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FRACTURE MECHANICS

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The Effect of Strain-Rate on Dynamic Characteristics of Structural Steals*

Nomenclature

$\dot{\varepsilon}$	-	strain rate
K	-	load rate
U_r	-	radial deformation
σ_I	-	initial pulse
σ_r	-	reflected pulse
σ_T	-	transmitted pulse
σ_{Imax}	-	critical value of initial pulse
Δg	-	crack growth increment
σ_0	-	nominal stress
σ_{crt}	-	critical stress
K_{Id}	-	dynamic fracture toughness
t_f	-	time to maximum load
$K_I(t)$	-	elastic stress concentration factor
σ_{ys}	-	static yield strength
σ_{yd}	-	dynamic yield strength

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E_{pl} - energy for specimen plastic deformation
CVN - Charpy V-notched test-impact toughness
B,W,a - geometrical dimensions of the specimen
EBC_{LL} - non-dimensional specimen compliance
τ - period of the inertial oscillations
$T_{R.}$ - system response time
$f_{0.9dB}$ - amplitude response of the electronic system

1. Introduction

Structural steel behaviour under dynamic test conditions considerably differs from their behaviour under static conditions. There exist tendencies of increasing the yield strength values (σ_y) and reducing the dynamic fracture toughness (K_{Id}) during crack propagation. From this point of view the change of the mechanical characteristics of structural steels operating under dynamic load conditions is of certain interest.

One of the most widely used methods of evaluating the behaviour of metal materials under dynamic load is the Charpy test, one of its variations being the use of fatigue precracked specimens and instrumentation.

Together with the obtained practical results this test method has a number of disadvantages too, namely the occurrence of evident inertia effects and the necessity of restricting the impact velocity. Studies reported from several authors [1,2] discuss dynamic load test problems. Recommendations and experimental data presented have led to the approval of standard documentation and procedure for carrying out dynamic tests (ASTM E 24.01, ASTM E 813). The observation of these recommendations allows the conducting of dynamic tests and obtaining of correct data about the mechanical characteristics of the material investigated.

In the development of characteristic mechanical evaluation methods there are certain marked tendencies towards avoiding the quasi-static approaches for analyzing the experimental data and for increasing the load rate ($\dot{K}$) from 10^5MPa $m^{\frac{1}{2}}s^{-1}$ to 10^7MPa $m^{\frac{1}{2}}s^{-1}$Both Impact Response Curve Method [3] and Hopkinson Pressure Bar Arrangement are typical examples. A number of investigations and publications, e.g. C o s t i n et al. [4], S t r o p p e et al. [5], S h o c k e y et al. [6], D u s e k [7], outline the theoretical and experimental advantages and disadvantages of the methods in question. The experiments differ mostly in specimen geometries and duration of generated pulses. It is interesting to note that as an alternative to the Charpy test, some authors [8] suggest Hopkinson Pressure Bar tests for solving some of the problems (such as inertia effects electronic filtration of load-time curve $P=f(t)$ [8]).

2. Testing equipment

A Charpy pendulum with a recording device has been used in the dynamic tests, see block diagram in Fig. 1. The evaluation tests of structural steels under dynamic load using fatigue precracked prismatic specimens at a load rate of $K \times 10^5 \mathrm{MPa\ m^{\frac{1}{2}} s^{-1}}$ are in accordance with ASTM E 24.03.03 [9] and ASTM E 399 [10] specifications. It is assumed that a quasi-static equilibrium with negligible inertia forces prevails in the specimen. Static analysis of the dynamic experimental data requires adherence to particular conditions: selection of instrumentation and electronic circuits with appropriate amplitude of response ($f_{0.9dB}$,T_R), inertia effect prevention by quasi-static loading of the specimen (response time T_R and period of inertial oscillations τ).

