Measurement techniques for determination of ductile crack initiation on Charpy specimens

Messmethoden zur Bestimmung der duktilen Rissinitiierung in Charpy-Proben

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In the engineering practice it is of importance to know the effect of loading rate on the material behaviour including the fracture mechanics properties. Depending on the material behaviour under a given loading condition, different fracture mechanics parameters should be determined. The critical values of these parameters are usually related to the onset of crack initiation which can be determined easier in the case of brittle fracture. But in the case of ductile fracture additional measurement techniques are required. This paper presents some possibilities to characterise the fracture resistance against ductile fracture using instrumented impact testing. The magnetic emission technique will be introduced as a potential measurement method for determining the onset of ductile crack propagation in magnetizable metals.

In der Ingenieurpraxis ist es wichtig, den Einfluss der Belastungsgeschwindigkeit auf das Werkstoffverhalten einschließlich der Bruchmechanik-Parameter zu kennen. Abhängig vom Werkstoffverhalten unter den jeweiligen Beanspruchungsbedingungen müssen unterschiedliche bruchmechanische Kennwerte verwendet werden. Kritische Kennwerte, mit denen gewöhnlich die Rissinitiierung festgelegt wird, lassen sich aber nur beim spröden Bruch einfach bestimmen.

Dagegen sind beim duktilen Bruch zusätzliche Messtechniken erforderlich. In diesem Beitrag werden einige Möglichkeiten zur Charakterisierung des Bruchwiderstandes beim duktilen Bruch mit Hilfe des instrumentierten Kerbschlagbiegeversuch vorgestellt. Die magnetische Emission kann als eine potentielle Methode zum Nachweis des Beginns der duktilen Rissausbreitung in magnetisierbaren Werkstoffen eingesetzt werden.

Introduction

The collection of metals behaviour under impact loading conditions has been started at the end of the last century. One of the milestone in the testing procedures was created in 1901 by G. Charpy [1]. From this period of time the specialists almost in all countries published their overviews [2–10] and the present state of the testing procedures and results. Implementing of the instrumented impact testing [3–10] has started a better knowledge of the materials behaviour under impact loading condition.

In fracture mechanics testing determining the instant of crack initiation is the basic task for the measurement of critical material parameters. This task can be solved easier in the case of brittle fracture since a sudden drop in the force signal usually accompanies brittle crack initiation. But in the case of ductile fracture or if stable crack propagation occurs before unstable one, the instant of crack initiation cannot be determined directly from the force signal. In these cases additional measurement techniques should be applied.

A number of techniques are available for quasi-static applications, but only some of them can be used when higher loading rate is applied. Due to the special arrangement of the impact pendulum the following direct measurement techniques can be used for crack initiation detection:

- laser COD-measurement – only with “reversed” pendulum [11],
- strain gauge measurement [12],
- acoustic emission measurement [13],
- potential drop measurement [14],
- magnetic emission measurement [15, 16].

Besides these methods there are two indirect methods:

- compliance method [17],
- stretch zone measurement [18].

In the present paper some methods for characterising the ductile crack initiation resistance will be demonstrated and compared.

Simple method for determining ductile crack initiation resistance

At the beginning of the application of instrumented impact testing, when there was not available measurement techniques for detecting the ductile crack initiation, initiation was thought to occur at the maximum load. On the basis of this approximation the fracture energy can be divided into two parts: crack initiation energy (W_i) and crack propagation energy (W_p) (*Fig 1*).

Both partial energy values can be determined by integration of the load-displacement curve:

$$W_i = \int_{s=0}^{s_m} F(s)ds, \text{ and} \tag{1}$$

$$W_p = W_t - W_i = \int_{s=s_m}^{s_t} F(s)ds, \tag{2}$$

where s_m – displacement at maximum load, mm
s_t – displacement at final fracture, mm
W_t – total absorbed energy for fracture, J.

