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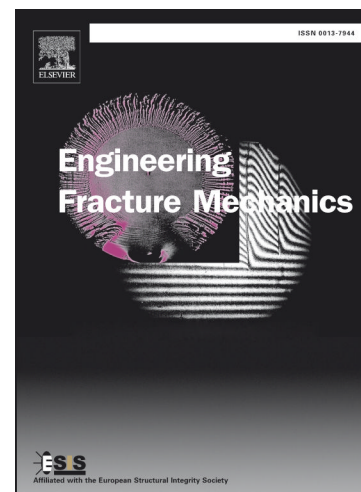
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EFFECT OF NOTCH SHAPE AND TEMPERATURE ON ELASTIC ENERGY RELEASE DURING IMPACT TESTING OF 17Mn1Si PIPE STEEL

S.V. Panin^{1,2}, A.V. Byakov^{1,2}, I.V. Vlasov^{1,2}, P.O. Maruschak³, F. Berto⁴, A. Vinogradov^{4,5}

¹ Institute of Strength Physics and Materials Science SB RAS, Tomsk 634055, Russia

² National Research Tomsk Polytechnic University, Tomsk 634050, Russia

³ Ternopil Ivan Puluj National Technical University, Ternopil 46001, Ukraine

⁴ NTNU, Department of Mechanical and Industrial Engineering, Trondheim 7491, Norway

⁵ Togliatti State University, 445020, Togliatti, Russia

Abstract. Main fracture mechanisms are determined in 17Mn1Si steel during impact Charpy testing of specimens with three types of notches at different test temperatures covering ductile-to-brittle transition. The influence of the notch shape on the amount of expended mechanical energy (according to the loading diagram) and released elastic energy (according to the recorded acoustic emission signal) is analyzed. A combined application of fracture mechanics and acoustic emission methods is proven effective for better understanding of dynamic fracture and ductile-to-brittle transition from the viewpoint of energy-based approaches to crack initiation and propagation.

Keywords: dynamic fracture; ductile-to-brittle transition; crack initiation; crack propagation; fractography; fracture mechanisms; acoustic emission

I. Introduction

The acoustic emission (AE) method has gained great popularity for in-situ monitoring and posttest analysis of the processes occurring during internal structural rearrangements underlying plastic deformation and fracture in a wide range of structural materials from pure metals to alloys, steels, and composites. Due to its outstanding sensitivity to the onset of fracture, the AE method has been used to estimate fracture toughness of different structural materials. Different approaches have been explored by different investigators. The determination of fracture mechanics characteristics by the AE method in the earlier studies was based on observable changes in the slope of AE parameter vs. fracture mechanics parameter – crack opening displacement [1, 2], stress intensity factor K [3-5] or J -Integral [6, 7]. The reliable distinction between the ductile and brittle fracture modes in the AE signal is of crucial importance for the successful application of this method in fracture mechanics. This distinction is made by fracture surface appearance post-mortem, while the chronology of fracture activation and progression is another critical input for either accurate characterization of damage processes or realistic modeling of the fracture behavior. The appearance of signals with characteristic amplitude and frequency distributions was recognized as a promising indicator of different fracture modes. Ono and Yamamoto [8] demonstrated that different AE sources could be distinguished in A533B steels: (i) plastic deformation of the ferrite matrix, giving rise to continuous acoustic emissions predominantly during yielding, and (ii) fracture events associated with deboning of non-metallic inclusions, emitting burst-type signals with the peak amplitude distribution of a Weibull type.

Despite a broad variety of methods used with a different level of success, identifying unambiguous signatures of ductile and brittle fracture and a brittle-to-ductile transition by the AE technique in fracture mechanics testing is still challenging. Contradictory results have been reported in the literature. For example, Kostryzhev et al. [9] applied a wavelet transform to investigate fracture evolution during impact testing of high strength steels. These authors associated a distinct low-frequency peak at about 50 kHz in the wavelet spectra with plastic deformation of ferrite. The high-frequency peak in the range of 200-500 kHz was attributed to the transgranular cleavage of ferrite. As opposes to this Kietov et al. [10] have recently reported the results of AE investigations during Charpy impact test of nodular cast iron. No AE signals generated by mechanisms related to plastic deformation and ductile crack propagation were detected, while local cleavage fracture was easily distinguished and

the AE amplitude was correlated with the size of the cleavage areas. Tronskar et al. [11] applied the AE method to determine the beginning of ductile tearing during impact fracture. The onset of fracture initiation and the crack propagation stage were successfully distinguished. The use of the Fourier transformation for AE signal processing revealed the characteristic phases and fracture modes based on the characteristic frequency and time of AE signals. The brittle fracture had characteristic peak amplitude frequencies in the 493–547 kHz range and a very short duration of the AE signals while ductile tearing occurred with energy release over a wide frequency range of 400–693 kHz (though overlapping with that from brittle fracture) and with significantly longer duration. Using an amplitude and frequency analysis Chuluunbat et al. [12] identified AE signals related to plastic deformation, fracture initiation and crack growth in X70 pipe steel. Conventional signal parameters were complemented by the spectral analysis of AE waveforms correlated with the load-displacement/load-time curves obtained during single edge-notched tensile specimens testing. It was shown that the strain rate, test temperature, and the stress concentrator shape affect the AE behavior. However, it should be noticed that the frequency bands corresponding to signals generated by plastic deformation and crack growth were found significantly overlapping because void nucleation and coalescence in the ductile steel was mediated by plastic deformation.

Charpy impact toughness tests are among the most widely used in routine industrial practice for express evaluation of materials resistance to stress concentration, evaluation of impact toughness and ductile-to-brittle transition temperature [13]. The literature regarding the AE application to dynamic testing including Charpy impact testing is still scarce. Admittedly, dynamic tests are among most difficult for implementation of AE methods due to the combined effects of strikers, short time of testing, limited statistics of events, etc. However, the amplitude analysis of the AE signals obtained during impact testing of fatigue pre-cracked Charpy specimens of dual phase by Richter et al. [14] has shown the possibility to distinguish the time when the AE activity is dominated by plastic deformation during ductile crack initiation from that associated with brittle crack growth: low amplitude continuous AE was associated with plastic deformation while the high amplitude transients were considered due to brittle crack behavior. However, this consideration is simplified since the occurrence of appreciable plasticity in ductile materials could generate high amplitude AE bursts and may cause difficulty in correctly determining the fracture toughness [15]. The sensitivity of AE signals to the mode of fracture made it possible for Roy et al. [16] to compare the value of fracture toughness of four steels having different ductility. The valid ASTM fracture toughness tests were performed. By analyzing the cumulative energy, cumulative counts, and intensity of AE signals, the fracture initiation point was determined with good accuracy. The advent of instrumented pendulum impact testers [17] enabled recording and analyzing the impact energy curves to quantify the energy expended during crack initiation and propagation. As a result, the fracture energy can be estimated at each of these key stages. A large part of the mechanical energy imposed into the specimen is dissipated due to plastic deformation (as well as in the form of heat) during impact bending. The other part is released in the form of elastic waves which can be detected by piezoelectric AE transducers.

