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RELATION BETWEEN DYNAMIC FRACTURE TOUGHNESS, IMPACT RESISTANCE KCV AND STRUCTURE OF SELECTED FRICTIONALLY WELDED JOINTS

One of important resistance parameters introduced into engineering calculations for selection of materials and evaluation of their operating properties is material crack resistance. Contrary to the stationary fracture toughness K_{Ic}, J_{Ic}, the dynamic fracture toughness K_{Id}, J_{Id}, a_d is also an important parameter. In this paper, the authors have evaluated the relation between the parameters of the dynamical fractures toughness and the structure as well as impact resistance in chosen frictionally welded joints. The above-mentioned joints are made of the following steel parts: N9E-45, 18G2A-St3S, St3S-45, 40H-45, 18G2A-40H. In this experiment, the instrumented bending impact test was used.

1. Introduction

Evaluation of material brittleness or its plasticity using tension, bending and torsion test results appears to be insufficient for many fields of engineering and for qualification societies [1], [2]. In particular such evaluation is insignificant for steel used in welded constructions [3], [4]. Joining metals, i.e. bonding and welding creates favourable metallurgical and stress conditions for the material brittle fracture, i.e. immediate ductile-to-brittle stage transitions. Additional factors enhancing this phenomenon are:

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multiaxial stress state, temperature, operating conditions, welding technology as well as impact loads that affect these materials, especially when they are used for making tools [4], [5], [6].

At present, frictionally welded metal joints are widely used in the tool industry. Frictional welding is also applied for saving metal resources, because some parts can be frictionally welded of a few smaller parts (segments) together.

Material fracture toughness evaluation using fracture mechanics for stationary loads is quite well known at present and a number of norms has already been elaborated for it (PN-EN ISO 12737: 2001, PN-91/H-04336).

From among existing experimental parameter determination methods of the dynamic fracture toughness K_{Id}, J_{Id}, an application of an instrumented bending impact test seems promising and prospective for evaluation of these parameters [7], [8], [9]. This opinion has been confirmed by an increase in interest in application of these tests in Poland and abroad in the aspect of using the criteria of fracture mechanics [10], [11], [12]. Especially, there is a lack of data concerning determination of dynamic fracture resistance and its changes in non-homogeneous materials such as frictionally welded joints. In this work, the authors analyse dynamic changes evaluation of the fracture toughness for selected frictionally welded joints compared to their structure and impact resistance KCV.

2. Test methodology and materials for tests

Evaluation of parameters of the dynamic fracture toughness J_{Id} of the tested frictionally welded joints was realized using the instrumented computerized impact hammer Psd 150/300 assembled in The Foundry Institute in Cracow. A description of this hammer was presented in [13], [14].

During impact bending test this system allows for making records of the registered graphs of such quantities as: force-time F(t), force-deflection F(f), and deflection-time f(t). The computer program FRACDYNA [14], [15] was used for processing the registered graphs.

The frictionally welded joints that are most often used for various tools and construction systems have been selected for evaluation of fracture toughness parameter changes and fracture process. The welded joints accepted for the tests were made using the frictional welder ZT4-13 by welding together steel shafts ϕ32x120 mm of various kinds of steel. The welding parameters are shown in Table 1.

Table 1

Frictional welding parameters selected for welded joint tests

Frictional welding parameters accepted for welded joint tests						
No.	Welded system	Speed of rotation, rad/s	Friction force, N	Friction time, s	Upset force, N	Upset time, s
1	18G2A-St3S	152	40000	25	45000	3,0
2	N9E-45	152	45000	18	50000	2,5
3	St3S-45	152	40000	16	50000	2,5
4	40H-45	152	50000	22	50000	3,0
5	18G2A-40H	152	45000	18	50000	2,5

These parameters were selected on the basis of available literature [4], [16] and initial fatigue tension tests R_m of the joints that were made in accordance with the Polish Standard PN-EN10002-1: 1998.