On the basis of large number of experiments on different structural steel it was proved that the crack initiation energy does not depend on the temperature when the fracture is duc-

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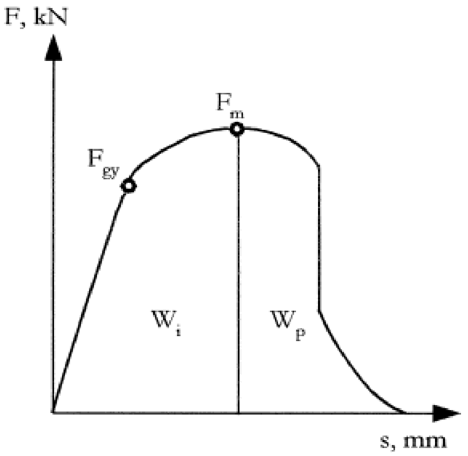


Fig. 1. Separation of impact energy into initiation and propagation energy

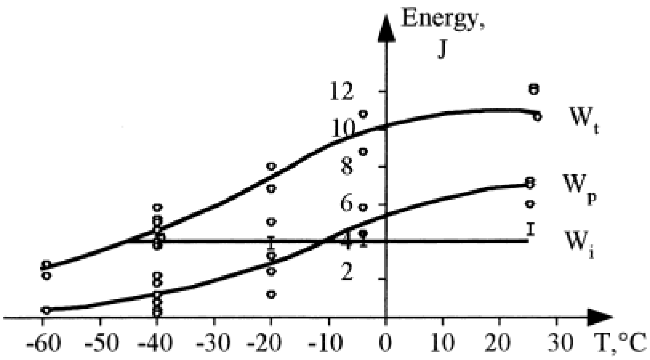


Fig. 2. Total, initiation and propagation energies of Charpy-V specimens as a function of temperature (St 52-3 steel)

tile or mixed (in the upper shelf and in the transition region) [19]. One example is shown in *Fig. 2*.

When some new measurement techniques had been developed for detecting ductile crack initiation during impact test, it was proved that the ductile initiation usually occurs much before the maximum load. One of these techniques was the magnetic emission measurement. Many investigations have been done during the last decade to study the applicability and limitations of this technique.

Magnetic emission measurement technique

The magnetic emission technique has been developed especially for impact testing [15, 16], but can be applied for investigating fast fracture processes as well, like brittle fracture. The principle of this measurement technique is demonstrated in *Fig. 3*.

Two physical phenomena contribute to the magnetic emission sigsnal:

(a) mechanically induced Barkhausen signals appear when the internal magnetic structure changes during loading, and

(b) a propagating crack causes the internal magnetic field to emerge from the solid into the gap between the two crack surfaces, thereby changing the external magnetic field. These field variations can be observed locally by a magnetic transducer which basically consists of a coil. The transducer's output voltage is the *magnetic emission (ME)* signal which is proportional to the derivative of the magnetic field (MF) (*Fig. 3*).

a/

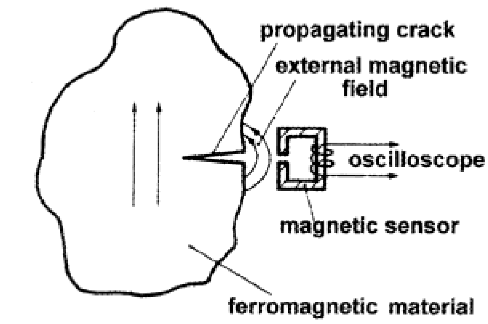


Fig. 3. The principle of magnetic emission technique

The emission probe was installed into an instrumented impact testing system with computer aided data-acquisition which is shown in *Fig. 4*. The force measurement is carried out by strain gauges glued on both sides of the tup (3). The magnetic emission probe (5) is located in a metal box close to the notch root of the specimen. The instrumented tup and the emission probe can be seen in *Fig. 5*.

An external optical trigger device (6) makes the data acquisition start. When the two pins flag on the hammer (7) goes through the optical trigger device, two pulses are produced and the time interval between these pulses is measured by a clock (9). From this time the impact velocity can be determined. The strain gauges and the emission probes are connected to the voltage supplies and the amplifiers (8) and their signals are recorded by a TEKTRONIX TDS 420A digital oscilloscope. The data could be transferred to the PC either through a GPIB interface or with diskettes. Then the data evaluation procedure is usually done with spreadsheet programs.