Thus, based on data available to date, one can conclude that (i) AE is very sensitive to both extrinsic loading conditions (strain rate, stress concentration, temperature, etc.) and intrinsic microstructural factors (phase content, grain size, distribution of non-metallic inclusions, dislocation density, etc.) governing the fracture behaviour under dynamic loading; (ii) a plethora of methods for AE analysis has been proposed and tested in a number of studies on many structural materials, albeit with contrasting results so that no consensus still exists regarding the “best” (or even just “commonly accepted”) methods of AE acquisition and processing in dynamic fracture mechanics testing.

The present work aims at reducing the deficit of AE data during dynamic testing. An instrumented Charpy impact bending was used for high strain rate loading of ductile 17Mn1Si pipe steel specimens with three geometries of notches at different temperatures covering the range the ductile-to-brittle transition. The obtained results will be interpreted in terms of brittle/ductile fracture behavior in conjunction with the notch shape effect on the amount of expended mechanical energy (according to the loading curve) and the released elastic energy (according to the detected AE signal).

To avoid any possible losses associated with amplitude thresholding, a continuous waveform recording was implemented during the entire test commencing from the striker's impact upon the specimen and ending with the specimen fracture into two parts. A methodology is proposed for the AE analysis guided by the features of the dynamic loading curve. The conventional temporal analysis of signals was complemented by the time-frequency analysis employing a continuous wavelet decomposition.

II. Experimental procedure

Mechanical impact tests were conducted on the standard Charpy specimens cut by electric spark machining from commercial 30 mm thick rolled sheet steel 17Mn1Si. The stress concentrators were introduced in the form V-, U-, and I-shaped notches of 2 mm depth. The notch shape was varied to study its effect on the fracture toughness at each stage of crack growth.

The specimens were tested at temperatures $T = 20, -20, \text{ and } -60^\circ\text{C}$ on an Instron 450MPX pendulum impact tester equipped with an instrumented striker. The dynamic loading curve was recorded during each test. Table 1 shows the notch geometries and dimensions.

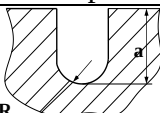
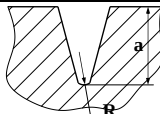
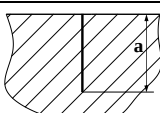
The AE signal generated during impact fracture was detected by a broadband WD (Physical Acoustics Ltd, USA) transducer was mounted on the tester support of 0.5 m apart from the specimen. The acoustic signal was therefore slightly attenuated so that the electric signal at the output of the transducer did not exceed the ADC input range. Due to the high amplitude of the recorded acoustic signal, the AE transducer was connected directly to the ADC board Adlink PCI-9812 operating at a sampling frequency of 10 MHz. The detected voltage range was $\pm 1\text{ V}$. All signals were normalized to the unit peak amplitude.

The continuous wavelet spectra were calculated in the frequency range was from 50 to 500 kHz with a 5 kHz step using the free AGU-Vallen Wavelet software [18]. The AE energy E_{AE} was calculated in the time domain as the time integral of squared voltage over the signal duration. The envelope of the AE signal recorded continuously during impact fracture was obtained by the Hilbert transform. It was then smoothed by a LOWESS (locally weighted least squares) procedure with a 20 μs window.

The mechanisms and stages of impact fracture were considered in depth in our previous companion study [19] where detailed fractographic analysis was presented. Two characteristic stages were readily distinguished (I - crack initiation stage and II - crack propagation stage) by the analysis of the shape of the dynamic loading curve $F(t)$ or, more precisely, of its derivative with respect to time dF/dt . They also can be recognized through characteristic changes in the AE signal as will be shown below.

After impact testing, the fracture surface was examined by a scanning electron microscope (SEM) Leo EVO 50 (Carl Zeiss) in the secondary electron mode. The fracture surface was observed at the crack initiation point and at the center of the sample.

Table 1 – Geometry of the notches in the 17Mn1Si steel specimens

Notch shape	Geometrical shape	Notch tip radius, R , mm	Notch depth, mm
U		1.0	2.0
V		0.25	
I		0.1	

III. Results and Discussion

Figure 1 shows the impact toughness curves of the specimens with different notches at different temperatures. The temperature plays a crucial role in fracture toughness. However, data in Table 2 show that the stress distribution influences strongly the toughness assessment: the increase in the notch tip radius leads to a significant increase in fracture toughness. The AE response was characterized by the change in the AE energy released during impact bending. Let us note it once again that the signal represented in Fig. 1 was recorded in a continuous mode. This signal is synchronized with the dF/dt curve to establish the correlation between two primary stages of impact loading and the AE signal. The AE envelope varies considerably making it possible to reveal the sub-stages during impact loading, c.f. [20].

Figure 2 shows the wavelet time-frequency representation of AE signals during dynamic fracture. The dashed line separates the stages of crack initiation and propagation according to the loading curve. A visual comparison of provided data reveals that the major part of the “energy” of the wavelet spectrum shifts towards stage II when the test temperature decreases and the brittle fracture component increases. This tendency is most pronounced for the specimens with the blunt U-notch, Fig. 2a, d, g. During impact bending at room temperature, when fracture toughness is relatively high, the amount of energy expended at first and second fracture stages, is comparable. Nevertheless, when the ductile crack initiates at stage I a considerable mechanical work is required. Therefore, the released elastic energy is somewhat higher at this stage. At the lowest temperature, the fracture is almost brittle and the energy is mostly released during crack propagation. The brittle crack growth is usually accompanied by the high power AE transients which are clearly seen in the wavelet spectra at low temperatures. That is why the amount of energy (per unit time) at the crack propagation stage is higher than in stage I at temperatures below ambient. For the sharpest I-notch, the AE waveform and the wavelet spectrum varies to a much lesser extent for all three test temperatures, Fig. 2, c, f, i. Overall, comparing Figs. 1 and 2 one can see that while the AE envelopes look similar for different tests, the wavelet representation shows that the onset of stage II depends on the notch shape and temperature.