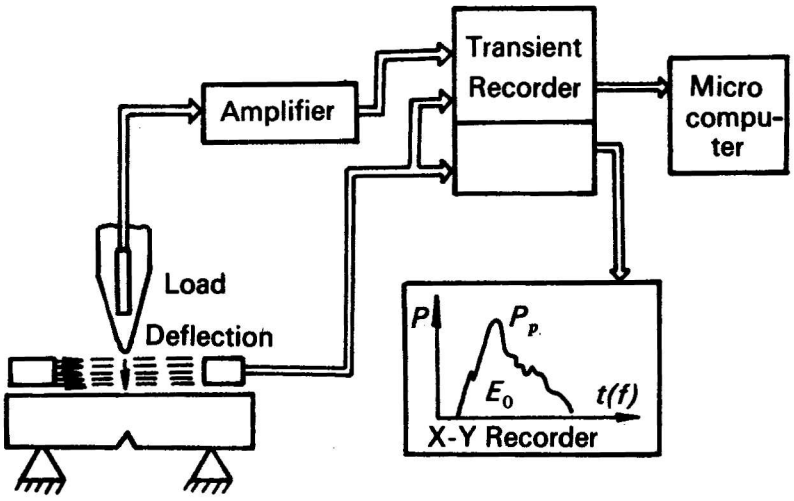


Fig. 1 - Block diagram of Charpy Test Equipment

This quasi-static approach restricts the dynamic character of the tests and K a l t h o f f [11] has shown that the precise measuring of the maximum force is not possible during high load rate fracturing especiallyof particularly brittle materials.

The present study shows an evaluation of the load-time diagrams $P=f(t)$ corresponding to the ASTM E 24.03.03 restrictions. Characteristic diagram data for the tested steels are shown in Table 1. The values of the load P_m have been taken from the load-time diagram satisfying

condition $t_f \geq 3\tau$ and $t_f \geq 1.1T_R$, where T_R is the system response time; this value is 25 μs for the Hotinger amplifier used. It is recommended that, when using that method, the values of the relative load rate K when using that method reach approximately 5 x 10^5 MPa $m^{\frac{1}{2}}s^{-1}$ and as the data from the experimental diagrams show, the conditions for the quasi-static analysis haye been satisfied.

Table 1 - Characteristic data for the criteria of quasi-static loading during Charpy testing

Steel	$\frac{a}{W}$	EBC_{LL}	τ	t_f	T_R	$\frac{t_f}{\tau}$	$\frac{t_f}{T_R}$	$K=\frac{K_Q}{t_f}$
10*G2SAF*	0.508	58.7	50.5	180	25	3.05	7.2	$1.9x10^5$
	0.488	51.7	46.7	147	25	3.2	5.9	$3.1x10^5$
17*G6SAF*	0.510	58.8	50.5	140	25	2.8	5.6	$2.45x10^5$
	0.483	51.0	47.0	147	25	3.12	5.88	$2.9x10^5$
23*G2SAF*	0.480	50.7	76.9	164	25	3.6	6.56	$2.75x10^5$
	0.517	60.1	51.0	147	25	2.88	5.9	$2.4x10^5$

Short pulse load tests have been carried out on Hopkinson Pressure Bar Arrangement as shown schematically in Fig. 2*a*. The test arrangement consists of two long elastic bars with circular cross sections, a pneumatic gun and a specimen with geometry in accordance with the type of testing. In order to achieve very short pulses the striking projectile is 25 mm long so that an almost sinusoidal pulse with a duration of about 28 μs can be generated.

Another embodiment of Hopkinson Pressure Bar Arrangement comprising ofa long operating bar of circular cross section, a pneumatic gun and a fatigue precracked rectangular specimen is shown in Fig. 2*b*.

The striking projectile generates in the bar an initial pulse which propagates through the bar and the specimen and further generates two other pulses: σ_r pulse reflected by the specimen free end (Fig. 2*b*) or by the specimen-second bar transition zone (Fig. 2*a*) and σ_T pulse, transferred to the second bar. Under certain conditions the reflected pulse can cause propagation of the crack which is perpendicular to the specimen axis.

