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FRACTURE MECHANICS

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Dynamic Loading Behaviour of Nitrogen-Alloyed Structural Steels

Nomenclature

a_{eff}	-	effective crack length
% B	-	plastic component of the fracture surface
$\dot{K}$	-	load-rate
KCV	-	impact toughness
K_{Id}	-	stress intensity factor
P_y	-	macro plastic deformation force (load)
R_e	-	yield stress
R_e^d	-	dynamic yield stress
R_e^{20}	-	yield stress at a temperature of 20°C
T_{cr}	-	critical temperature of brittleness
$T_{cr_{35}}^{KCV}$	-	critical temperature determined by the value of KCV = 35 J/cm^2
$T_{cr_{20}}^{KCV}$	-	critical temperature determined by the value of KCV = 20 J/cm^2
T_{cr}^{50}	-	critical temperature determined by %B = 50

Introduction

Both economic and technologic considerations determine the widespread application of low carbon, low alloy steels as structural materials. The significant sensitivity of the structural steel mechanical properties towards the load-rate and the operating temperature restricts their application in brittle state, i.e. when fracture occurs at nominal stress in the elastic deformation area.

The nitrogen-alloyed structural steels, developed in the Institute for Metal Science and Technology, are largely applied nowadays. The annual production of Kremikovtzi State Company progressively increases and in 1990 it reached 100 000 tons. The company's team of experts has developed a programme called "Feasibility study for the Production of Gas Pipes made of Low Alloy Hot Rolled Non-heat Treated Strips and Coils" and its implementation resulted in the development of 10G2SAF steel modifications alloyed with Ti, Nb, Mo, W or a combination thereof. 17G2SAF and 23G2SAF steels are now largely applied in industrial trucks, electric hoists and in other industrial fields as well.

The development of nitrogen-alloyed steels and their application in industry is accompanied by a detailed study of their strength and plasticity behaviour after different heat treatment. In a previous work [1] the basic mechanical characteristics of nitrogen-alloyed steels under static and cyclic loading in a wide temperature range have been investigated.

This report presents the results obtained from the dynamic loading tests of nitrogen-alloyed structural steels.

The high requirements for operation reliability of the structural steels impose the necessity of their mechanical characteristics evaluating and an accounting for the presence of different defects such as notches and cracks of both structural and technological nature. Therefore, it is indispensable to determine not only the standard mechanical characteristics but, also, the parameters, describing the material resistance to defect initiation and development which result in brittle fracture of the products or structures.

Materials and procedures

Chemical compositions of the studied steels are given in Table 1 and the condition for heat treatment and static yield stress R_e are given in Table 2.

The tests have been carried out on a dynamic loading stand (Charpy tests), equipped with devices for registering of the load time indicator diagram. Standard Charpy V-notched specimens have been used. The dynamic tests have been carried out in the temperature range from -100°C to +20°C. The initial impact speed has been 5,5 m/s for determining KCV and R_e^d and 1,5 m/s for determining K_{Id}. Both initial speeds ensure dynamic loading at load-rate of $2{,}5x10^5 MPam^{\frac{1}{2}}s^{-1}$. The impact energy is enough for the complete fracture of the specimens [2].

Table 1. Chemical composition

Element wt.% / Material	C	Si	Mn	P	S	N_2	V
10G2SAF	0,10	1,44	0,6	0,024	0,022	0,016	0,10
17G2SAF	0,16	1,41	0,5	0,024	0,018	0,017	0,10
23G2SAF	0,21	1,60	0,58	0,025	0,017	0,15	0,12

To assess the steel behaviour we have experimentally established the temperature relationships of energetic (KCV - impact toughness) and structural (%B - plastic component of the fracture surface) properties, dynamic yield stress R_e^d and stress intensity factor K_{Id}, which specifies the steel crack resistance.

The dynamic yield stress values R_e^d have been determined through P = f(t) diagrams using the relationship between the force at the macro plastic deformation limit P_y and the dynamic yield stress R_e^d [3].

(1) $$R_e^d = \frac{2.99\, P_y W}{B(W-a)^2}$$

where P_y is yield load. There has also been used the empirical dependence of the yield stress on the load-rate and on the temperature [4]

(2) $$R_e^d = R_e^{20} - 40 + 1100\exp\,[C(\dot{\varepsilon})\ (273+T)]$$

T - temperature °K.