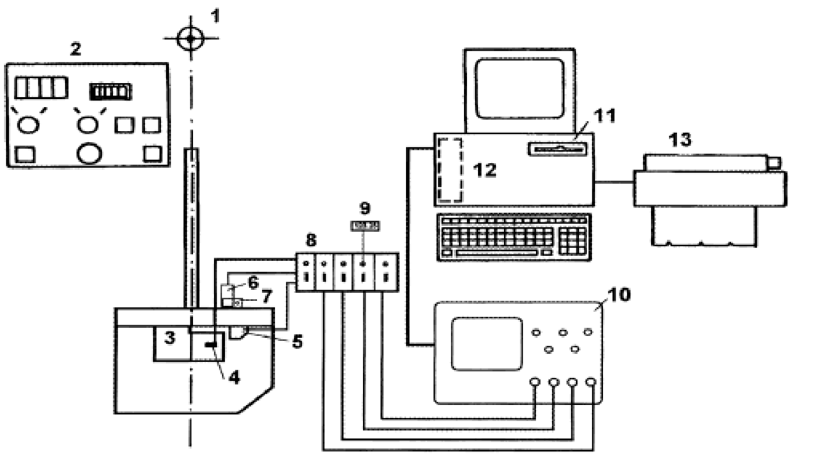
Application of magnetic emission technique for detecting ductile crack initiation

Establishment of the "field method"

Stable crack initiation can usually not be determined directly from ME signals. This is demonstrated by an experiment using a ductile behaving pre-cracked steel specimen (BS4360-50E), see *Fig. 6a* [22]. For these applications a so called *"field method"* was developed [21] which uses the integrated ME signal, i. e., the magnetic field history, MF(t):

$$MF(t) = \int_{r=0}^{t} ME(\tau)d\tau \qquad (3)$$

It was observed that ME signals originated by crack propagation can be distinguished from those originated by Barkhausen noise in the field curve by a change of the slope. This is demonstrated in *Fig. 6b* [22]. A continuous increase of the field can be seen from the beginning of the impact event



1	Angle measurement	8	Voltage supply and amplifiers
2	PSD 300 /150 impact pendulum	9	Clock display
3	Instrumented tup	10	Digital memory scope
4	Strain gage	11	Computer
5	Magnetic probe	12	GPIB card
6	Optical trigger device	13	Printer
7	Triggering flags		

Fig. 4. Instrumented impact pendulum and the data acquisition system

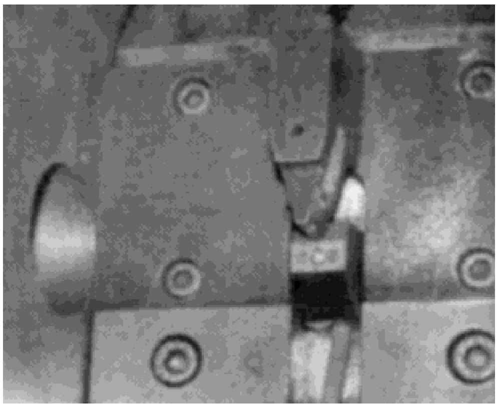


Fig. 5. The instrumented tup with the magnetic emission probe

with increasing force. The rupture event is indicated by a discontinuity in the slope of the field curve. This becomes even more obvious when this result is compared with a field curve of a low-blow experiment with no crack extension (*Fig. 7*). In both cases first the MF curve is increasing continuously. After the elastic part of the load curve a stabilisation can be seen in the MF curve. The magnetic field starts to change again when crack propagation occurs.

Application for V-notched specimens

This method was applied for determining initiation energy of Charpy-V specimens of a heat resistance steel. In some cases a significant change was observed in the slope of the

