.I., Shamanovskii S.V. (1988). Procedure of assessment of the material and welded joint resistance to crack initiation under dynamic loading. Avtomat. svarka, N 5, P.16-20.

Kir'yan V.I., Vashchenko A.P., Volgin L.A., Shamanovskii S.V. (1993). Assessment of structural steel fracture toughness under high-rate deformation conditions. Problemi prochnosti, N 5.

Otsuka A., Miyata T., Nishimura S., Uozato S., Inoue K., Ebara R. (1978). Fracture Toughness Evaluation of Welds from the Crack Tip Opening Behaviour Leading to Fracture Initiation. In: Criteria for Preventing Service Failure in Welded Structures (The Third International Symposium of the Japan Welding Society, September, Tokyo). P.161-166.

Satoh K., Toyoda M. (1984). A probabilistic approach to evaluation of fracture toughness of welds with heterogeneity. IIW DOC-1064-84. P.24.

Toyoda M., Satoh K. (1984). Fracture toughness of welds: The incidence of mechanical heterogeneity in the correlation of toughness parameters. Welding in the World,. Vol 22, N 3/4, P.76-87.

Toyoda M. (1989). Fracture toughness evaluation of steel welds (Review Part I). IIW Doc.-1191-89. P.175.

Zemzin V.N., Boikova K.I. (1982). Crack resistance of welded joints of dissimilar steels. Part I. The effect of mechanical heterogeneity of the welded joint. Svarochnoje proizvodstvo, N 5, P.4-7.