The resistance to brittle fracture (crack resistance) is characterized by K_{Id} which has been determined in the present work is accordance with ASTM E 24.03.03 [5] and Standard of Comecon[6].

Table 2. Type of heat treatment of studied steels

Material Steel	Condition	Fig.	Heat Treatment	R_e MPa
10G2SAF	normalized	2a,3a	normalization at 900°C	412
17G2SAF	normalized	2b,3b	normalization at 900°C	502
	quenched	2c,3c	oil quenching from 900°C	
			air tempering at 180°C	635
	martemperet	2d,3d	oil quenching from 900°C	
			air tempering at 650°C	730
23G2SAF	quenched	2e,3e	oil quenching from 900°C	
			air tempering at 180°C	816
	martempered	2f,3f	oil quenching from 900°C	
			air tempering at 550°C	970

K_{Id} is determined on the basis of P=f(t)-diagrams which have been obtained for the fracture of notched and fatigue precracked specimens. The following relation has been used:

(3) $$K_{IQ} = \frac{P_y}{B\sqrt{W}} Y$$

where Y = f(a/W) is a specimen geometry - and crack size-dependent coefficient.

Results and discussion

One of the basic characteristics which evaluates the material tendency to brittle fracture is the transition temperature T_{cr} of brittleness. T_{cr} defines the temperature at which the material fracture behaviour changes from ductile to brittle. Depending on the criterion for specifying T_{cr}, its value may vary over a wide range. As this temperature is used as a basis for indicating the possibility of brittle fracture occurrence, it is especially important to determine it as precisely as possible.

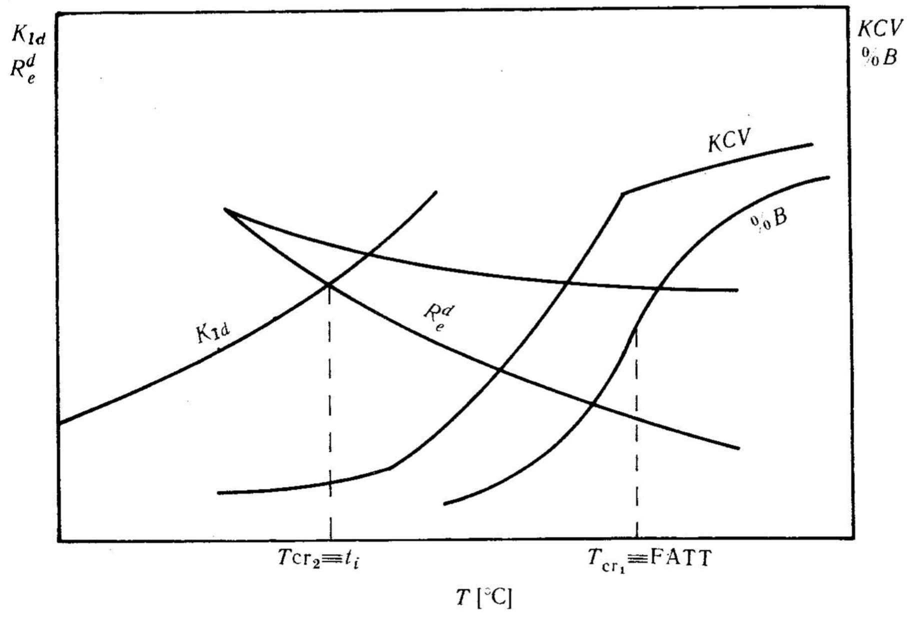

Fig.1. Illustration of temperature relationships between the strength and plasticity parameters of structural steels.