The impact resistance specimens were cut out off the welded joints. On these specimens, the notches were made according to PN for resistance evaluation KCV and for dynamic fracture toughness J_{Id} evaluation. A notch with a fatigue crack was made according to ASTM-E [17] and BS [18]. Notches V and notches with a fatigue crack were made according to ASTM-E [17] hardness changes in places characterized as these of an increase and a decrease in hardness on the tested joints. The cutting-out technique of the impact resistance specimens and the notching method are presented in Figure 1.

The distribution of hardness on frictionally welded joints with a notch is given in the followiong part of this paper. All tests of joints were performed at room temperature 293 K. The striking velocity v of the impact hammer at a fracture of the specimens with a notch was 3,5 m/s, and at a fracture of specimens with a notch deepened by a fatigue crack was 2 m/s.

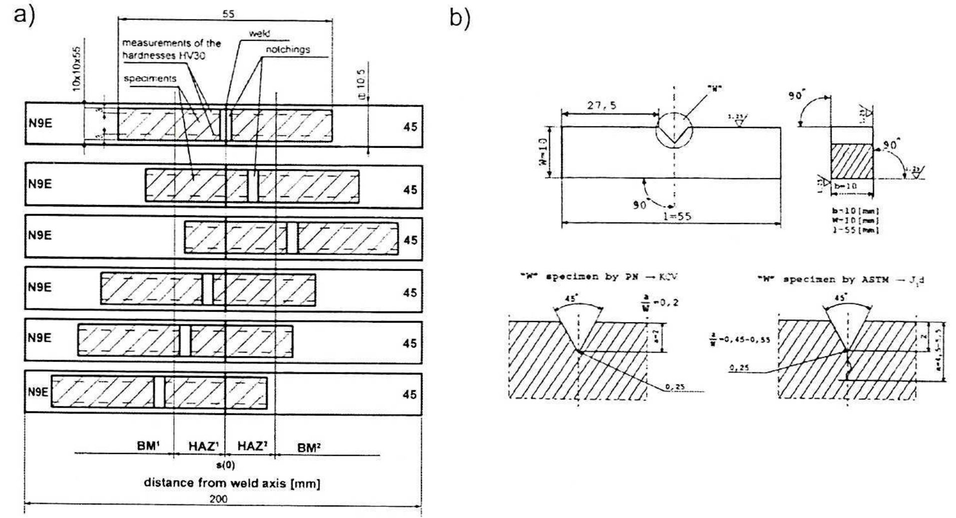

Fig. 1. The cutting-out technique of impact resistance specimens for tests for the dynamical fracture toughness J_{Id} and the impact resistance KCV on the frictionally welded joints: a) cutting-out technique of specimens and the location of the notch, b) method of notching

A relatively precise and applicable compliance change method ΔC/C of an impact bent specimen [14], [15] was applied as an evolution method of the crack initiation point which allows for calculations of the parameter J_{Id}. The compliance changing rate is defined as:

$$\Delta C / C = (C - C_e) / C_e , \tag{1}$$

where: ΔC/C – compliance changing rate,
C – secant compliance, mm/N,
C_e – elastic compliance, mm/N.

As ΔC/C against the deflection is plotted, a sudden transition point of the gradient appears on the plot of ΔC/C, as it is schematically shown in Figure 2.

In the zone of plastic deformation, one can observe steady increase in ΔC/C that depends on the factor of material consolidation. When the gap enlarges (increase in crack start point), then ΔC/C significantly increases, too. As the cross-section of a specimen fracture decreases, a clear point of inflexion (change in the slope direction) appears in the ΔC/C characteristic. This point indicates the crack initiation. The inflexion point corresponds to the read-outs of the graphs F(f) and allows for determination of the value of the force at a crack initiation F_p and the energy needed for a crack initiation E_p (Fig. 2).