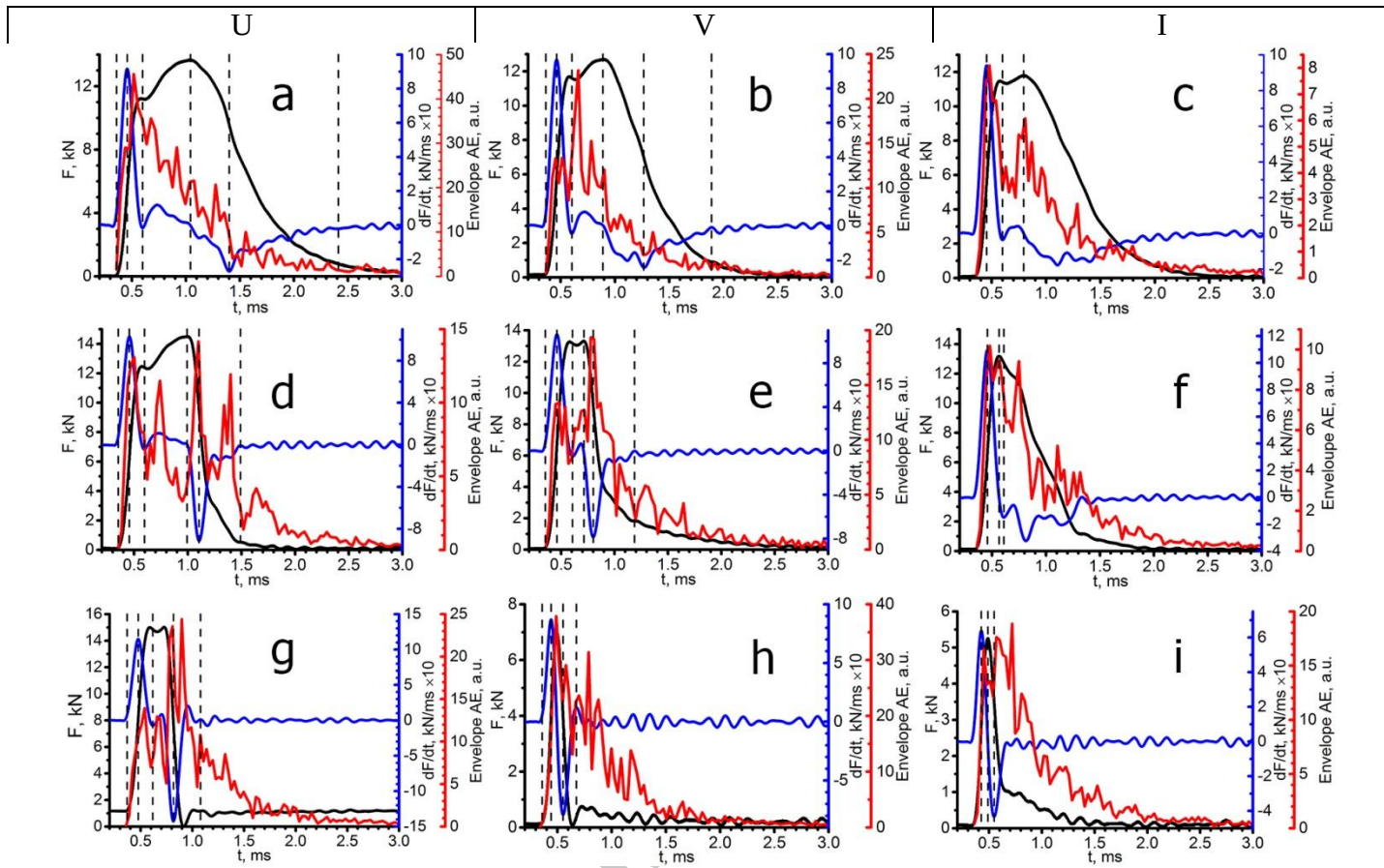


Fig. 1. Time dependence of the loading parameters $F(t)$ and $dF(t)/dt$ synchronized with AE envelope obtained during dynamic Charpy testing of the specimens with different notch shapes at $T = +20$ °C (a–c), -20 °C (d–f), and -60 °C (g–i);

The values of the mechanical energy expended during fracture and the elastic energy released in the form of AE were analyzed using the dynamic loading curves and the accompanying AE signals for initiation and propagation stages separately. The ratio of the elastic energy released at these two stages for both the sharpest and the bluntest notch also tends to change depending on the stress concentration, Table 2. For the U-notched specimen, this ratio is two times higher during stage I than during stage II at room temperature, while for the I-notched specimen the released AE energy is almost equally distributed between both stages. On the other hand, for the U-notched specimen, the energy released during stage II at $T = -60$ °C is about 2.8 times higher than that during stage I. For the sharpest I-notched specimen this ratio is over 8. These observations show undoubtedly that when the fracture toughness drops because of cold embrittlement, the release of elastic energy associated with AE during crack propagation prevails over that during crack initiation. It can be suggested that the latter is accompanied by energy dissipation due to high-rate plastic deformation.

The fracture energy determined from the impact toughness curve (expended energy - E_{exp}) is expressed in Joules, and the energy estimated from the AE envelope (released energy - E_{rel}) is in arbitrary units. These quantities are summarized in Table 2 for different specimens and temperatures.

