

The role of notch tip shape and radius on deformation mechanisms of 12Cr1MoV steel under impact loading. Part 1. Energy parameters of fracture

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ABSTRACT Impact loading curves and fracture energy of the notched 12Cr1MoV ductile steel specimens are analysed. The qualitative description and quantitative parameters are obtained for major stages of ductile and brittle fracture depending on the shape of the notch and the stress stiffness ahead. It was shown that a zone with enhanced plasticity forms in the vicinity of V-, U- and I-shaped notches at 20 °C testing temperature, giving rise to ductile fracture. The stress stiffness at the notch tip increased with testing temperature reduced to −40 °C. We demonstrated that the size of shear lips on a fracture surface is a quantitative characteristic of fracture. Using this approach, which is close by nature to non-linear fracture mechanics, together with the quantitative description of fracture surfaces, a physical–mechanical scheme of the specimen fracture was suggested for the case of enhanced and localized (constrained) plasticity near the stress concentrator tip.

Keywords impact loading; scale levels of deformation and fracture; shear lips; stages; stress concentrator.

NOMENCLATURE

a = notch depth
U, V, I = notch shape
 T = testing temperature
 P = load
 $P_{0.2}$ = yield load
KCV, KCU, KCI = impact toughness of specimens with different type of notch
 S = relative area
 t_o = width of the initial width of the specimen
 t_f = width of the crack propagation zone
 t_s = width in the zone of maximum shrinkage

INTRODUCTION

The metal of steam pipe-lines at thermal power stations at various stages of manufacturing and operation suffers from the accumulation and development of microdefects that can lead to the generation of macrocracks and failure of the structure as a whole.¹ Understanding the process of damage accumulation and, particularly, its localization in structural materials (alloys and steels) under pseudo-elastic loading at service is still far from being comprehensive.^{1–3} In the first order approximation, the flaws in

structural materials are often modelled by notches of various shapes. Under static or dynamic loading, this approach requires application of fundamental analytical approaches and numerical solutions of fracture mechanics on one hand while accounting for the microstructure of the material on the other.^{4–8} Investigation of the influence of the stress–strain state onto microscopic mechanisms of fracture is still topical.^{9,10} The models of deformation and fracture, which are based on various force criteria of crack (or fracture) mechanics, do not always take into account the features of deformation of a specimen with different notch radii.^{11–13} The effect of the stress–strain state, in

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particular, localization of stresses at the notch (or crack) tip, is primarily manifested through the formation of plastic deformation zone in the area of a crack tip, which assumes the elastic–plastic formulation of the problem.^{14–18} It is, therefore, timely to re-consider the energy and deformation parameters and to develop criteria for crack resistance evaluation for different stress–strain states based on elastic–plastic analysis of a crack tip region with corresponding consideration of boundary conditions.^{19–22}

In the earlier studies run out with the use of various techniques, some static and dynamic problems on stress concentrator tip radius were investigated. In doing so, regularities on materials fracture under static and complex type loading were the matter of the research.^{23–25}

Under this point of view of actuality is application of a technique widely used in the physical mesomechanics concept aimed at revealing fracture mechanisms at various scale levels. In doing so, it is of importance to take into account strain localization processes with employing energetic and deformation approaches of fracture mechanics.

The present work suggests the study of the notch shape influence on the distribution of the stress–strain state in Charpy specimens made from ductile (heat resistant) 12Cr1MoV steel with due consideration of energy parameters of its fracture.

EXPERIMENTAL

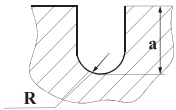
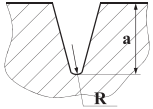
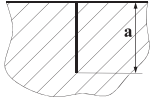
The specimens for testing were cut from a section of a steam pipe of 30 mm diameter using electric discharge machine. Every specimen was subjected to standard thermal treatment involving normalization at 960–980 °C

followed by high-temperature annealing at 740–760 °C. A batch of specimens with V-, U- and I-shaped notches with equal depth of 2 mm was machined. V- and U-notches were induced by standard milling cutters Blacks CNM, while the I-shaped notch was made by electro erosion after standard thermal treatment. Impact testing was conducted at room temperature and at –40 °C using Charpy method (Table 1).