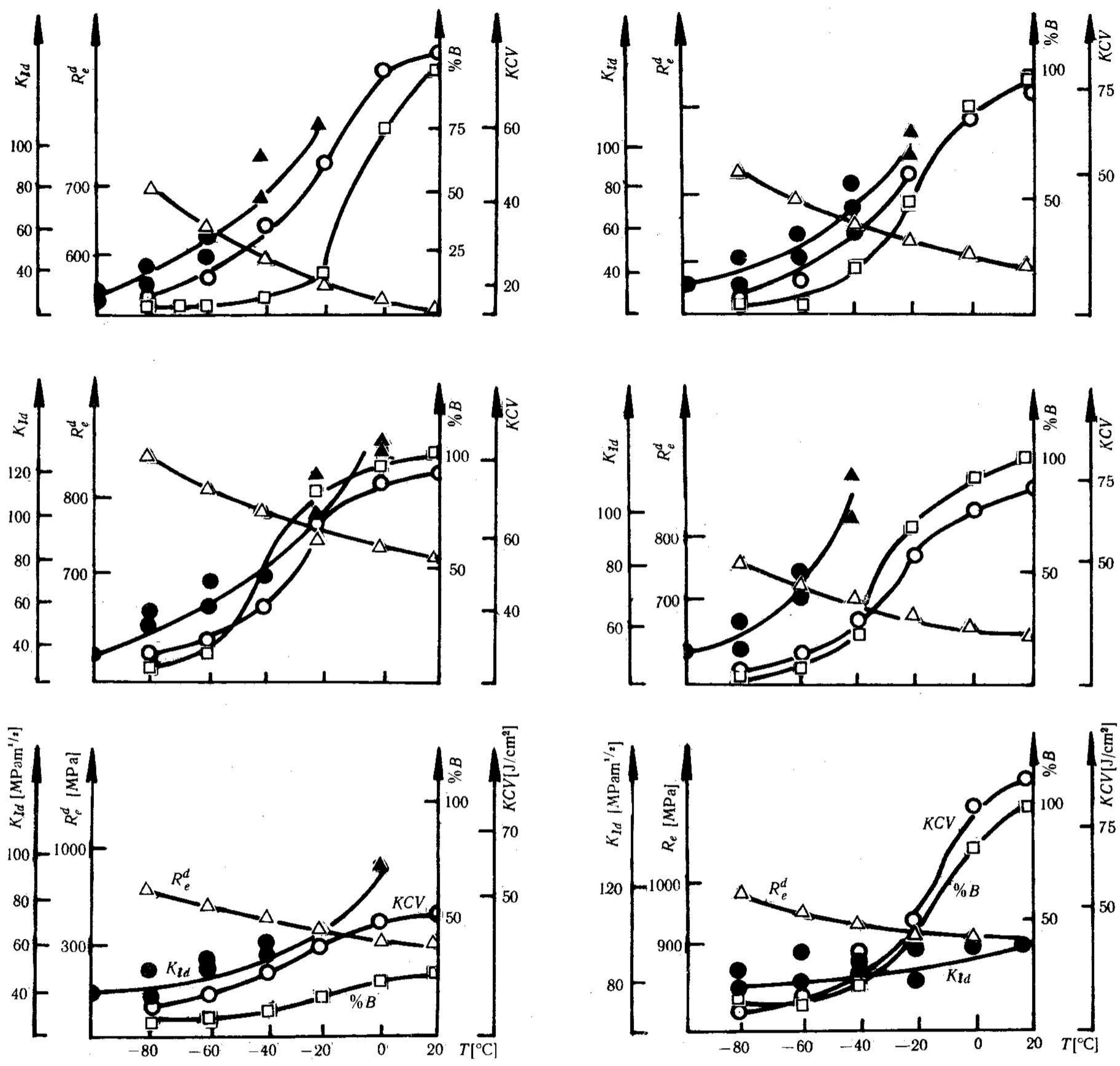

Fig.2. Temperature relationships between the dynamic characteristics of nitrogen-alloyed structural steels.

- ● – stress intensity coefficient
- △ – dynamic yield steels
- ○ – impact toughness
- □ – plastic component of the fracture surface (%)

a. normalized 10G2SAF steel
b. normalized 17G2SAF steel
c. quenched 17G2SAF steel
d. martempered 17G2SAF steel
e. quenched 23G2SAF steel
f. martempered 23G2SAF steel.