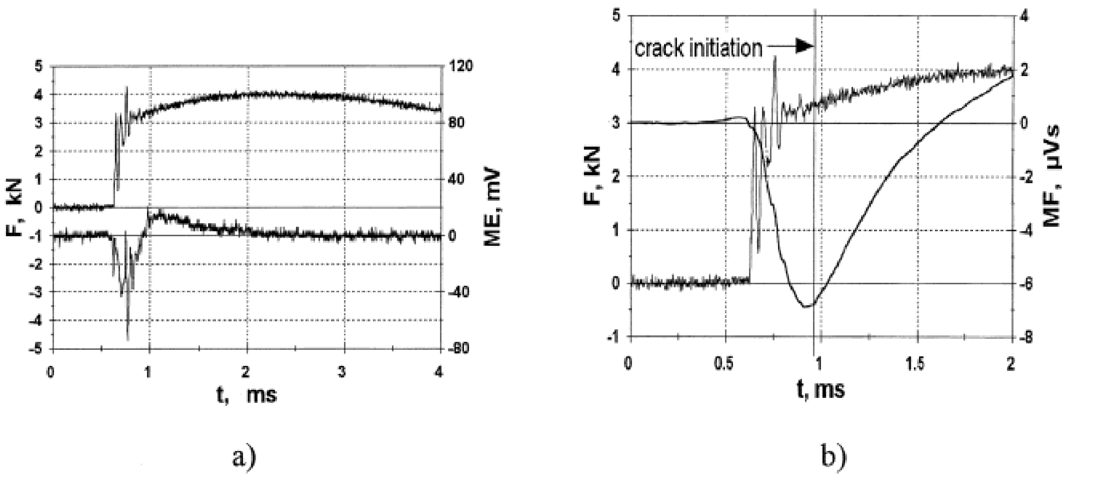


Fig. 6. Force, ME and MF signals of a low-blow experiment on a pre-cracked BS4360-50E steel sample (v_0 = 1,57 m/s)

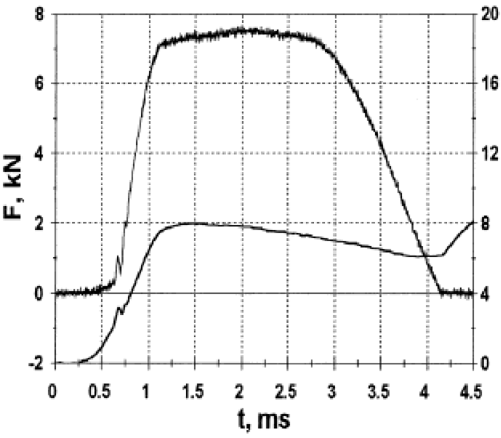


Fig. 7. Force and MF signals of pre-cracked BS4360-50E steel sample without crack extension, (low-blow experiment: $v_0 = 0{,}8$ m/s)

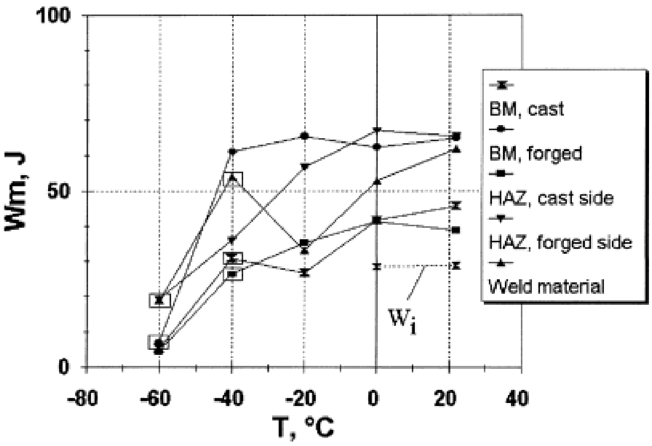


Fig. 9. Average W_m values and real initiation energies (zones of the welded joint of 10 Cr Mo 9 – 10 forged and GS 18 Cr Mo 9 10 cast pipe)

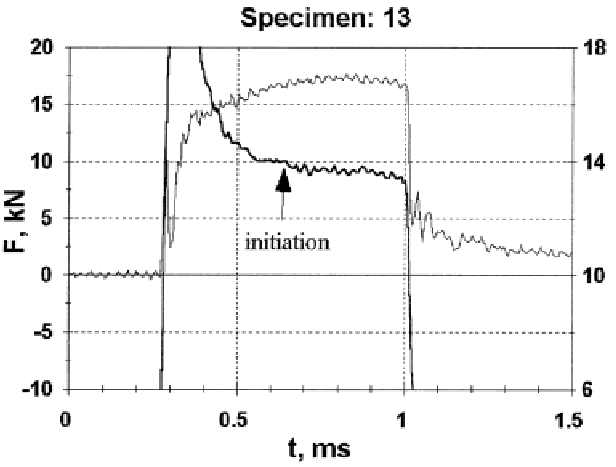


Fig. 8. Force and magnetic field curves of a Charpy-V specimen of GS 18 Cr Mo 9 10 cast base material ($T = 0\,°C$; $v_0 = 5{,}5$ m/s)

field signal (MF) before the maximum point – as is shown in *Fig. 8* – which can be correlated to the initiation of stable crack propagation [23]. The energy absorbed up to this initiation point (W_i) has been calculated for two specimens of the cast base material and is plotted in *Fig. 9*. For these specimens the initiation energy was 56% and 65% of the W_m (energy absorbed up to the maximum load) values.