The lower testing temperature was used to reduce relaxation capacity of the material. In order to run low-temperature impact loading, the specimens were preliminary exposed in the refrigerator (cooling chamber) ‘Lauda rp870’ for 10 min at temperature of –40 °C and then fast installed into the grips of the impact pendulum for testing. The time interval between specimen extraction from the cooling chamber and further testing did not exceed 5 s. At least three specimens of each type and each temperature were tested.^{26,27}

The impact toughness was determined by Instron 450MPX instrumented pendulum impact tester. The total fracture energy was divided into two main constituents: crack initiation energy and crack propagation energy. The resolution on fracture energy at the measurements made 0.01 J. The impact testing was run according to ASTM E 23:2007 and ISO 148-2:2008. The fracture toughness at each temperature was estimated by averaging data over three tests. The specimen dimension made 55 × 10 × 10 mm³. The surface roughness at specimens machining for their height, width and length corresponds to ASTM E 23:2007 and ISO 148-2:2008.^{26,27} The standard sensors employed in the Instron 450 MPX machine were used for measuring P and Δl . The features of plastic deformation and fracture were studied with the use of the fracture surface micrographs obtained by the LEO EVO 50 scanning electron

Table 1 Experimental parameters for impact testing of specimens

Notch shape	Geometrical shape	Notch tip radius, R [mm]	Concentrator length, a [mm]	Testing temperature [°C]	
U-shaped		1.0	2.0	20	–40
V-shaped		0.25			
I-shaped		0.1			

microscope (Zeiss, Germany). Optical micrographs were registered with the help of light microscope Carl Zeiss Stemi 2000-C.

RESULTS

Macroscopic features of fracture. Force, deformation and energetic characteristics of impact loading

The obtained diagrams of dynamic loading of specimens reflect their sensitivity to localization (fracture) conditions depending on the concentrator shape and radius of its tip (Fig. 1a) and testing temperature (Fig. 1b).

Testing temperature $T = 20^\circ\text{C}$

V-notch. V-notched specimens are fractured in a ductile way, which is evidenced by the slowly decaying tail of the loading diagram (see Fig. 1a, curve 1). Deformation mechanisms at micro-scale provide quite effective stress relaxation^{28–32} so that the process of crack initiation and propagation unfolds gradually, without breaks and sharp bifurcation transitions. The material has considerably high strength and cracking resistance, which is typical of ductile ferrite–pearlite steels.

U-notch. The impact fracture of specimens with the U-notch is accompanied by intensive plastic deformation. The observed macroscopic deformation behaviour of the material is indicative of the activation of relaxation processes, which are accompanied by the noticeable increase in fracture toughness, which is determined on the basis of the significant contribution of crack propagation into the fracture energy (Table 2).

I-notch. The shape of the loading diagram (Fig. 1a, curve 3) for the I-notched specimen is similar to that of the V-shaped one (Fig. 1a, curve 1). Despite the sharpest stress concentrator, the fracture behaviour of the I-notched specimen does not appear to be much more brittle than that of the V-notched one because plastic deformation relaxes elastic stress around the tip of the main crack during crack propagation. However, the impact fracture toughness KCV (or better to say KCI) in the I-notched specimen, 256 J/cm^2 , is higher than in the V-notched one, 226 J/cm^2 . Furthermore, the work of crack propagation A_p in the I-notched specimen is also significantly higher than in the counterparts (see Table 2). Thus, besides the dependence on the notch radius,^{32–35} the impact toughness and fracture work are sensitive to the stress–strain state of a material ahead of the stress riser,

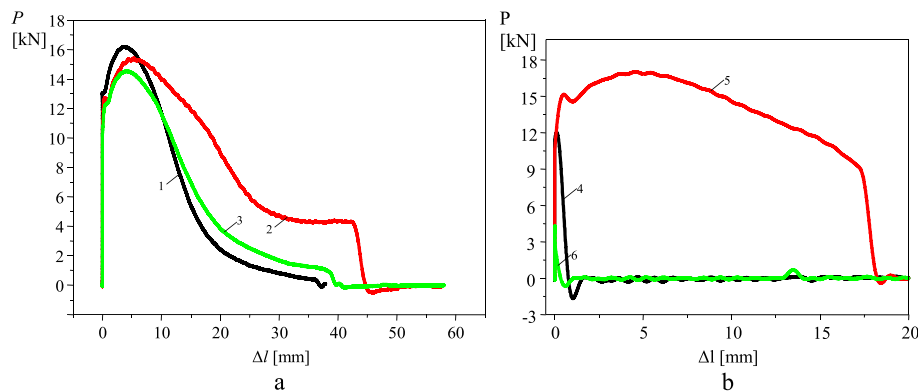


Fig. 1 'Load – bending' diagram under impact loading at 20°C (a) and -40°C (b); notch shape: V – curve 1, 4; U – 2, 5; I – 3, 6.