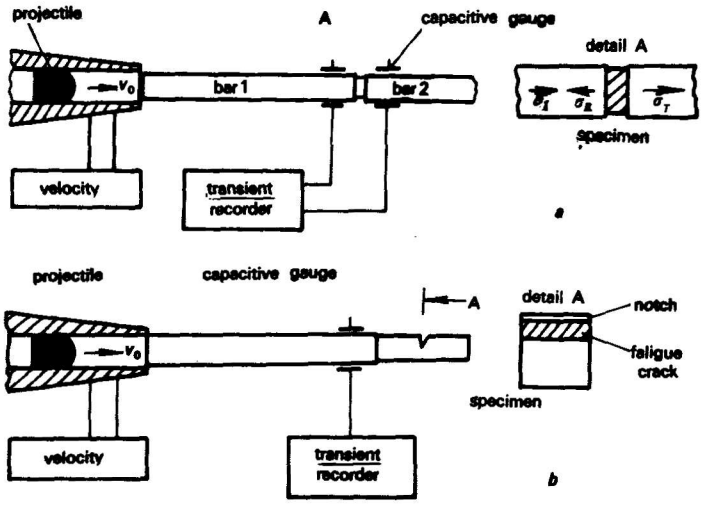


Fig. 2a - Experimental setup for deformation tests
2b - Experimental setup for fracture tests

3. Materials and procedure

Low-alloy, low-carbon, ferritic-pearlitic structural steels have been studied. Their chemical compositions are shown in Table 2. These steels are used for the production of main gas pipes and pressure vessels for the chemical industry. In almost all cases they are subjected to various pressures and temperatures. From this point of view, the purpose of the present work is to present data on the variations of steel mechanical characteristics as a function of test temperature using two load rates $\dot{K}\sim 2.5 \times 10^5$ MPa $m^{\frac{1}{2}}s^{-1}$ and $\dot{K} \sim 5 \times 10^6$ MPa $m^{\frac{1}{2}}s^{-1}$.

Table 3 shows the values of standard mechanical characteristics based on tests carried out under static load rates $\dot{K}\sim$ 2.0 MPa $m^{\frac{1}{2}}s^{-1}$ ($\dot{\varepsilon} \sim 10^{-3}s^{-1}$) Data refer to studied steels, normalized for 1 hour at T = 900°C.

a - Dynamic yield strength

Besides the energetic characteristics (ASTM E 23-82, DIN 50115 [12]), dynamic yield strength σ_{yd} and dynamic fracture toughness K_{Id}

also help evaluating steel behaviour under dynamic load. Because σ_{yd} and K_{Id} are in a correlation according to the ASTM requirements, the point is to determine σ_{yd} values under increased load rates. There are no ASTM, DIN or ISO methods for determining σ_{yd}, but a number of publications describe such experimental or empirical ones.

Table 2 - Chemical composition of investigated steels

Steel	Chemical composition in %						
	C	Mn	Si	V	N	S	P
10*G2SAF*	0.10	1.44	0.60	0.10	0.016	0.022	0.024
17*G2SAF*	0.16	1.41	0.50	0.12	0.017	0.018	0.024
23*G2SAF*	0.21	1.60	0.56	0.12	0.015	0.017	0.025

Table 3 - Mechanical characteristics of studied steels (normalized)

Steel	Mechanical characteristics	Test temperature, C				
		-80	-40	-20	0	
10*G2SAF*						
	[MPa]	500	470	440	425	412
	CVN [J]	20.9	30.8	44.8	67.2	80
17*G2SAF*						
	[MPa]	580	560	540	530	502
	CVN [J]	16.2	25.8	38.7	54.4	64
23*G2SAF*						
	[MPa]	660	640	630	621	616
	CVN [J]	14.4	18.6	33.2	64	78

Note: Equivalent steels in chemical composition and mechanical characteristics: France - N6/N; USA - ASTM 242, ASTM 304.

Charpy instrumented pendulum, prismatic V-notched specimens and load-time diagrams $P=f(t)$ allow to determine σ_{yd} according to Server's formula [13]:

$$\sigma_{yd} = \frac{2.99\ P_y W}{B\ (W - a^2)} \tag{1}$$

H o l z m a n n et al. [17] have shown the relation between dynamic yield strength σ_{yd} and the yield strength load $P_{0.1}$,

$$P_{0.1} = k\ \sigma_{yd}\ , \tag{2}$$

as well as the possibility for empirical determination of σ_{yd} :

$$\sigma_{yd} = \sigma_{ys} - 40 + 1100 \exp\ [C(\dot{\varepsilon})\ (273 + t)] \tag{3}$$

In their investigation S h o e m a k e r and S e e l e y [15] have described an alternative way for determining σ_{yd} where they have used test temperature, load time to specimen fracture and σ_{ys} values during static tests. K r a s o v s k i et al. [16] also describe the use of Charpy specimens for σ_{yd} determination.