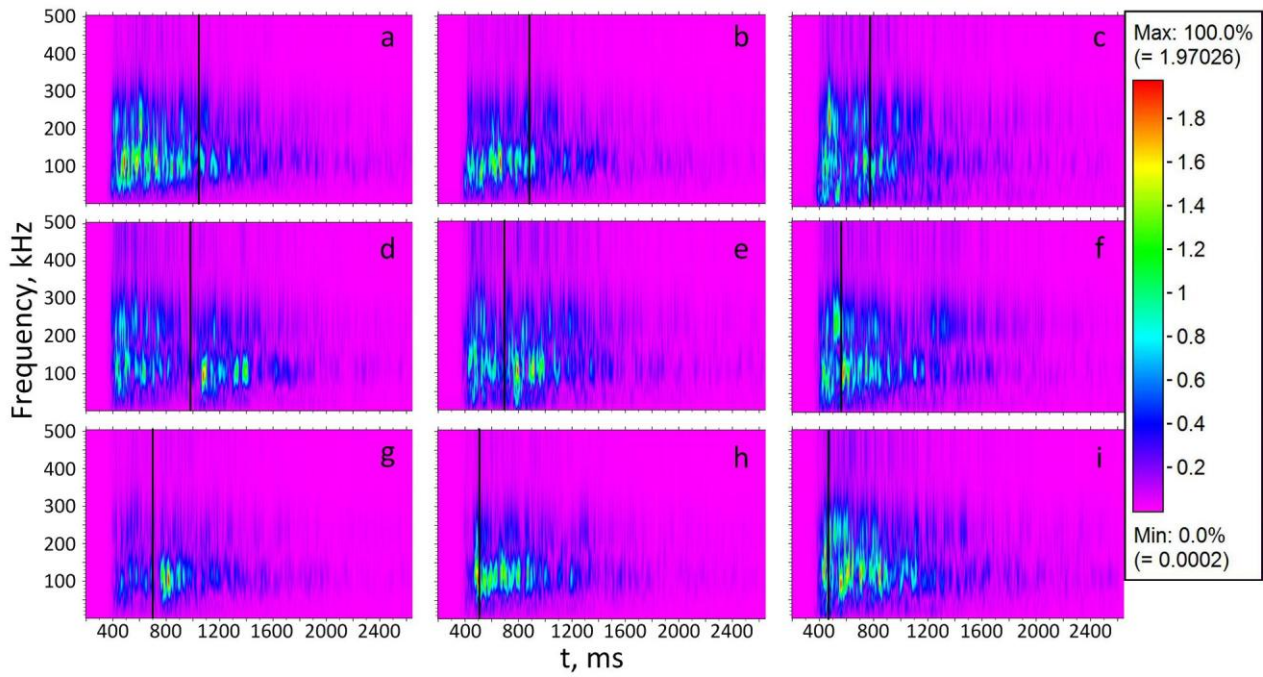


Fig. 2. Wavelet spectrum of the AE signal corresponding to impact fracture of specimens with different notch shapes (a,d,g – U-notch; b,e,h, -V-notch; c,f,i – I-notch) tested at temperatures $T = +20\text{ }^{\circ}\text{C}$ (a–c), $-20\text{ }^{\circ}\text{C}$ (d–f), and $-60\text{ }^{\circ}\text{C}$ (g–i).

Table 2. Expended mechanical energy E_{exp} and released AE energy E_{rel} in impact bending of 17Mn1Si steel during stage I/stage II (and their ratios) at different test temperatures

$T, ^{\circ}\text{C}$	E_{exp}, J	$E_{\text{rel}}, \text{a.u.}$	E_{exp}, J	$E_{\text{rel}}, \text{a.u.}$	E_{exp}, J	$E_{\text{rel}}, \text{a.u.}$
	U-notch		V-notch		I-notch	
+20	37.6 / 43.2 (0.85)	40.2 / ~22 (1.83)	27.4 / 30.1 (0.91)	26.7 / ~18 (1.48)	21.1 / 34.0 (0.62)	25.6 / ~32 (0.80)
-20	38.8 / 12.8 (3.03)	31.7 / ~38 (0.83)	18.3 / 18.0 (1.02)	17.9 / ~40 (0.45)	7.7 / 30.3 (0.25)	13.6 / ~48 (0.28)
-60	20.2 / 4.8 (4.21)	13.5 / ~38 (0.36)	2.57 / 4.8 (0.54)	5.6 / ~41 (0.14)	2.1 / 5.3 (0.40)	6.4 / ~52 (0.12)

U-notch

$T = +20\text{ }^{\circ}\text{C}$ (the most ductile fracture behavior, the critical fracture toughness $KCU_{+20\text{ }^{\circ}\text{C}} = 106\text{ J/cm}^2$). The analysis of data shown in Fig. 1 reveals that the maximum AE energy corresponds to the initial loading stage before the load reaches its maximum P_{max} ($t < 1.08\text{ ms}$). This is in good agreement with the AE envelope shape. The subsequent transition from the crack initiation stage to the stage of propagation is accompanied by a decrease in the recorded AE signal. This indicates that the dissipation of the elastic energy imposed into the Charpy specimen during ductile fracture on stage II is mainly associated with the heat release due to dislocation mechanisms of plastic deformation. The crack initiation resistance is overcome on stage I with a large energy release (cf. $E_{\text{rel I}} = 40.2\text{ a.u.}$, $E_{\text{rel II}} \sim 22\text{ a.u.}$). Concurrently, the fracture energies at both stages are comparable (cf. $E_{\text{exp I}} = 37.6\text{ J}$, $E_{\text{exp II}} = 43.2\text{ J}$), which is most probably caused by a relatively long time of crack propagation.

$T = -20\text{ }^{\circ}\text{C}$ ($KCU_{-20\text{ }^{\circ}\text{C}} = 51.6\text{ J/cm}^2$). Compared to room temperature testing, Figure 1d shows that the fracture behavior appears to be more brittle. The shape of the impact toughness curve resembles that observed at room temperature. However, the maximum AE energy corresponds to the load beyond P_{max} ($t > 1.01\text{ ms}$), which is also seen in the AE wavelet spectrum, Fig. 2d. Similarly to testing at room temperature, the largest fraction of AE energy is produced in the frequency range of

50–150 kHz. The amount of energy released during stage I decreased by ~ 10 a.u. compared to that measured at 20°C . However, during crack propagation, the same parameter increased by ~ 20 a.u. (cf. $E_{\text{rel I}} = 31.7$ a.u., $E_{\text{rel II}} \sim 38$ a.u.). Thus, the more brittle fracture behavior during stage II was accompanied by a significant increase in the released energy. This is consistent with the fact that the fracture energy at the second stage (more brittle) was almost four times lower than in the first stage (more ductile) (cf. $E_{\text{exp I}} = 38.8$ J, $E_{\text{exp II}} = 12.8$ J). Compared to room temperature testing, the amount of the released AE energy during the crack initiation stage changed appreciably although the approximately equal amount of the mechanical energy was expended on the same stage. This means that the AE energy and the mechanical energy are not related unambiguously.