Table 2 Macroscopic characteristics of impact toughness testing of 12Cr1MoV steel specimens

Notch shape and testing temperature	KCV (' KCU ', ' KCI ') [J/cm ²]				
	$P_{\max}$ [kN]	A [J]	A_i [J]	A_p [J]	
$V_{20/-40}$	$226 \pm 15/$ 12 ± 1	$16.2 \pm 0.2/$ 11.9 ± 0.3	$189.7 \pm 11/$ 9.12 ± 0.2	$110 \pm 7/^{*}$	$79.7 \pm 0.6/^{*}$
$U_{20/-40}$	$368 \pm 27/$ 262 ± 12	$15.4 \pm 0.6/$ 17.1 ± 0.7	$286 \pm 4/$ 203.3 ± 6	$48.3 \pm 2/$ 58 ± 4	$237.8 \pm 9/$ 145.3 ± 10
$I_{20/-40}$	$256 \pm 14/$ 4.8 ± 0.5	$14.5 \pm 1.2/$ 4.2 ± 0.3	$196.6 \pm 5/$ 3.6 ± 0.4	$39.6 \pm 4/^{*}$	$157 \pm 6/^{*}$

*Not determined.

which is conditioned in our case by temperature and force factors.

Testing temperature $T = -40^\circ\text{C}$

V-notch. It was shown in Ref. ³⁶ that in the specimens with a V-shaped notch (Fig. 1b, curve 4), the high stress concentration in a local region at the notch tip during impact loading causes the origination and merging of microscopic cracks, which leads to brittle fracture.

U-notch. In the U-notched specimens, the ascending part of the loading diagram (Fig. 1b, curve 5), which corresponds to the crack initiation, is similar to that obtained at ambient temperature (c.f. curves 2 and 5). At the same time, the decaying tail corresponding to resistance to crack growth is appreciably shorter and ends steeply. The loss of load bearing capacity corresponding to fracture is the transition from a stable stage to the nonequilibrium stage of structural failure at post-critical stage and indicates the brittle-plastic state of the material.³⁷

I-notch. During impact loading of specimens with the sharp I-shaped concentrator, the vicinity of its tip experiences high intensity of stresses, according to classical elastic theory. The high stresses suppress material's microplasticity and facilitate crack propagation (Fig. 1b, curve 6). At the same time, the average stresses across the specimen are lower than the maximum engineering strength of the material, which is seen by the value of $P_{\max}$ and the diagram shape. Among all three types of the studied specimens, the one with the I-shaped notch showed the smallest impact toughness A_i (see Table 2 below) and the smallest $P_{\max}$ value (i.e. the stress corresponding to the onset of the macroscopic crack advance).

As opposite to testing at room temperature, the works of fracture and impact toughness are lowered with reduction of the notch tip radius. Moreover, the most interesting result is that the impact toughness of the specimen with U-shaped notch at lower temperature is higher than that for the specimens with V- and I-shaped notches under testing at the room temperature.

Within general philosophy of fracture mechanics, two characteristic stages are distinguished at impact loading: (i) macroscopic crack initiation (up to $P_{\max}$) and (ii) macrocrack propagation (after reaching $P_{\max}$). Accordingly, in the present work, the corresponding constituents of the fracture work were calculated.

The obtained results (Table 2) show that lower temperature causes sharp drop of the fracture energy for the specimens made from the ductile ferrite-pearlite steel, which is reasonably expected. This is particularly evident for the cases of concentrators with small tip radii. This phenomenon is known as cold brittleness, which has been a root cause of many technological disasters.^{38–40}

Transition from ductile to brittle fracture occurs usually within a narrow temperature range – cold embrittlement threshold – the physical nature of which is still a matter of controversial discussions.

Table 2 displays force and energetic parameters of impact toughness of the 12Cr1MoV steel. The maximum load during impact testing $P_{\max}$ can be considered as a macroscopic parameter reflecting material's strength^{33,34}: $P_{U\max20} = 15.4\text{ kN}$, $P_{V\max20} = 16.2\text{ kN}$ and $P_{I\max20} = 14.5\text{ kN}$. Obviously, with the increasing notch radius, the maximum load at fracture changes in a non-linear manner. For instance, the greatest value of this parameter is obtained for the specimen having average notch tip radius (0.25 mm). On the other hand, when the stress state stiffness increases at lower temperature, the values of $P_{\max}$ decrease proportionally to the notch tip radius: $P_{U\max-40} = 17.1\text{ kN}$, $P_{V\max-40} = 11.9\text{ kN}$ and $P_{I\max-40} = 4.2\text{ kN}$.