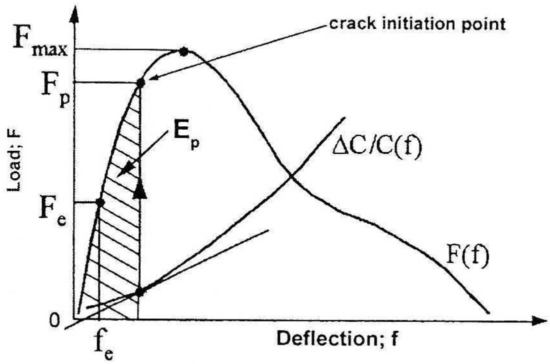

Fig. 2. Schematic explanation of the compliance changing rate method

For the calculation of the critical value of the integral of J_{Id}, the following formula (2) has been used [10]:

$$J_{Id} = \frac{2E_p}{B(w-a)}, \tag{2}$$

where: E_p – strain energy of an impact bent specimen corresponding to the area under the load-deflection characteristic in the initiation point, in Jouls,

B – thickness of the specimen, mm, w-width of the specimen, mm,

a – length of the gap in the specimen, mm.

The graphs F(t) and F(f) were taken from the characteristic places of the tested joint. These places are defined by the hardness distribution. Microstructural tests were performed in these places, too.

3. Tests results and their analysis

Figures 3–7 present a graphic set of the test results of frictionally welded joints made of such steel parts as: 18G2A-St3S, N9E-45, St3S-45, 40H-45, and 18G2A-40H. Figures on the left side present the hardness distribution on the joint and the notch incision places on the impact resistance specimens. In these figures, evaluation of KCV and the fracture toughness parameter are marked with arrows. The tests of structure were also performed. The figures on the right side present changes in parameter J_{Id} values, impact resistance KCV, and crack sensitivity coefficient U_J on the joint and HAZ (heat affected zone). The coefficient U_J on the tested joint was calculated using the following formula:

$$U_j = \frac{J_{Idr} - J_{Ids}}{J_{Idr}}, \tag{3}$$

where: J_{Idr} – critical value of the integral of J on the left-hand or right-hand side of the welded joint on the base material, (BM),

J_{ds} – critical value of the integral of J in a weld on the selected side of the welded joint in HAZ (heat affected zone).

The changes in the fracture toughness J_{Id} that are observed in the figures result from structural changes that occurred during the frictional welding process. The results prove that the welded joint made of steel parts 18G2A-St3S is characterized by quite a high value of the fracture toughness, especially on the side of 18G2A steel (Fig. 3b). The values of the parameter J_{Id} still do not exceed 140 kN/m. The lowest fracture toughness J_{Id} is observed on the tested joint in the heat affected zone (HAZ) at a distance of 2 mm from the weld on the side of 18G2A steel (100 kN/m). The maximum hardness corresponds to this zone. On the side of 18G2A steel, the fracture toughness increases with the distance from the weld axis and reaches the highest value in the case of the base steel 18G2A. The fracture toughness of the weld itself is lower than the fracture toughness of BM. Nevertheless, it is still twice as high as the fracture toughness of HAZ and BM on the side of St3S steel.

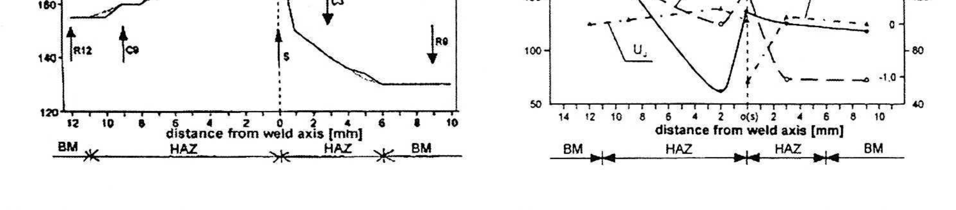

Fig. 3. Dynamic fracture toughness test results on a frictionally welded joint made of the steel parts 18G2A-St3S: a) hardness distribution on the joint and in notch incision places, b) characteristics of changes of J_{Id}, KCV, U_J on the joint