$T = -60^\circ\text{C}$ ($KCU_{-60^\circ\text{C}} = 32 \text{ J/cm}^2$). Figure 1g shows the results of testing at the lowest temperature below the ductile-to-brittle transition. The brittle fracture behavior is evident from the impact loading curve. The maximum AE energy is again seen at loads beyond P_{max} , i.e., during stage II ($t > 0.75$ ms). The AE energy at the crack initiation stage is almost three times lower than at the propagation stage (cf. $E_{\text{rel I}} = 13.5$ a.u., $E_{\text{rel II}} \sim 38$ a.u.). In comparison with the results of testing at -20°C , the amount of energy released at the crack initiation stage decreased more than twice, while during stage II it remained almost unchanged. Thus, the brittle crack propagation was systematically accompanied by a high energy AE: the greater the brittleness, the higher the AE. This agrees well with the fracture energy estimates (cf. $E_{\text{exp I}} = 20.2$ J, $E_{\text{exp II}} = 4.8$ J). The test temperature did not affect the characteristic AE frequency range significantly, Fig. 2f.

For the sake of comparison, the energy values characterizing the impact fracture behavior are represented in Fig. 3 together with typical SEM micrographs of fracture surfaces for both stages.

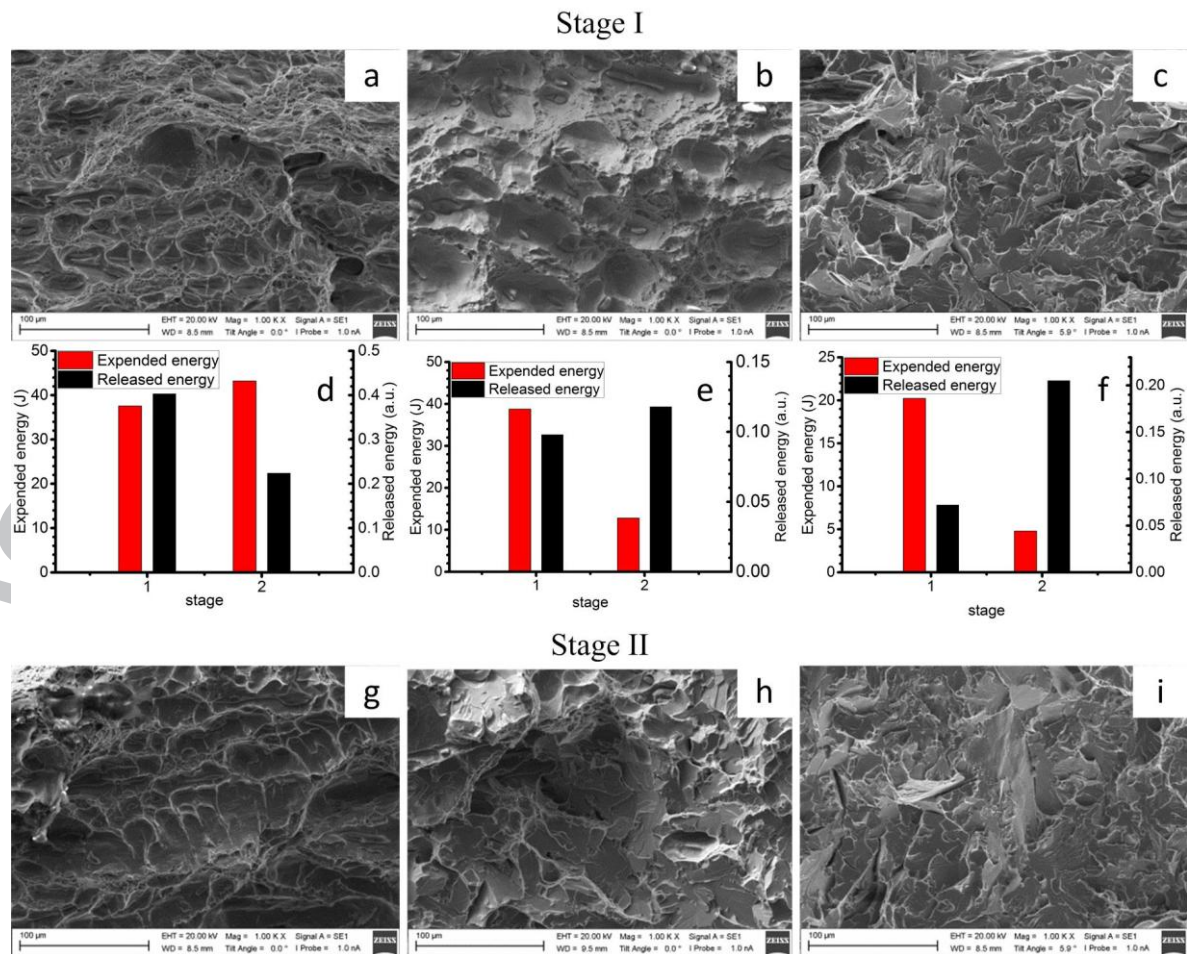


Fig. 3. Morphology of fracture surface and characteristic energy parameters for crack initiation (I) and propagation (II) stages calculated from the dynamic loading curve (red) and from AE data (black) for U-notched specimens tested at $+20^\circ\text{C}$ (a, d, g), -20°C (b, e, h), and -60°C (c, f, i).

Thus, the decreasing test temperature results in a gradual decrease of the amount of the expended mechanical energy and of the AE released during stage I crack initiation. On the other hand, the amount of the mechanical energy expended during stage II crack propagation also gradually decreases, while the AE energy increases.

V-notch

$T = +20\text{ }^{\circ}\text{C}$. A decrease in the notch tip radius leads to an increase in the stress concentration factor. It should also contribute to the increase in the brittle fracture component (especially at the initiation stage I). Figure 1b shows the results of room temperature testing of the specimens exhibiting the most ductile fracture behavior for the given notch shape (the fracture toughness $KCV_{+20\text{ }^{\circ}\text{C}} = 73.3\text{ J/cm}^2$). Similarly to the U-notched specimen tested at the same temperature, the maximum AE energy is observed at the load lower than $P_{\max}$ ($t = 0.92\text{ ms}$), which also agrees well with the AE envelope shape, Fig. 2b. The KCV value decreased by more than 30 J/cm^2 if compared to the KCU value of the specimen tested at the same temperature. However, in the case of the sharper notch, the ratio of the fracture energy during stages I (cf. $E_{\exp I U} = 37.6\text{ J}$, $E_{\exp I V} = 27.4\text{ J}$) and II remained almost the same (cf. $E_{\exp II U} = 43.2\text{ J}$, $E_{\exp II V} = 30.1\text{ J}$). Apparently, for this reason, the transition from the crack initiation stage to the crack propagation stage is accompanied by a decrease in the AE energy (cf. $E_{\text{rel } i} = 26.7\text{ a.u.}$, $E_{\text{rel } p} \sim 18\text{ a.u.}$). On the other hand, the fracture energy corresponding to each stage is comparable.