It is specifically worth mentioning that for the specimen with the most blunt notch, the $P_{U\max-40}$ value is even higher, than at the ambient testing temperature (compare $15.4 < - > 17.1\text{ kN}$). The understanding of the reasons of such a particular deformation behaviour can be achieved by a detailed analysis of the processes occurring near its tip. This will be performed in the second part of the present paper during the discussion of results of numerical modeling.

Obtained results are of significance for understanding the influence of stress stiffness on the resistance of steels to crack propagation, because $P_{\max}$ corresponds to the moment of transition from the macroscopic defect (main crack) initiation to its propagation. At the lower temperature, for V- and I-shaped concentrators, the crack develops at lower stresses, which testifies for the higher stress state stiffness at the notch tip.⁴¹ This result will be discussed below together with the analysis of the fracture surface morphology.

The obtained results shed some light on multifold reduction of the work of crack initiation at low temperature. It can be supposed that the change in the fracture mechanism for 12Cr1MoV steel at the testing temperature of -40°C is related to appreciable fluctuations of the rate of energy supply to the specimen at a certain stage of high-rate deformation. As a result, the specimen remains in an excited state, while the excess of energy being supplied to the material dissipates in the zone adjacent to the concentrator.^{41,42}

On the other hand, the reasons of cold brittleness are commonly attributed to the inefficiency of micro-scale plastic deformation mechanisms at low temperature for the relaxation of stresses via dislocation slip at the notch tip, because the notch sharpness causes the concentration of high energy flow rate at the tip. The relevant discussion will be unfolded in the part 2 of

the paper where fracture micromechanisms will be analysed.

However, in the specimen with the U-shaped notch, the energy distributes over a larger area. For this reason, at ambient temperature, despite the lower crack initiation work as compared to the V-shaped notch (c.f. $48.3 <-> 110$ J), the further propagation of the crack consumes more than 3 times higher energy ($237.8 <-> 79.7$ J). Obviously, this is the reason, which at the temperature lowered down to -40°C allowed the effective redistribution of stresses at the tip of the U-shaped notch, thus promoting ductile fracture.

Analysis of impact fracture stages based on loading diagrams

The analysis of fracture process by distinguishing its characteristic stages is a traditional approach of physical mesomechanics of materials. The following part analyses two characteristic stages of impact fracture (macrocrack initiation and propagation) with a due account for their duration and load values, at which the corresponding stage started or ended, and the values of fracture work (Table 2).

Testing temperature $T = 20^{\circ}\text{C}$

Stage I (macrocrack initiation). For the specimens with V-shaped notch, the stage of macrocrack initiation began at maximum load of $P_{\max} \sim 13$ kN, while this stage ended at the displacement of impact tester striker equal to about 3 mm. The average rate of load increment (versus the displacement) can be estimated as equal to 1.1 kN/mm. For the I-shaped notch, this parameter can be estimated as equal to 0.58 kN/mm (for the displacement/deflection at stage I of about 4 mm, while $P_{\max}$ has the lowest value of 14.5 kN; for the most blunt notch, it is of 0.51 kN/mm, the deflection on this stage is largest among others and equals to 5 mm approximately and $P_{\max}$ has the average value of 15.4 kN). Looking at the diagram of impact fracture of the last specimen, one can see a characteristic load drop similar to the yield drop occurring during tensile testing of low-carbon steels, testifying that before the crack initiation at the notch tip dislocations are liberated from pinning points and plastic deformation occurs. The similar yield drop is also manifested on the impact diagram at negative testing temperature (Fig. 1b, curve 5). Thus, even at stage I the parameter 'load increase rate' for specimens with I- and U-shaped notches is similar, which should be related to the features of plastic processes developing at the notch tip.

Stage II (macrocrack propagation). Similar to the approach implemented in the previous study,⁴³ the longest falling part of the diagram corresponding to stage II

was selected and linearly approximated to determine the inclination angle characterizing the 'load decrease rate'. In general, the end of the linear section can be considered as the end of the macrocrack propagation stage and transition to final rupture. The rupture stage corresponds to the portion of loading diagram, when the external load is slightly varied while being close to zero. That is why the rupture stage is considered separately as a part of fracture process when the specimen does not exhibit any resistance to main crack propagation. The ending of the linear section for the three types of notches was characterized by the following values of extension: V-shaped notch, $\Delta l = 15$ mm; U-shaped notch, $\Delta l = 25$ mm, I-shaped notch, $\Delta l = 17$ mm. Moreover, for the specimen with the U-shaped notch, rupture begins at the external load exceeding 4 kN, which is considerably larger than respective values for other two types of specimens.