In the present work σ_{yd} values have been determined at a load rate of 2.5 x 10^5MPa $m^2 s^{-1}$ by means of the load-time diagram $P=f(t)$. The method suggested by Holzmann et al. and the results have been controlled by Server's formula.

The procedure as described in [20] has been used for determining values under pulse load of $\dot{K} \sim 5.0 \times 10^6$MPa $m^2 s^{-1}$. At one and the same temperature several identical specimens (20mm in dia., 2mm thick) have been dynamically loaded, meanwhile increasing the maximum value of the initial pulse. For every initial pulse σ_{Imax} it is possible to measure both the reflected σ_r and the transferred σ_I pulses; and after loading it is possible to measure specimen deformation as well. Fig.3 shows an example of the pulse value variations, the specimen relative deformation and the σ_{yd} determination. Obvioiusly there exists a critical value of σ_{Imax} (in this case σ_{Imax} value in the pulse transmitting bar is about 700 MPa) below the maximum of which the bar response is only elastic (the critical stress value σ_{Imax} in the specimen, calculated relative to its diameter is approximately 860 MPa).

Above this critical value the initial pulse σ_I is devided into reflected σ_r and transmitted σ_T pulses and a residual strain in the specimen is observed. The so determined critical stress value may be defined as material yield strength taking into consideration the "delay

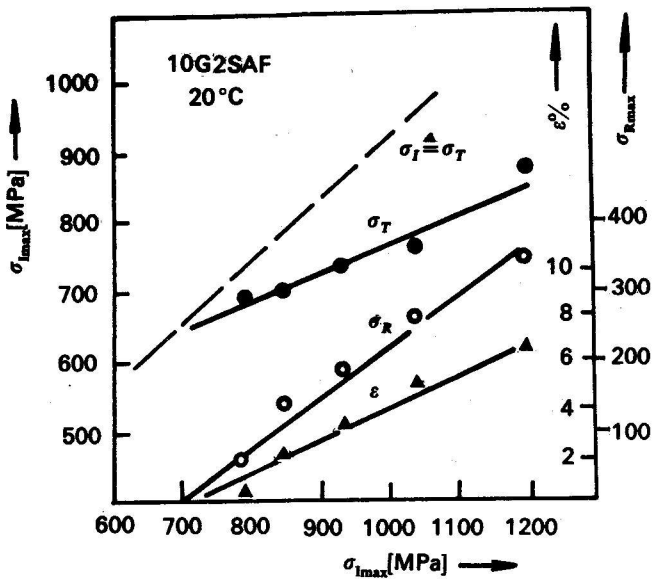


Fig. 3 - Stress maximum σ_{Imax} and the permanent deformation vs. incident pulse maximum for 10*G2SAF* steel

time" τ_d during which the material resists to the applied loading without noticeable deformation, as schematically shown in Fig. 4. In case when loading is terminated before reaching τ_d, the material is only elastically loaded and we can speak of elastic reserves under dynamic load. The bigger the difference between the experimental load rate and the test static rate, the shorter the delay time.

b - Dynamic fracture toughness

Dynamic fracture toughness has been determined in the present work in accordance with the specifications of ASTM E 24.03.03 and ASTM E 399. Charpy fatigue precracked (a/W = 0.45-0.55) specimens (L=55mm, W=10 0.025mm, B =10 0.025mm) have been used in the tests. When fracture occurs before total deformation, then dynamic fracture toughness is calculated by P_Q