$T = -20\text{ }^{\circ}\text{C}$. Results of testing at this temperature are shown in Fig. 1d. The fracture occurs in a more brittle mode ($KCV_{-20\text{ }^{\circ}\text{C}} = 46\text{ J/cm}^2$, which, however, is only by 5 J/cm^2 lower than the fracture toughness of the U-notched specimen). The shape of the dynamic loading curve is again similar to that for room temperature tests. The maximum AE energy is seen after the maximum load $P_{\max}$ ($t = 0.72\text{ ms}$), like that in the U-notched specimen. This is also seen in the wavelet spectrum of the AE signal, Fig. 2e. The fracture energies during both stages I and II were approximately equal, unlike those for the U-notched specimen (cf. $E_{\exp I} = 18.3\text{ J}$, $E_{\exp II} = 18.0\text{ J}$). On the other hand, as compared to the U-notch, the amount of the released energy at stage I decreased considerably, while during stage II it increased only slightly.

$T = -60\text{ }^{\circ}\text{C}$. In contrast to tests on the U-notched specimen, the fracture of the V-notched specimen was almost brittle at -60°C ($KCV_{-60\text{ }^{\circ}\text{C}} = 9.3\text{ J/cm}^2$). The embrittlement affected both the shape of the impact loading curve and the duration of the characteristic stages, Fig. 1h. For this reason, the maximum AE energies correspond to the load range both before and mostly after reaching $P_{\max}$. Moreover, the brittle fracture behavior during stage II is reflected in the AE signal/spectrum shape, Fig. 2h, even at the time when the external load dropped. The brittle fracture behavior is also in good agreement with the low fracture energies measured (cf. $E_{\exp I} = 2.47\text{ J}$, $E_{\exp II} = 4.79\text{ J}$). Compared to the U-notched specimen, the amount of the released energy during stage I decreased by a factor of three. However, it remained almost unchanged during the propagation stage (cf. $E_{\text{rel } i} = 5.6\text{ a.u.}$, $E_{\text{rel } p} \sim 41\text{ a.u.}$).

Figure 4 shows typical SEM micrographs of the fracture surfaces and compares the energy characteristics of impact fracture for both stages in the V-notch specimens.

Thus, these findings corroborate the thesis that the more brittle fracture behavior is accompanied by a higher-energy AE signal. It should also be highlighted that the AE energy released during the initiation stage I decreases significantly if compared to the U-notched specimen. However, only small relative change is noticed during stage II. It has been shown that the increase in the stress concentration factor at the notch tip of Charpy specimens and the test temperature reduction is accompanied by a decrease in the amount of the mechanical energy expended during crack initiation and propagation, as compared to the that in the U-notched specimens, while the amount of (normalized) AE released energy remains approximately the same.

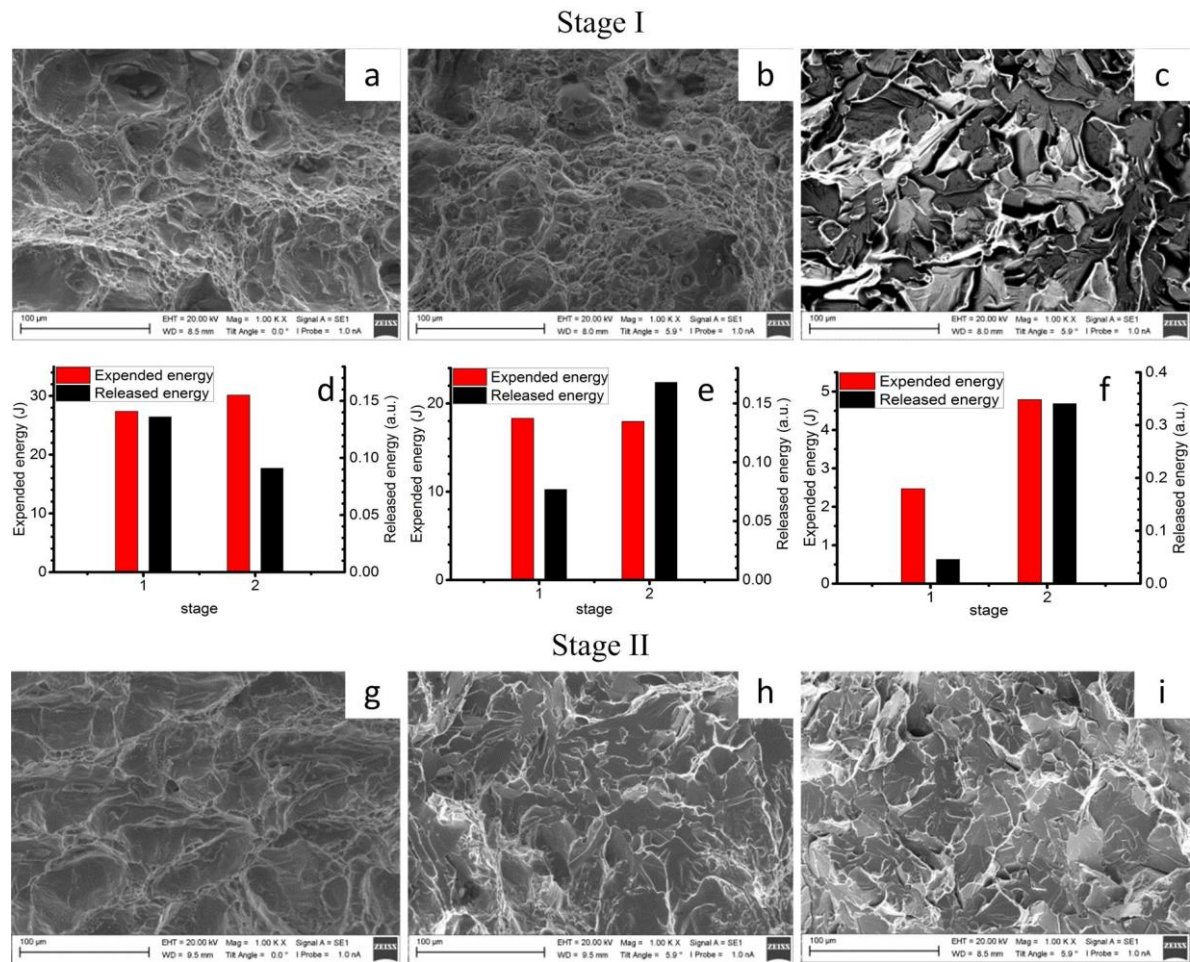


Fig. 4. Morphology of fracture surface and characteristic energy parameters for crack initiation (I) and propagation (II) stages calculated from the dynamic loading curve (red) and from AE data (black) for V-notched specimens tested at +20°C (a, d, g), -20°C (b,e,h), and -60 °C (c,f,i).