The average load decreasing rate (versus the displacement) for the specimen with V-shaped notch can be evaluated as -1.1 kN/mm (recall that it was about 1.1 kN/mm during stage I). For the I-shaped notch, this parameter can be estimated as ~ 0.66 kN/mm (c.f. ~ 0.51 kN/mm at stage I). For the bluntest notch, it is of 0.581 kN/mm (c.f. ~ 0.61 kN/mm at stage I). Thus, the values of modules of the analysed parameter at stages I and II are comparable.

Testing temperature $T = -40^{\circ}\text{C}$

Stage I (macrocrack initiation). The impact loading at low temperatures has enabled the stage-wise analysis only for the specimen with the U-shaped notch. For this reason, these specimens were compared for the 'load increase/decrease rate' at two temperatures. The deflection at the first stage somewhat shortened ($\Delta l = 4.5$ mm). The value of $P_{\max}$ increased noticeably ($15.4 <-> 17.1$ kN). The average load increase rate (because of displacement) as compared to room testing temperature decreased by a factor of 2 and amounted to of 0.53 kN/mm (it was 1.1 kN/mm).

Stage II (macroscopic defect propagation). As was said above, the lower testing temperature conditioned the decrease of impact toughness, but the process of specimen fracture was not brittle. At the second stage, the load decrease rate (versus the displacement) for the specimen with the U-shaped notch can be estimated to be of -0.6 kN/mm (c.f. ~ 0.52 kN/mm during stage I). This again shows that the absolute value of this parameter is pretty close during both stages of impact loading. On the other hand, almost brittle final fracture began at $P = 9$ kN and the striker displacement of $\Delta l = 17.5$ mm, which is of 3 times lower than for the beginning of final fracture stage at ambient temperature. Thus, the change of testing temperature accompanied by the change in

the stress state at the tip of the U-shaped notch and the relaxation capacity of the material in the local area near the tip conditioned the almost twofold change in the impact load increase/decrease rate, while the impact toughness decreased roughly by 70%. In contrast to other two type notches, this value appeared very high. To rationalize such a behaviour, numerical modeling was employed. The results of modeling efforts will be presented in the companion part 2 of this paper.

Morphology of fracture surface and characteristic zones of fracture

The analysis of dynamic deformation diagrams testifies to formation of deformation localization zones at a scale of the whole specimen (Fig. 2). It was shown that the process of deformation and fracture of specimens includes consequent interchanging stages of ‘extensive localized deformation’ and ‘fracture’ (zones I, II, III and IV in Fig. 2). The measurements were conducted with the help of automated technique based on the algorithm described in Ref. ⁴⁴. Each fracture zone exhibits distinctive morphological features and regions. At the same time, it is practically impossible to separate (in terms of time of appearance and energy) the formation of the crack propagation zone and shear lips, that is, they develop almost simultaneously not only at different sections of the specimen, but also in adjacent zones.

The development of all these processes is accompanied by the formation of corresponding sections that are well distinguished on the fracture surface (Fig. 2). The given optical photographs were used to calculate the relative areas (S) of corresponding regions of fracture at different testing temperatures (Table 3).

Crack initiation zone (I). For the studied notch shapes, the area of this section changes non-linearly for different notch tip radius: $S_{I20} = 17\% < - > S_{I20} = 14\% < - > S_{U20} = 31\%$. On the other hand, the zone area changes completely non-proportionally to the energy of crack initiation determined from the

Table 3 Quantitative characteristics of fracture zones

Fracture zones	Relative area of fracture zones of Charpy specimens S for different concentrator shapes [%]		
	V	U	I
Crack initiation (I)	14 ± 1	$31 \pm 3/14 \pm 2$	17 ± 2
Crack growth (II)	51 ± 6	$36 \pm 4/26 \pm 2$	62 ± 8
Shear lips (III)	15 ± 3	$19 \pm 3/8 \pm 1$	15 ± 2
Final fracture (IV)	20 ± 4	$14 \pm 3/52 \pm 7$	6 ± 1

*For specimens with V- and I-shaped concentrators at testing temperature -40°C , the characteristic fracture zones are hardly distinguishable.