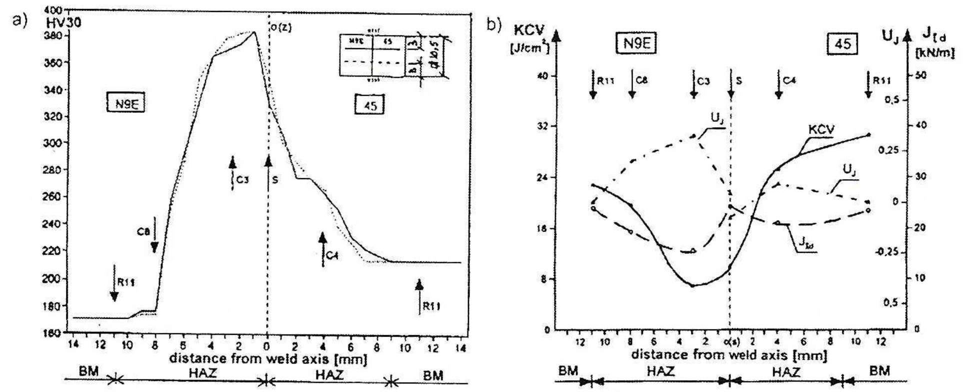

Fig. 4. Dynamic fracture toughness test results on a frictionally welded joint made of the steel parts N9E-45: a) hardness distribution on the joint and in notch incision places, b) characteristics of changes of J_{Id}, KCV, U_J on the joint

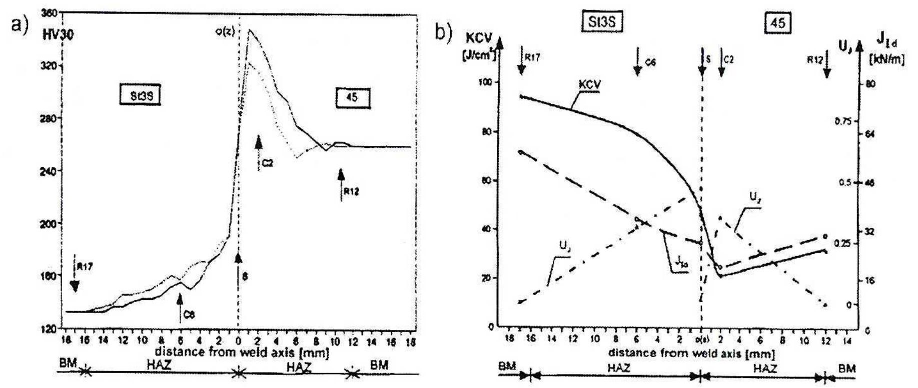

Fig. 5. Dynamic fracture toughness test results on a frictionally welded joint made of the steel parts St3S-45 a) hardness distribution on the joint and notch incision places, b) characteristics of changes of J_{Id}, KCV, U_J on the joint

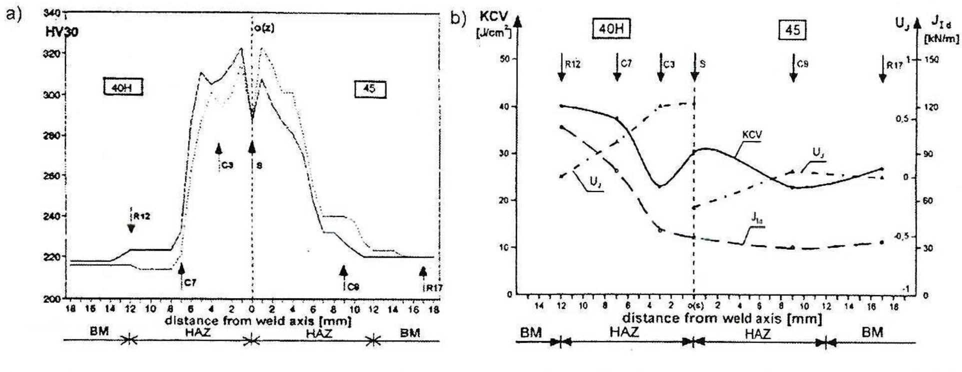

Fig. 6. Dynamic fracture toughness test results on a frictionally welded joint made of the steel parts 40H-45 a) hardness distribution on the joint and in notch incision places, b) characteristics of changes of J_{Id}, KCV, U_J on the joint

The test of structure on the joint 18G2A-St3S (Fig. 8) that is performed in characteristic places (notch incisions) allows for explaining the observed fracture toughness J_{Id} changes using a qualitative analysis of phenomena on the tested joint and in its zones.