I-notch

$T = +20^{\circ}\text{C}$. Reduction in the notch tip radius increases the stress concentration and promotes brittle fracture, which is particularly pronounced during the initiation stage I. Figure 1c shows the testing results for specimen loaded at room temperature. The fracture toughness $K_{CI+20^{\circ}\text{C}} = 70 \text{ J/cm}^2$ is found to be close to that for the V-notched specimen. Similarly to the U- and V-notched specimens, the maximum AE energy is noticed at loads smaller than $P_{\max}$ ($t < 0.81 \text{ ms}$), which is again nicely seen in the wavelet spectrum of the AE signal, Fig. 2c. In contrast to the less sharp V-notch, there is only a little difference in the fracture energy values measured during the first and the second stages, Table 2. Evidently, it is the shorter duration of stage I and the smaller amount of fracture energy in the specimen with the sharpest notch at this stage that caused a comparable level of AE energy in both stages I and II (which is different from the behavior of the U- and V-notched specimens tested at room temperature). Nevertheless, the amount of the released energy in the I-notched specimen during stage II is highest compared to other notches.

$T = -20^{\circ}\text{C}$. Figure 1f represents the results for the V-notched specimen tested at -20°C . The brittle fracture component increased and the fracture toughness reduced reasonably to $K_{CI-20^{\circ}\text{C}} = 38 \text{ J/cm}^2$, which is by approximately 8 J/cm^2 smaller than that for the V-notched specimen. The shape of the impact loading curve having only one maximum is no longer similar to that obtained at room temperature impact testing. Compared to specimens with other notch shapes, the AE energy peak shifts further to shorter loading times. The AE maximum is attained before the $P_{\max}$ ($t < 0.56 \text{ ms}$) value is reached (see also the AE wavelet spectrum shown in Fig. 2f). The amount of AE energy measured

during stage II of the crack growth is still significant (cf. for the I-notched specimen $E_{rel I} = 13.6$ a.u., $E_{rel II} \sim 48$ a.u.). Compared to the room temperature test, the value of this parameter decreased almost twice for stage I, while for the crack propagation stage it increased almost 1.5 times. The fracture energy was found to be more than twice as large as that during stage I, similarly to the V-notch in stage II.

$T = -60$ °C. The fracture at this temperature was almost brittle resembling that in the V-notched specimen. The fracture toughness was estimated as $KIC_{-60\text{ °C}} = 9.4 \text{ J/cm}^2$. Therefore, both the shape of the dynamic loading curves and the characteristic fracture stages are similar to those in the V-notched specimen, Fig. 1i. In contrast to room temperature testing, the position of the maximum AE energy is observed beyond P_{max} ($t > 0.4$ ms). Similarly to the V-notched specimen tests at the same temperature, the brittle fracture behavior during stage II is recognized in the AE wavelet spectrum, Fig. 2i. The released AE energy during stage I is substantially less than that during stage II (cf. $E_{rel I} = 6.4$ a.u., $E_{rel II} \sim 52$ a.u.). Furthermore, it reduced appreciably in comparison to that obtained at -20 °C. In comparison with the V-notched specimen, only the energy released on stage II increased noticeably (by more than 10 a.u.). The brittle fracture behavior results in low mechanical energies estimates (cf. $E_{exp I} = 2.06 \text{ J}$, $E_{exp II} = 5.29 \text{ J}$). Although the fracture energy value during stage II is only of 2.5 times larger than during stage I, the AE energy emitted during the stage of crack propagation is almost by order of magnitude higher than that during stage I. Thus, the fracture energy ratio $E_{exp I} / E_{exp II}$ does not necessarily correlate with the respective ratio of the AE energy.

The results obtained on the I-notched specimen tests are summarized in Fig. 5 showing both the SEM images of the typical fragments of the fracture surface observed during both crack initiation and propagation stages and corresponding AE energies. Overall, the observed experimental findings related to the change in the mechanical energy expended and released during fracture of Charpy specimens with decreasing temperature are qualitatively similar for the specimens with V- and I-notches, though they are not quantitatively identical.

Experimental data concerning the expended mechanical energy and the released AE energy measured during impact testing represented in Table 1 and Figs. 3-5 reveal systematic trends in the behavior of the mechanical impact fracture energy and the AE energy depending on the notch shapes and temperatures. For the crack initiation stage one can see that the lower the temperature is, the lower both energy components are. A different trend is observed at the crack propagation stage: the expended mechanical energy decreases with decreasing temperature, but the fraction of the released AE energy increases. This result can be rationalized as follows. The ductile fracture mode dominates during the initiation stage I. The ductile behavior is mediated by dislocations whose activity generates measurable AE. However, the AE energy (or power) associated with dislocation motion is low compared to that during initiation and propagation of a brittle crack. Temperature reduction strongly reduces the thermally-activated dislocation activity, which is particularly clear in BCC metals, alloys, and steels. During crack propagation, especially at low temperatures, a smaller amount of energy is expended in damping due to plastic deformation, and therefore the fraction of the released energy is higher.