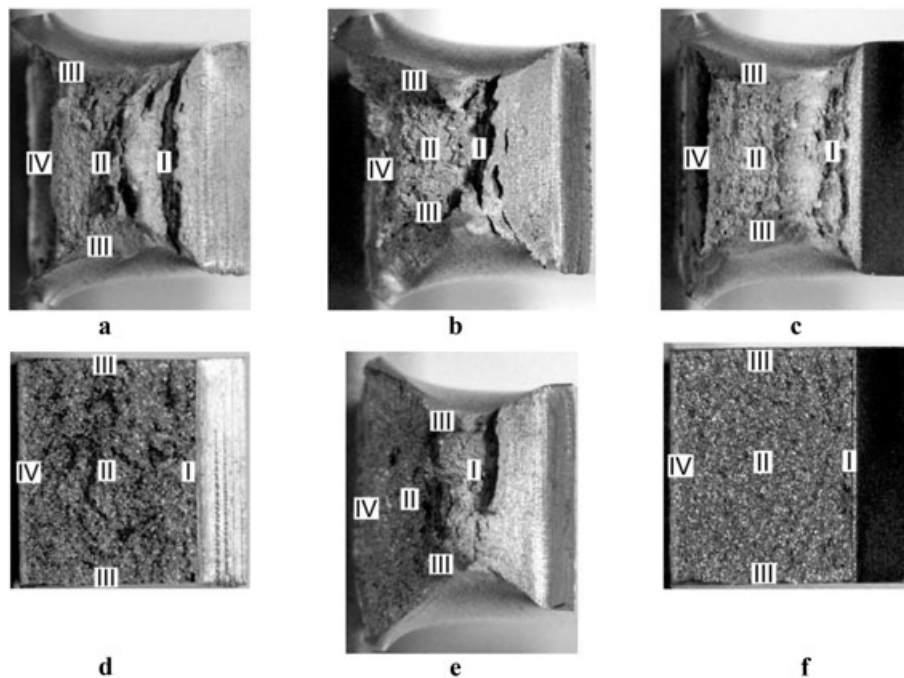


Fig. 2 Optical photographs of the specimen fracture surfaces with V-shaped (a, d), U-shaped (b, e) and I-shaped (c, f) notches for the testing temperatures of 20°C (a–c) and -40°C (d–f).

impact loading diagram (compare: $A_i = 39.6 <-> 110 <-> 48.3 \text{ J}$).

Crack growth zone (II). The area of this zone gradually decreases with the reduction of the notch sharpness: $S_{I20} = 62\% <-> S_{V20} = 51\% <-> S_{U20} = 36\%$. Similarly to the afore-described case, the area of zone II changes non-proportionally to the crack propagation energy (compare $A_i = 157 <-> 79.7 <-> 237.8 \text{ J}$).

Shear lips (III). The area of shear lips for all studied notch shapes is comparable: $S_{I20} = 15\% <-> S_{V20} = 15\% <-> S_{U20} = 19\%$, so that the features of their formation in different specimens can be neglected.

Final fracture zone (IV) has the following dimensions: $S_{I20} = 6\% <-> S_{V20} = 20\% <-> S_{U20} = 14\%$, which shows that for the specimen with the largest fracture toughness, the size of this zone is largest too.

The influence of increased stress stiffness at reduced testing temperature $T = -40^\circ\text{C}$ on the dimensions of characteristic sections of specimen fracture surface was characterized quantitatively only for the specimens with U-shaped notch. It was established that the energy of specimen fracture at crack propagation stage decreases from 237.8 J to 197 J (Table 2), while the area of this zone amounted to 26% of the specimen total section area (at room temperature it was of 36%).

Development of transversal deformation of specimens and its localization

Plastic zones at the notch tip during impact loading at room temperature begin to form at $P_{0.2}/P_{\max} = 0.8-0.85$. At lower temperature $T = -40^\circ\text{C}$, this relation for

specimens with U-shaped notch amounts to 0.87, while for the specimens with V- and I-shaped notches, it is equal to 1.0. This testifies to the active involvement of macroscale plastic deformation mechanisms. The reduction of testing temperature was accompanied by decreased accommodation role of deformation processes in the crack vicinity, and it was the most evident demonstration of the notch shape influence.

One can compare the width of the crack propagation zone t_f with the initial width of the specimen t_0 : t_f/t_0 . This variable has been proven to be very sensitive to strain localization.⁴⁵ Besides, it strongly depends on the stress-strain state in the notched specimen, which makes it useful for the analysis of dynamic fracture. Because the fracture process during impact loading is associated with appreciable reshaping in the concentrator zone, accompanied by formation of shear lips, an additional parameter t_s/t_0 was used that represented the relation of the specimen width in the zone of maximum shrinkage t_s to the initial specimen width (Fig. 3a). This parameter, which can be experimentally measured from fracture surface observations, allows comparing the intensity of deformation processes at the notches of different radius (Fig. 3b).