Application for pre-cracked specimens

Other methods have also proved [11, 12, 14] that in the case of pre-cracked specimens the ductile crack initiation also occurs before the maximum load. *Fig. 10* shows an example how the magnetic emission measurement delivers the initiation point applying the field method [24]. The ductile crack extension preceded the brittle fracture can be observed on the SEM picture of the fracture surface as well (*Fig. 11*).

Knowing the onset of initiation the critical J-integral value related to the ductile initiation can be then derived with eq. 4 [25]:

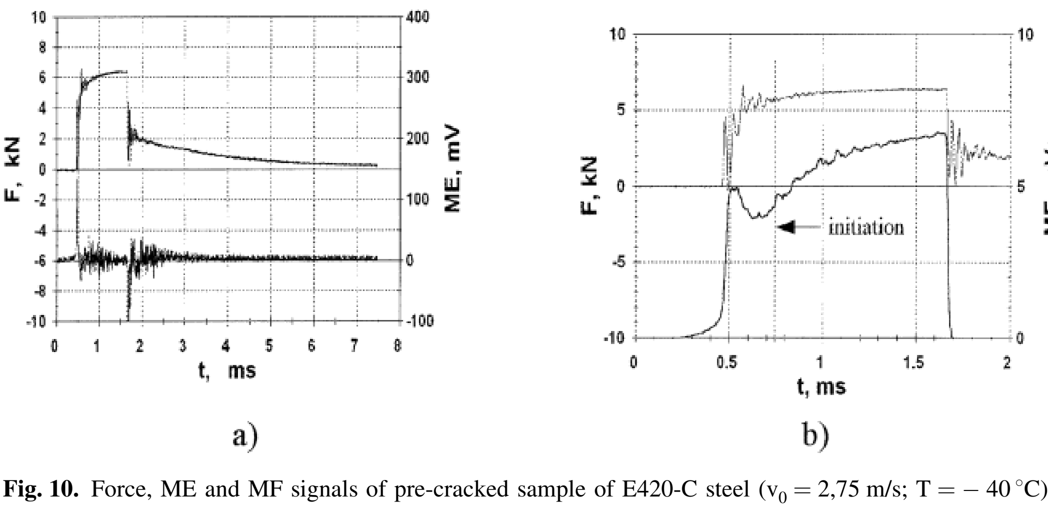


Fig. 10. Force, ME and MF signals of pre-cracked sample of E420-C steel ($v_0 = 2{,}75$ m/s; $T = -40\,°C$)

$$J_{id} = \frac{2 \cdot U_i}{B \cdot (W - a_0)} \tag{4}$$

where U_i is the energy absorbed by the specimen up to the initiation and is calculated by integrating the force-displacement (F-f) curve using eq. 5:

$$U_i = \int_{f=0}^{f_i} F(f)df \tag{5}$$

Then the initiation toughness (K_{Id}) can be determined for plain stress condition using eq. 6:

$$K_{Id} = \sqrt{E \cdot J_{id}} \tag{6}$$

where E is the Young modulus of the investigated material.

In this way the real material resistance against ductile crack initiation can be characterised. Experiments on pre-cracked specimens of E420-C steel showed that while the transition temperature can depend on impact velocity (*Fig. 12, 13*), the ductile initiation toughness does not depend on it.

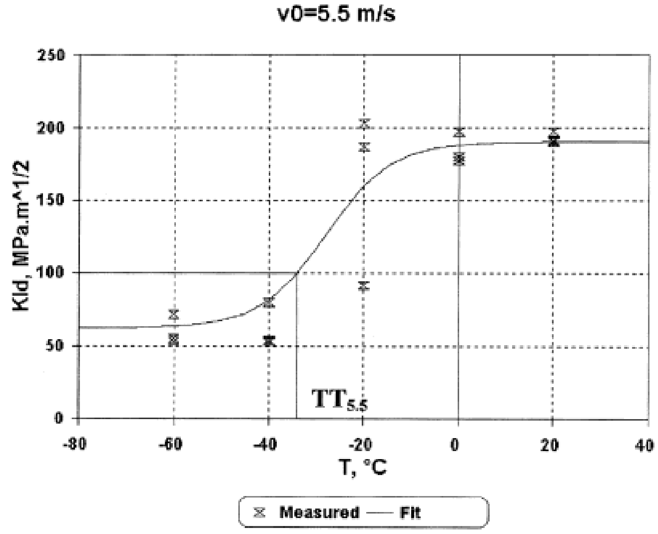


Fig. 13. Dynamic fracture toughness vs. temperature for $v_0 = 5{,}5$ m/s impact velocity (E420-C steel)