$$K_Q = \frac{P_Q \; S}{B \; W^{3/2}} f\left(\frac{a}{W}\right) . \tag{4}$$

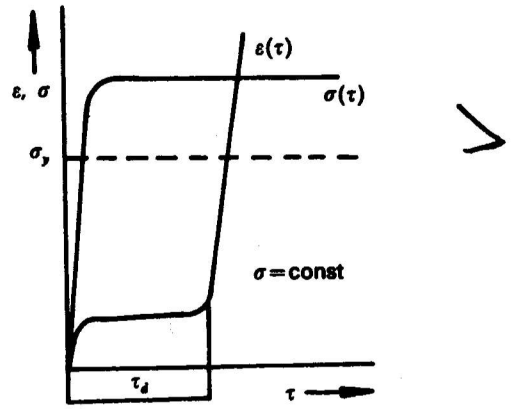


Fig.4 Schematic representation of stress variation in specimens as a function of the delay time τ_d

J-integral values and fracture toughness are calculated when brittle fracture with a certain plastic zone occurs at the crack tip by the following relation:

$$K_{IJd} = \sqrt{\frac{E}{1-\nu^2} J_{Id}} \quad (5)$$

To determine the dynamic fracture toughness under pulse loading, prismatic specimens (L = 130 mm, W = 17.4 mm, B = 17.4 mm) having a fatigue precrack (a - 5 mm, a/W - 0.45) have been used. Crack growth increment has been determined after subjecting the specimen to pulses of various amplitudes. In this way it is possible to calculate the critical stress so that for $\sigma_o \leq \sigma_{crit}$ no crack growth occurs and for $\sigma_o \geq \sigma_{crit}$ the crack propagates.

To analyze the experimental results in terms of material dynamic fracture in an elastic zone, the criterion for fracture initiation [17]

$$K_{Id}(\dot{K}) > K_I(t = t_f) , \quad (6)$$

where t_f is the time to the maximum load, the former being replaced by the equivalent criterion for maximum stress intensity,

(7) $$K_{Id} \geq \text{Max} \left\{ K_I(t) \right\}$$

$K_I(t)$ has been determined by means of elastodynamic analysis of precracked specimen under specific geometric and loading conditions using the finite difference method. Details on the calculation method are given in [18]. As a result we have got the possibility to calculate the fracture toughness under dynamic load on the basis of experimental data as follows:

(8) $$K_{Id}=1.3\ \sigma_{crit}(\pi a)^{\frac{1}{2}},$$

Results presented in [19] show that within the error bounds (10 to 15 %) at a certain temperature there are correct K_{Id} values, independent of the crack length.

4. Experimental results and discussion

Fig. 5 shows the results of the yield strength variation with the indicated load rates. The tests have been carried out within the temperature range from -100°C to +20°C. Any increment of the load rate leads to considerable changes of the yield strength values as well as to a narrowing of the temperature range within which the macroplastic deformation occurs. When K is approximately 2.5 x 10^5MPa $m^{\frac{1}{2}}s^{-1}$this range is limited to - 60°C and when it is around 5 x 10^6MPa $m^{\frac{1}{2}}$ s^{-1} the range is limited to - 40°C. The pronounced brittle fracture of studied steels under pulse loading is related to the high yield strength values. The results shown in Fig. 5*a*, *b* and *c* indicate a characteristic decrease of the sensitivity to load rate in steels with higher strength parameters (Fig. 5*c*). Tests have been carried out for determining the mechanical parameters of the heat treated steels (σ_{ys} is within the range of 850 to 1000 MPa for 17*G2SAF* and 23*G2SAF* steels) and have shown a closeness to σ_y values under static ($\dot{\varepsilon}\sim 10^{-3}s^{-1}$) and dynamic ($\dot{\varepsilon}\sim 10^{2}s^{-1}$) loading. Fig 6 shows data that indicate a correlation between experimental values under static ($\dot{K}\sim$2 MPa $m^{\frac{1}{2}}s^{-1}$), dynamic ($\dot{K}$ ~2.5 x 10^5M Pa $m^{\frac{1}{2}}s^{-1}$) and pulse ($\dot{K}\sim5x10^6$MPa $m^{\frac{1}{2}}s^{-1}$) loading (correlation functions obtained by the least square method). Standard error S_E for the obtained values of σ_y is 73.3 MPa along the ordinate and 75.8 MPa along the absciss. Correlation factor is 0.98.