The occurrence of the local maximum of impact resistance KCV and the fracture toughness J_{Id} inside the weld may be attributed to fragmentation of austenite grains as a result of plastic strain in this zone (Fig. 8a). The decrease in parameter values on the side of 18G2A steel at a distance of 2 mm from the weld (HAZ) can be attributed mainly to the occurrence of a certain amount of non-eutectoidal structure, most probably of bainite. Thus, the maximum hardness can also be observed in this zone. The minimum value of hardness in this zone may also result from large magnitudes of austenite grains. Long ferrite needles prove this supposition. High intensity of cooling in the discussed area deep to the non-heated parts of material causes probably supersaturation of ferrite with interstitial minerals (C-N) Fig. 8b.

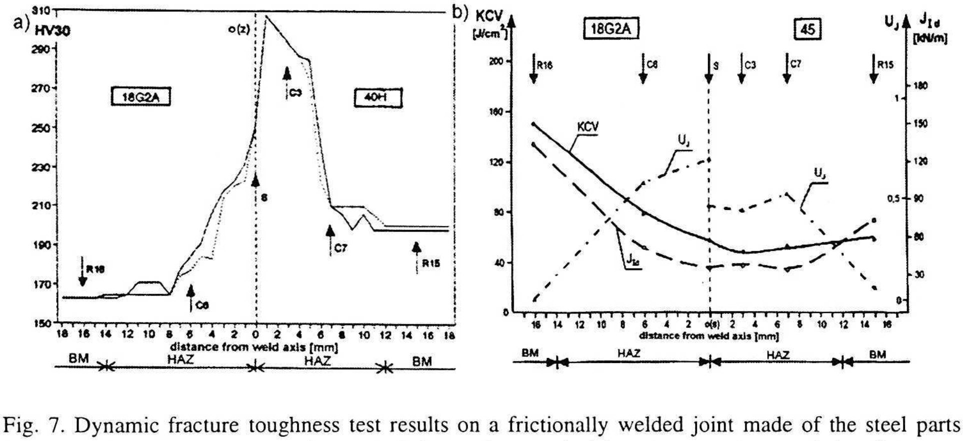

Fig. 7. Dynamic fracture toughness test results on a frictionally welded joint made of the steel parts 18G2A-40H a) hardness distribution on the joint and in notch incision places, b) characteristics of changes J_{Id}, KCV, U_J on the joint

The zone 9 mm distant from the weld (HAZ) on the side of 18G2A steel (Fig. 8c) is the zone of partial recrystalization, thus it lies between temperatures A_1 and A_3. We do not obtain here non-eutectoidal structures as a result of cooling. The structure in this zone composed of non-transformed ferrite grains, fine ferrite grains originating from austenite transformation and compact pearlite, is most probably the reason for a significant increase in the crack parameter J_{Id} compared to the zone 12 mm distant from the weld.