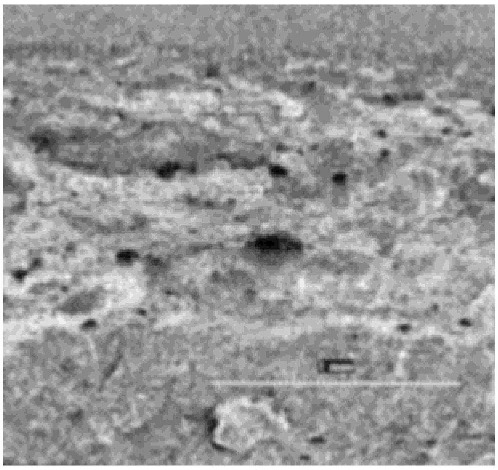


Fig. 11. SEM picture of pre-cracked sample of E420-C steel with ductile crack extension followed by brittle fracture ($v_0 = 2{,}75$ m/s; $T = -40\,°C$)

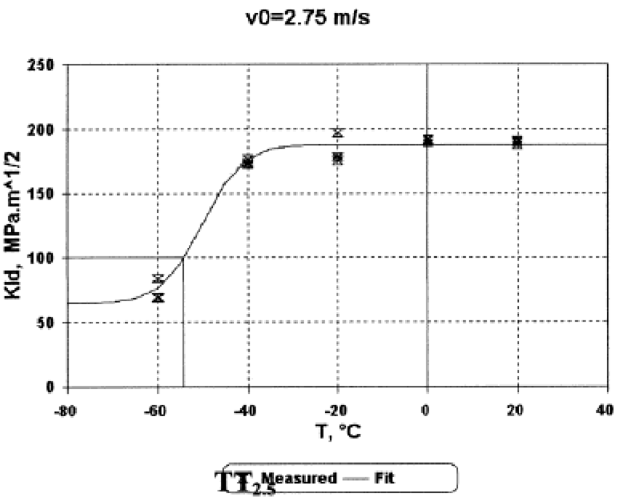


Fig. 12. Dynamic fracture toughness vs. temperature for $v_0 = 2{,}75$ m/s impact velocity (E420-C steel)

Comparison with other methods

In order to compare the magnetic emission measurement results with other methods, different measurement and evaluation procedures were applied to determine the critical dynamic J-integral value for 15H2MFA steel at $T = 200\,°C$ (*Table 1*) [21]. The critical J-integral values determined on the basis of the magnetic emission signal are in a good agreement to those obtained with stretch zone measurements [18]. Both methods detect the onset of physical crack growth. There is, however, a considerable difference to the $J^d_{0.2}$ values based on the dynamic R-curve. This method uses the artificial 0.2 point on the J-R curve, consequently these values are usually much larger.

Summary and conclusions

In the present paper some possible methods for determining ductile crack initiation toughness of metals have been introduced and compared. On the basis of the presented results the following conclusions can be drawn:

Table 1. Critical dynamic J-integral values determined with different methods for 15H2MFA reactor pressure vessel steel ($T = 200\,°C$)

Evaluation method	Critical dynamic J-integral, [kJ/m²]
on the basis of dynamic R-curve according to ASTM E 813-89 [26]	$J^d_{0.2} = 350$
stretch zone measurements according to DVM 002 [18]	$J^d_{is} = 123 \pm 20$
magnetic emission detection of crack initiation	$J^d_{im} = 103 \pm 16$

1. The energy absorbed up to the maximum load in instrumented impact testing can be used for characterising the ductile initiation toughness of materials, but physically the ductile initiation occur before this point. This energy is proportional with the real initiation energy, and it is independent of temperature.
2. The magnetic emission measurement technique has a potential ability to detect the ductile crack initiation as well applying the field method. This has been proved for many cases: for V-notched and pre-cracked specimens as well. But to interpret the magnetic signals sometimes requires the investigation of the fracture surface as well. To clarify the limitations of this method requires further investigations.
3. With applying the magnetic emission measurement to Charpy-V specimens the ductile initiation was observed before the maximum load, and the initiation energy for the tested material was obtained between 55% and 65% of the energy absorbed up to the maximum load.
4. The critical J-integral values determined on the basis of the magnetic emission signal showed good agreement to those obtained with stretch zone measurements.

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