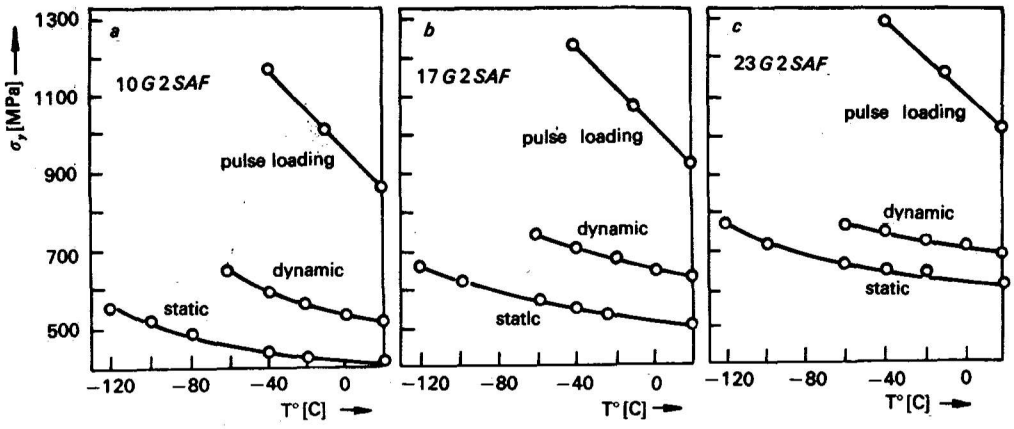


Fig. 5 - Comparison of the yield strengths under static ($\dot{K} = 2$ MPa m$^{\frac{1}{2}}$ s^{-1}) dynamic ($\dot{K}=10^5$MPa m$^{\frac{1}{2}}$s^{-1}) and pulse ($\dot{K} = 10^6$MPa m$^{\frac{1}{2}}$s^{-1}) loading for the tested steels
a - 10*G2SAF*; *b* - 17*G2SAF* *c* - 23*G2SAF*.

Fig.7 shows the variation of tested steel fracture toughness. The increment of load rate shifts the brittle-to-ductile fracture transition of the specimen to considerably higher temperatures.

When load rates, characteristic of the Charpy tests are used, fracture toughness values are obtained which do not satisfy the condition:

$$a, W \geq 2.5\left(\frac{K_Q}{\sigma_{yd}}\right)^2, \tag{9}$$

These values are calculated by introducing an effective crack length (including also a plastic zone at the crack tip), equal to

$$a_{eff} = a + \frac{1}{6\pi}\left(\frac{K_Q}{\sigma_{yd}}\right)^2 \tag{10}$$

and by using *J*-integral according to the relation.

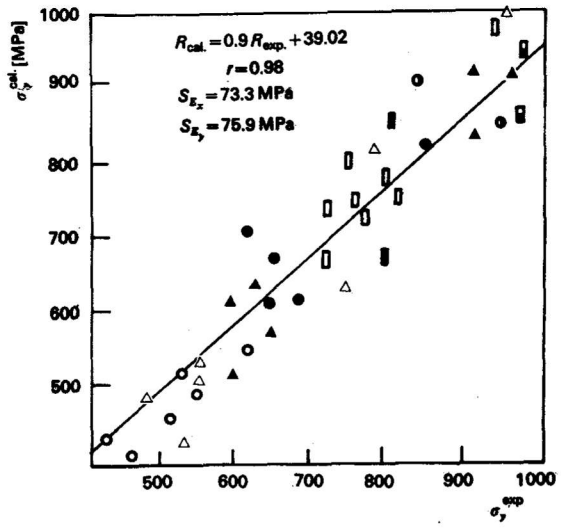


Fig. 6 - Correlation between the experimentally determined and the calculated values of σ_y under static, dynamic and pulse loads $\dot{K}$=2 MPa $m^{\frac{1}{2}}s^{-1}$ $\dot{K}$=10^5MPa $m^{\frac{1}{2}}s^{-1}$, $\dot{K}$~10^6MPa $m^{\frac{1}{2}}s^{-1}$

Table 4 shows some of the experimental data used for determining the fracture toughness values of the studied steels at $\dot{K}$~2.5×10^5MPa $m^{\frac{1}{2}}s^{-1}$. It is obvious that the condition for specimen fracture in plane strain state is met in the range below - 60°C only. As a result of the considerable increase of yield strength values under pulse load the fracture toughness values satisfy condition (9) during fracture within the temperature range up to +20°C.