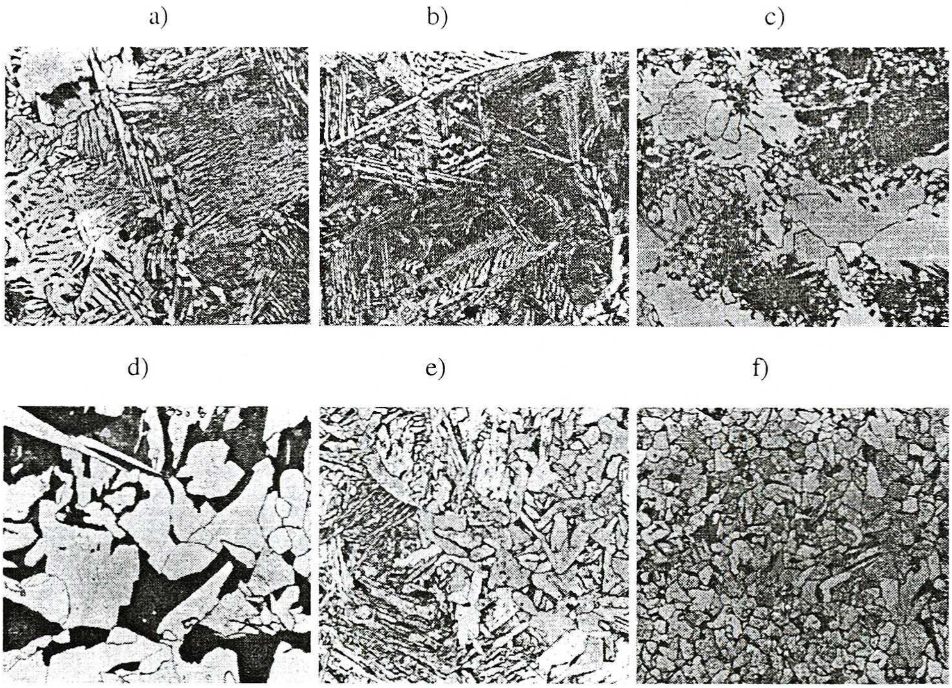

Fig. 8. Microstructure of frictionally welded joint made of steel parts 18G2A-St3S (250 times magnified) a) along the weld axis, b) at a distance of 2 mm from the weld on the side of 18G2A steel (HAZ), c) at a distance of 9mm from the weld on the side of 18G2A steel (HAZ), d) at a distance of 12 mm from the weld on the side of 18G2A steel (BM), e) at a distance of 3 mm from the weld on the side of St3S steel (HAZ), f) at a distance of 9 mm from the side of St3S (BM) steel

In the zone 12 mm distant on the side of the 18G2A steel (BM) there are no signs of transformation process. The majority of ferrite grains is equiaxial and together with relatively uniformly distributed pearlite supports a progressive increase in the fracture toughness parameter J_{Id} (Fig. 8d). The structure of St3S steel in close proximity of the weld (Fig. 8e) is created by fine needle ferrite grains most often forming the Widmannstatten structure, and by a small amount of compact pearlite. Due to differences in chemical composition of both kinds of steel (especially the manganese content), a larger amount of ferrite is on the side of St3S steel. It is known that manganese shifts point S to the left causing a higher content of pearlite. The above described structure corresponds to a very small decrease in KCV and also to a significant decrease in the fracture toughness in comparison to the value of this parameter pertaining to the welded joint. One might suppose that a strong diversity of ferrite forms, as well as their supersaturation, may be the reason for the observed decrease in the fracture toughness J_{Id} and in impact KCV.

The structure of St3S steel in the zone of the base material (BM) is ferritic with equiaxial grains with a not large amount of ferrite forming the Widmannstatten structure and with a samall amount of compact pearlite. This structure does not cause significant changes in the analysed parameter values compared to the structure described before (Fig. 8f).