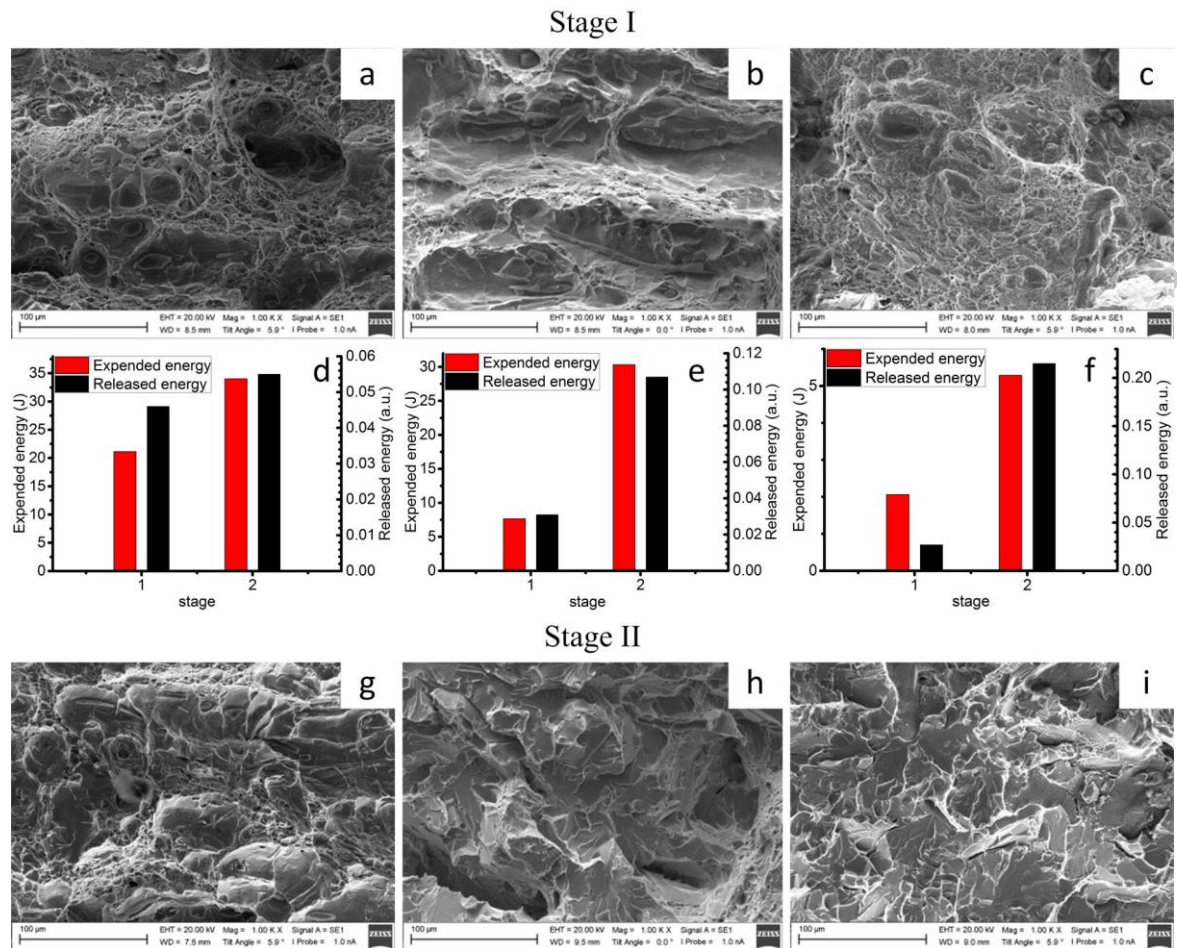


Fig. 5. Morphology of fracture surface and characteristic energy parameters for crack initiation (I) and propagation (II) stages calculated from the dynamic loading curve (red) and from AE data (black) for III-notched specimens tested at +20°C (a, d, g), -20°C (b, e, h), and -60 °C (c, f, i).

IV. Summary

The impact fracture behavior of ductile 17Mn1Si pipe steel with different notch shapes was investigated during testing at different temperatures between +20°C to -60°C covering the range of ductile-to-brittle transition. The analysis was performed by comparing the energy expended in crack initiation and propagation according to the dynamic loading curve and the released AE energy in all cases. The energy distribution of AE signals accompanying impact fracture was investigated in the time-frequency domain by continuous wavelets revealing a distinction between main stages of fracture development. In short, the results are summarized as follows.

U-notched specimens. A typical trend with decreasing test temperature is seen as a gradual decrease in the amount of expended and released energy during stage I. The amount of expended energy during stage II also gradually decreases, while the amount of AE energy increases.

V-notched specimens. The fracture behavior is more brittle with an appreciably larger amount of the released AE energy than that in the U-notched specimens. Compared to the U-notched specimen, there is a noticeable decrease in the AE energy released during the stage I fracture, while during stage II it changes only slightly.

I-notched specimens. The behavior of expended and released energy components during fracture the V- and I-notched specimens is qualitatively similar (though not identical) because their crack tip radii are similar and the brittle fracture dominates in both specimens.

Both the expended mechanical impact energy and the released AE energy exhibit similar trends during the crack initiation stage: the lower the temperature, the lower the energy regardless of the notch geometry. A significantly different behavior is observed during the crack propagation stage:

while the expended energy decreases with temperature similarly to that on stage I, the released energy, on the contrary, increases appreciably.

There is still a lot of room for optimization of all elements in the AE acquisition-processing chain. This concerns (i) the sensor type and its location; (ii) a way of a time-frequency representation of a signal; (iii) a process of information squeezing to physically and mechanically justifiable criteria, etc. A radical departure is needed in this way from qualitative correlations to causation and quantitative relations between the measurable parameters of fracture mechanics and AE characteristics. The progress in this direction is anticipated through a thorough constitutive (possibly multiscale) modeling of dynamic fracture in conjunction with microstructural processes underlying both brittle and ductile fracture and their interactions.

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Highlights

of article «Acoustic emission study on the effect of notch shape and temperature on elastic energy release during impact testing of 17Mn1Si pipe steel»

The impact fracture behavior of ductile 17Mn1Si pipe steel with different notch shapes was investigated covering the range of ductile-to-brittle transition.

The energy expended at crack initiation and propagation according to the dynamic loading curve and the released acoustic emission (AE) energy was compared.

The energy distribution of acoustic emission (AE) signals at impact fracture was investigated in the time-frequency domain by continuous wavelets revealing a distinction between main stages of fracture.

Both the expended mechanical impact and the released acoustic emission (AE) energy exhibit similar trends during the crack initiation stage: the lower the temperature, the lower the energy.

During the crack propagation stage the expended energy decreases with temperature similarly to that on stage I, while the released energy, on the contrary, increases appreciably.

Wavelet spectra of AE signals corresponding to impact fracture of specimens with different notch shapes and testing temperatures