The fractographic analysis shows the fracture mechanism with the load rates used in the tests. Fig. 8 shows the types of fractured surfaces of specimes tested at the temperatures of their brittle fracture and at the temperatures of their brittle-to-ductile fracture transition. As already mentioned hereabove brittle fracture of tested steels occurs up to T_{test} = -60°C and above this temperature fracture is accompanied by the presence of a plastic zone at the crack tip (Fig. 8 *a*). Under pulse load the fracture mechanism is typically brittle within the whole temperature range used in the tests (Fig. 8 *b*)

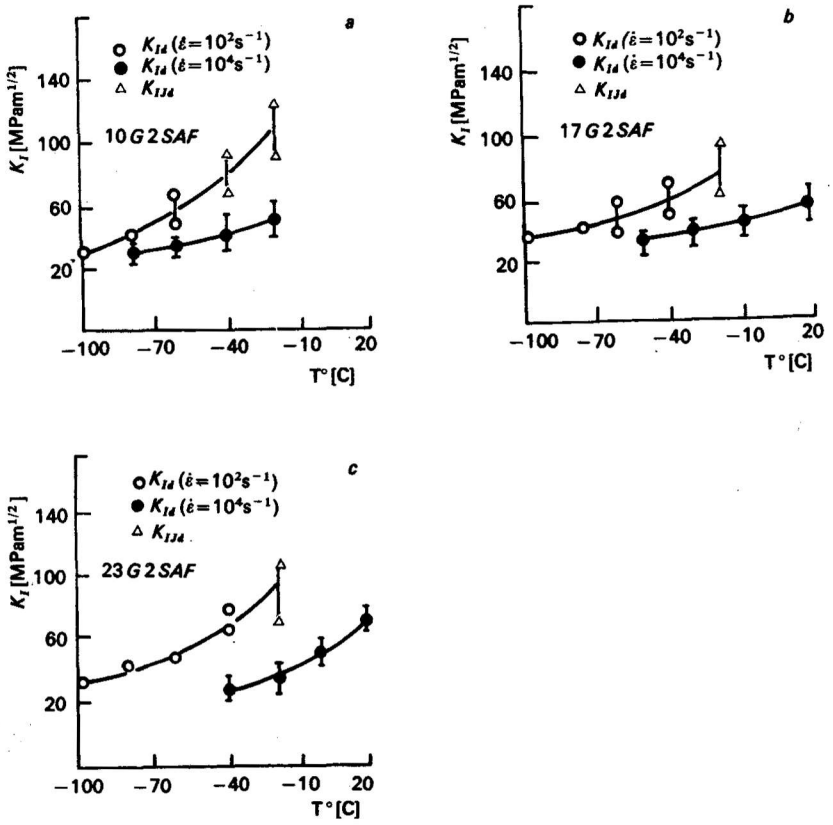


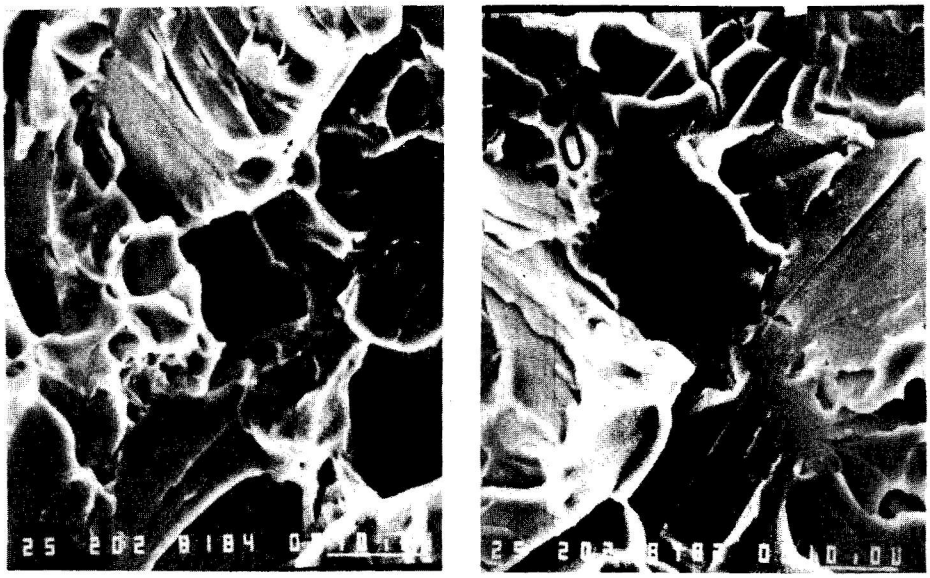
Fig. 7 - Comparison of dynamic fracture toughness values, investigated by pulse loading and by Charpy tests

Table 4 - Experimental data for determining the fracture toughness of studied steels (Charpy test)

T	B	W	a	P	E_{pl}	σ_{yd}	K_Q	K_Q^*	J_{Id}	K_J
	mm	mm	mm	kN	J	MPa	$MPam^{\frac{1}{2}}$		kNm^{-2}	$MPam^{\frac{1}{2}}$
					10G2SAF					
-100	10.01	10.00	4.92	3.12	0.00	726	31.7	-	-	-
-80	10.02	9.98	4.77	4.62	0.00	683	43.6	48.7	-	-
-60	10.03	9.98	4.70	4.85	0.00	645	53.3	64.7	-	-
-40	9.98	10.02	5.08	6.25	0.40	611	65.9	-	43.1	87.8
-20	10.00	9.98	5.06	7.30	1.14	590	80.3	-	73.0	131.1
					17G2SAF					
-100	9.98	10.00	5.20	3.1	0.00	776	34.2	-	-	-
-80	9.98	10.00	4.85	4.5	0.00	747	43.6	46.1	-	-
-60	10.00	10.02	5.10	5.4	0.00	710	58.8	66.7	-	-
-40	10.00	10.00	4.85	5.52	0.00	680	55.8	62.7	-	-
-20	10.01	10.01	5.02	6.0	0.5	670	64.1	-	37.6	92.1
					23G2SAF					