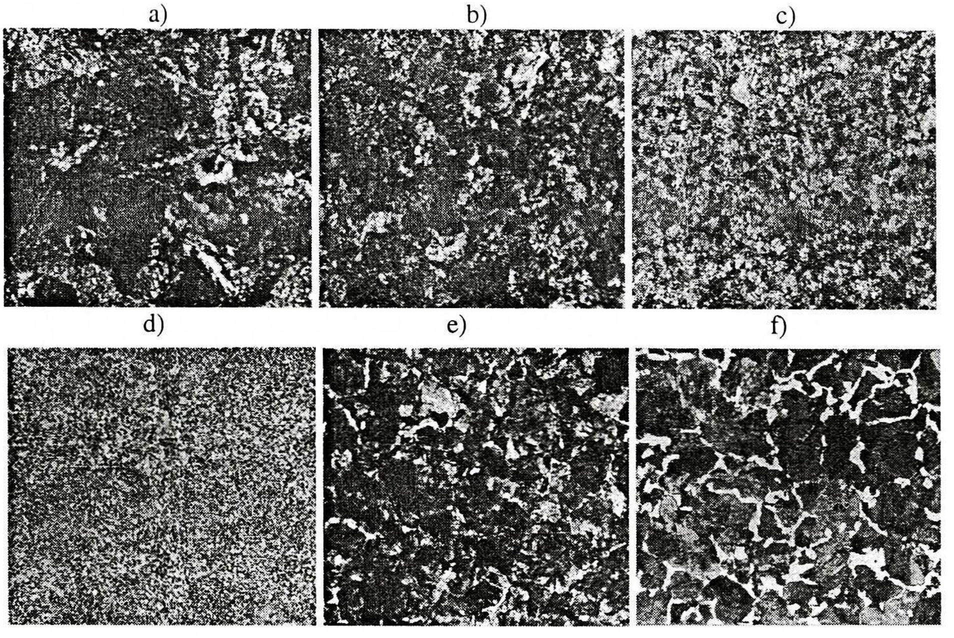

Fig. 9. Microstructure of frictionally welded joint made of steel parts N9E-45 (250 times magnified), a) along the weld axis, b) at a distance of 3mm from the weld on the side of N9E steel (HAZ), c) at a distance of 8 mm from the weld on the side of N9E steel (HAZ), d) at a distance of 11 mm from the weld on the side of N9E steel (BM), e) at a distance of 4 mm from the weld on the side 45 steel, f) at a distance of 1 mm from the weld on the side of 45 steel (BM).

The fracture toughness changes J_{Id} on the frictionally welded joint made of steel parts N9E-45 observed in Fig. 4b result from structural changes taking place during the frictional welding process.

Tests of structure on the joint N9E-45 performed in characteristic places (Fig. 4a) show that along the weld axis fine-lamellar pearlite appears in relatively large colonies (Fig. 9a). At a distance of 3 mm on the side of N9E steel, one observes fine-grained fine-lamellar pearlite as well as light grains that are most probably a product of non-eutectoidal transformation (Fig. 9b). At a distance of 8 mm from the weld axis on the side of N9E steel, divorced cementite appears against a background of ferrite as well as areas of lamellar pearlite originating from a partial eutectoidal transformation (Fig. 9c). The structure of N9E steel at a distance of 11 mm is identical to the base material. It is divorced cementite against a background of fine grained ferrite (Fig. 9d).

In 45 steel, at a distance of 4 mm from the weld axis (Fig. 8e) one can observe, compact pearlite (line lamellar) with a small amount of ferrite creating discontinuous lattice along the boundaries of this pearlite. This zone recrystalized during the welding. At a distance of 11 mm from the weld axis on the side of 45 steel, pearlite-ferrite structure appears, and it corresponds to the base material state (BM) (Fig. 9f).

Using a similar method, one can estimate from Figures 5, 6, 7 the changing tendency for such parameters as: the dynamical fracture toughness J_{Id} and impact resistance KCV as well as the crack sensitivity index U_J on the frictionally welded joints made of steel: St3S-45, 40H-45, 18G2A-40H.

An approximation was used to determine from Figures 3–7 a correlation function for the dynamic fracture toughness versus impact resistance KCV and the distance l from the weld axis on the frictionally welded joints being tested (Table 2).