In the experiments performed at $T = 20^\circ\text{C}$, deformation and fracture of materials is uniform for different notch radii (ρ) of the specimens and is accompanied by their considerable residual shrinkage. At $T = -40^\circ\text{C}$ at micro-scale, both brittle fracture mechanism (at the notch radius $\rho = 0.1 \text{ mm}$ and 0.25 mm) and mixed brittle/ductile mechanism (at $\rho = 1.0 \text{ mm}$) are involved.

It should be emphasized that after fracture at $T = 20^\circ\text{C}$, the lowest strain localization was noticed for U-notched specimen, while the largest one was for the V-notched one (Table 4).

The I- and V-notched specimens at $T = -40^\circ\text{C}$ fractured in a brittle way: the values $t_s \approx t_f \approx t_0$. For the U-

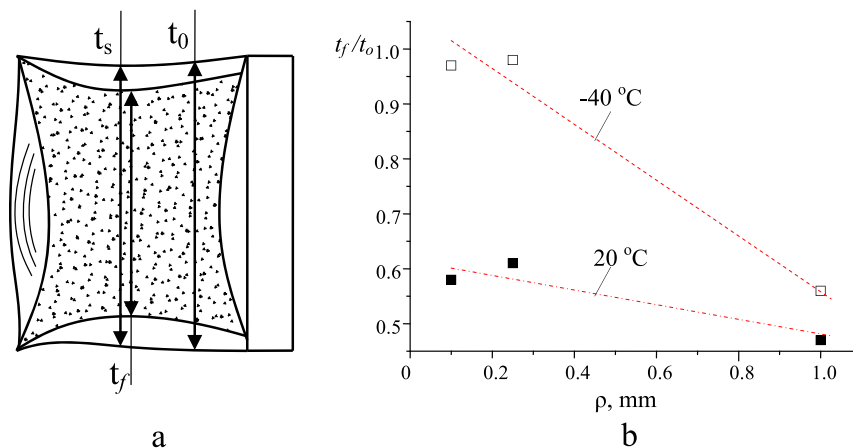


Fig. 3 Scheme of specimen fracture width measurement in the crack propagation zone t_f at the section of maximum shrinkage t_s ⁴⁵ (a) and the influence of the notch radius (ρ) on parameter t_f/t_0 (b).

Table 4 Parameters of specimen fracture process localization

Testing temperature, °C	Relative shrinkage at different testing conditions, t_f/t_0 ; t_s/t_0		
	<i>V</i>	<i>U</i>	<i>I</i>
20 °C	0.61 ± 0.05/ 0.81 ± 0.04	0.47 ± 0.03/ 0.68 ± 0.04	0.58 ± 0.02/ 0.73 ± 0.05
-40 °C	0.98 ± 0.2/ 1 ± 0.1	0.56 ± 0.04/ 0.72 ± 0.03	0.97 ± 0.1/ 1 ± 0.2

notched one, the relations t_f/t_0 and t_s/t_0 were also appreciably higher than at $T=20\text{ °C}$. This testifies for the lesser reshaping of the specimen after fracture, particularly, at greater strain localization.

DISCUSSION AND GENERALIZATION OF EXPERIMENTAL RESULTS

Fracture mechanics analysis

Impact toughness characterizes the capacity of a metal to resist the crack propagation owing to localized plastic deformation. However, determination of impact toughness is important not only for engineering structures and machine parts operating at high rates of loading. Comparing steels with equal strength, the value of impact toughness can be used as an additional characteristic of plasticity at the notch or as a design criterion for estimating materials degradation long-term operational deterioration.^{33–36}

Relation between fracture energy and plastic deformation at the notch tip

Plastic deformation develops during loading in the vicinity of a stress riser.^{37–39} In cases, when the dimensions of the plastic zone are comparable with the length of a crack-like defect (concentrator), the adequate description of deformation behaviour requires the use of non-linear fracture mechanics approaches. The main features of

the fracture of the studied Charpy specimens were determined using the scheme proposed in Ref.⁴⁶ with a due account for a translation-rotational (vortex) character of local displacements under load as outlined in Ref.⁹.