-100	10.01	10.00	4.95	3.4	0.00	840	35.4	-	-	-
-80	10.00	9.98	4.82	4.1	0.00	790	41.1	44.9	-	-
-60	10.00	10.01	5.05	4.3	0.00	760	46.3	48.7	-	-
-40	10.01	9.98	4.70	6.3	0.00	745	60.8	66.85	-	-
-20	9.98	10.00	4.85	6.4	0.90	720	54.7	-	45.1	110.7

5. Conclusions

Behaviour evaluation of the studied structural steels, subjected to two different dynamic load rates, is related to the determination of brittle-to-ductile fracture transition. The considerable increase of the yield strength values as well as the use of bigger size specimens provide a possibility for the fracture to occur in the state of plane strain and for the equation (9) to be satisfied in a wider temperature range.



a *b*

Fig. 8 - Fracture surfaces of specimens tested under:
a - dynamic loading $\dot{K}\sim10^5$ MPa $m^{\frac{1}{2}}s^{-1}$
b - pulse loading $\dot{K}\sim10^6$ MPa $m^{\frac{1}{2}}s^{-1}$

Although the evaluation of mechanical structural steel parameters on the basis of the aforesaid methods leads to many problems, a number of scientists show an interest in these problems and the ways of their solving.

The data presented on the variation of yield strength values $\dot{K} = 10^5 \div 10^6$ MPa $m^{\frac{1}{2}}s^{-1}$ meet the ASTM specifications, i.e., yield strength tested materials has been determined under conditions (load rate and temperature) comparable to the test conditions for determining their fracture toughness.

Experimental data given in this work further show the effect of the increased load rate on the fracture mechanisms of tested steels.

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