Table 2.
Experimental expressions for the dynamic fracture toughness J_{Id} versus impact resistance KCV of frictionally welded joints

No.	Welded system	Expressions for steel
1	18G2A-St3S	for 18G2A steel $J_{Id(l)} = 0{,}2526 \cdot KCV_{(l)} + (0{,}27 \cdot l^2 - 3{,}07 \cdot l + 89{,}3)$ for St3S steel $J_{Id(l)} = KCV_{(l)}\,(0{,}62 \cdot l^{-0{,}1541})$
2	N9E-45	for N9E steel $J_{Id(l)} = 0{,}578KCV_{(l)} + (0{,}2 \cdot l^2 - 2{,}9 \cdot l + 18{,}7)$ for 45 steel $J_{Id(l)} = -\,1{,}03KCV_{(l)} + 3{,}215 \cdot l + 34{,}08$
3	St3S-45	for St3S steel $J_{Id(l)} = KCV_{(l)}(0{,}464 \cdot l^{0{,}066})$ for 45 steel $J_{Id(l)} = 0{,}383KCV_{(l)} + 0{,}78 \cdot l + 10$
4	40H-45	for 40H steel $J_{Id(l)} = 1{,}344KCV_{(l)} + 4{,}844 \cdot l - 5{,}66$ for 45 steel $J_{Id(l)} = 0{,}955KCV_{(l)} + 0{,}18 \cdot l + 6{,}4$
5	18G2A-40H	for 18G2A steel $J_{Id(l)} = KCV_{(l)}\,(e^{-0{,}503+0{,}024 \cdot l})$ for 40H steel $J_{Id(l)} = -\,1{,}17KCV_{(l)} + (0{,}408l^2 - 3{,}51 \cdot l + 100{,}5)$

These expressions allow for calculating with a high correlation coefficient ($R=0{,}9891 \div 1{,}0$), the dynamic fracture toughness J_{Id} on frictionally welded joints using the test results of impact resistance KCV on tested joints.

4. Conclusions

Based on the tests results presented above one can make the following observations, and draw the conclusions given below:

1. Calculations of the dynamic fracture toughness resistance parameter J_{Id} can be made by registering graphs F(f), by means of an instrumented and computerized impact bending test using the methodology of compliance $\Delta C/C$ change of an impact bent specimen for determination of the crack initiation point on the tested specimen.
2. The frictionally welded joints being tested are characterized by a great variety of dynamic fracture toughness value changes determined by the parameter J_{Id} along the entire weld length. The zones in close proximity to the weld (at a distance of 1,5–3 mm from the weld axis) display significantly reduced dynamic fracture toughness compared to HAZ and BM. The observed changes are the result of structural changes which occur during welding process and which are the effect of cooling intensity changes in particular zones of joints caused by the applied technological parameters.
3. Crack sensitivity coefficient changes U_J of the frictionally welded joints being tested, presented in this paper, can be a quantitative measure of structural changes that occur in the area of the tested welds (in the weld, HAZ, in superheating zone, BM) and of dynamic fracture resistance. A process of frictional welding and possible initial and final thermal treatment should be selected in such a way that the values of the coefficient U_J in all zones of the joint would be as low as possible.
4. Expressions for the dynamic fracture toughness and impact resistance KCV in frictionally welded joints allow for using impact resistance KCV test results as a useful resistance parameter for design and selection of optimal technological conditions which guarantee the required fracture toughness of welded joints.

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Związek między dynamiczną odpornością na pękanie a strukturą i udarnością KCV wybranych złączy zgrzewanych tarciowo

Streszczenie

Jednym z ważnych parametrów wytrzymałościowych wprowadzanych do obliczeń inżynierskich dla doboru materiałów i oceny ich własności eksploatacyjnych jest odporność materiału na pękanie. W odróżnieniu od statycznej odporności na pękanie K_{Ic}, J_{Ic} ważnym parametrem jest też dynamiczna odporność na pękanie K_{Id}, J_{Id}, a_J. W pracy na przykładzie oprzyrządowanej próby udarowego zginania oceniano związek parametrów dynamicznej odporności na pękanie J_{Id} w złączach zgrzewanych tarciowo ze strukturą i udarnością KCV wykonanych ze stali: N9E-45, 18G2A-St3S, St3S-45, 40H-45, 18G2A-40H.