Room testing temperature, 20 °C

At room temperature (Fig. 3a), a meso-scale zone is formed in the Charpy specimens at the notch tip. This zone encircles the area of localized plastic deformation developing the vortex pattern as per the ‘translation + rotation’ scheme (Zone I). It is believed that the vortex nature of localized plastic flow allows accumulating the critical density of defects promoting crack initiation in this zone. After initiation, the consequent propagation of a macrocrack is accompanied by the formation of plastic hinge (Zone II) accommodating the crack in the surrounding material by shear deformations. The latter mechanisms are most active at the specimen surface, where they have the least energy. As a result, after impact loading the development of the main crack (Zone III) is accompanied by shear lips formation. On the specimen side opposite to the notch, a region of rotational-shear deformation is formed because of high rate fracture and its high localization. This is clearly seen at the final fracture stage (Zone IV). This interpretation corresponds well with the afore-described characterization of impact fracture stages of the three types of specimens at different testing temperatures.⁴⁷

This simplified scheme highlights the mechanism of shear lips formation, which maximum height is related to the shape and size of plastic deformation zone under conditions of mutual translational-rotational torsion of specimen parts (Fig. 4).

Low testing temperature, -40 °C

At lower testing temperature, plastic deformation is localized in narrow layer adjacent to the crack (notch) tip. In this layer, plastic deformation develops via micro-scale dislocation mechanisms, while the remaining volume of the specimen either stays undeformed, or deforms

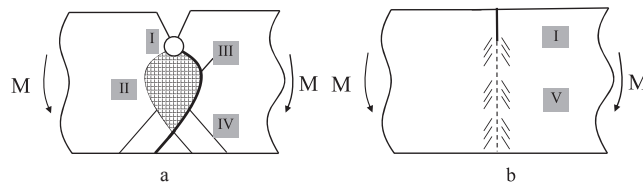


Fig. 4 The mechanisms of ductile (a) and brittle (b) fracture of specimens and formation of shear lips under impact loading⁴⁰: a – fracture with the formation of plastic deformation zone; b – fracture with the formation of a series of microshear regions of plastic deformations; I is the region characterized by translational-rotational vortex-wise movement of the material in the crack initiation zone; II is the plastic hinge; III are the lines outlining the formed shear lips; IV is the region of deformation development as per ‘shear + rotation’ scheme, preceding final fracture; V corresponds to traces of microshear plastic deformation.

elastically. Such a situation can be described analytically assuming plain strain conditions,^{48,49} where the stress concentrators give rise to the bands of localized plastic deformation.⁵⁰

Specimens with V- and I-shaped notches fractured in a brittle manner (Fig. 3b), because the tensile stresses in the vicinity of the concentrator (e.g. near a microcrack) reach the theoretical fracture strength, while relaxation mechanisms, which are provided by plastic deformation, were hindered. Fracture developed at micro-level in the 12Cr1MoV steel by nucleation and coalescence of multiple brittle microcracks in the section of maximum stress concentration.

The analysis of obtained experimental data shows that mechanical properties of the material in the zone of stress concentrators can vary in a wide range depending on the stress stiffness. Moreover, their alteration will to a large extent affect the kinetics of crack initiation and propagation under impact loading.

In real conditions, structural elements always contain defects, and some of them can be considered as narrow stress risers. Thus, they can be modelled by ideal linear sections in mathematical formulations. However, some of defects have the shape that cannot be imitated by a sharp notch, for example, welding defects and pores. For such defects, the radius of curvature in its tip should be considered.

CONCLUSIONS

The performed analysis of the loading diagram shape and values of the fracture energy for specimen made from the 12Cr1MoV steel with notches of different shape under impact loading allowed establishing behaviour and quantitative parameters of typical stages of ductile and brittle fracture, depending on the concentrator shape and stress stiffness at the tip of a crack-like defect.

It was shown that the presence of V-, U- and I-shaped notches at 20 °C leads to the occurrence of an enhanced plasticity zone and ductile fracture of the material. The decrease of testing temperature down to minus 40 °C has led to an increased stiffness of the stress state in the defect tip. At low temperatures, in the specimens with V- and I-shaped notches, the crack tip suffers from the formation of complex (triaxial) stress state, which conditions the brittle fracture of the specimen and reduction of fracture energy from 189.7 J down to 9.12 J and from 196.6 J down to 4.8 J, respectively. For the specimens with U-notch, the increase of the rigidity of the stress state lead to appreciable fracture energy drop from 286.1 J down to 262 J, but it was significantly lower than that for the specimens with V- and I-shaped notches.

In the work, the further development was made for the approach based on the implementation of the size of shear lips as a quantitative fracture parameter under the conditions of ambient and negative temperatures, which is close by its physical nature to deformational approaches of non-linear fracture mechanics. This approach complements the available techniques. We believe that it can be also used for higher temperature applications.

Using the energy-based approach and quantitative analysis of fracture zones of the specimens, a physical-mechanical scheme of specimen fracture was suggested and comprehensively interpreted for the case of enhanced and localized plasticity near the notch tip.

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