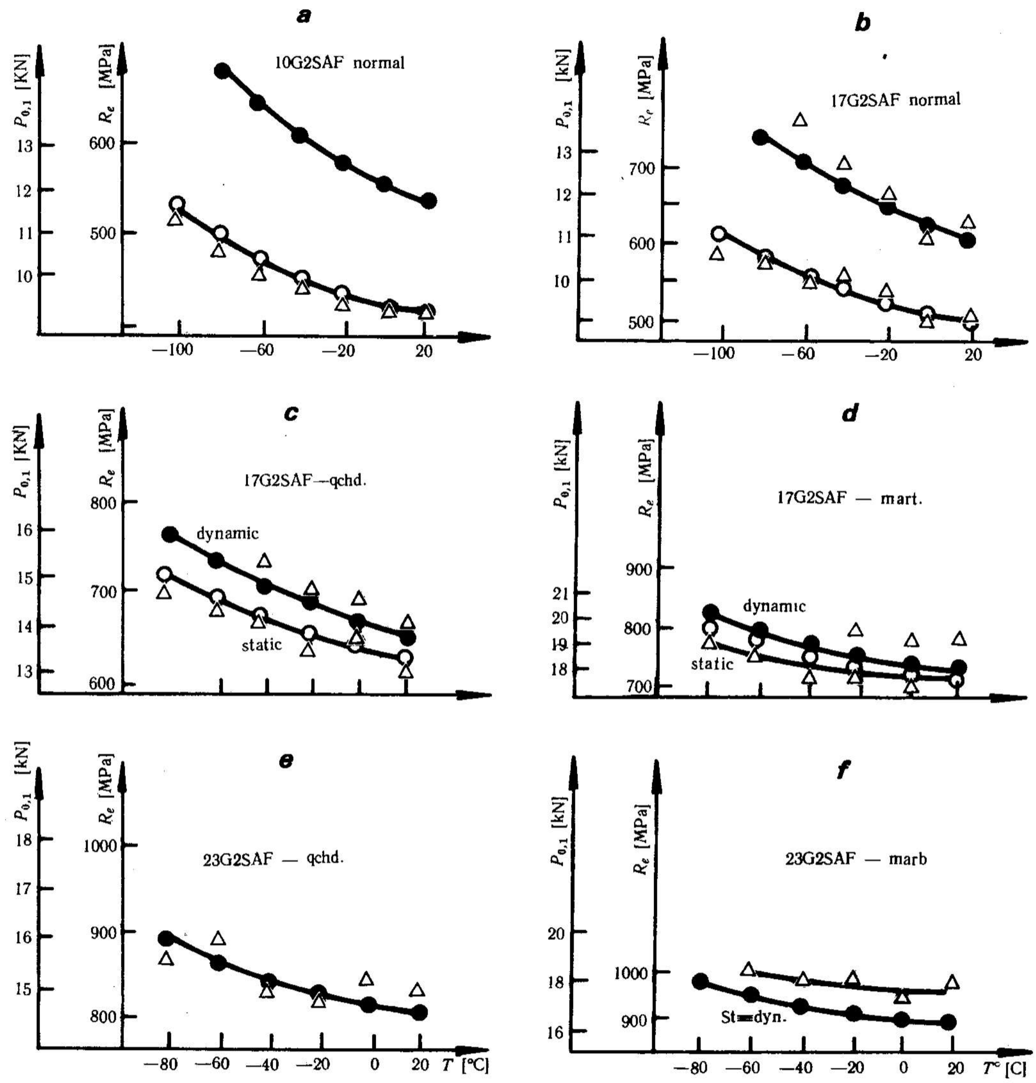

Fig.3. a-f. Temperature relationships between the static and dynamic yield stresses for the studied steels.

△ — experimental (1)

○ — empirical (2).

One of the techniques for determining the critical temperature of brittleness is using the temperature relationships between steel mechanical characteristics and inter dispositions of their curves (Fig.1). This approach helps in outlining the specific fracture areas. For the purpose of determining the critical temperature T_{cr1} and T_{cr2} of brittleness and the respective fracture areas some diagrams have been drawn showing the dynamic parameters changes of the investigated steels as a function of the temperature (Fig.2 a-f).

Heat treatment and especially tempering temperature strongly influence the character of the fracture. The results show that at a test temperature of -70°C the martempered 17G2SAF and 23G2SAF steels have a high percentage of plastic component of the fracture surface (from 9 to 20%) while the normalized steels have a plastic component from only 1 to 3% (Fig. 2a,b). The tests carried out for specifying the impact toughness change as a function of the tempering temperature T_t, show that the impact toughness continuously increases in the range of T_t = from 200 to 650°C. The dynamic tests show that the heat treated steels at T_t = 200°C have poor structural and energetic characteristics. At a test temperature of T_{test} = -70°C the fracture surface is %B = from 0 to 3 % and KCV has much lower values than those of normalized and martempered steels. This is particularly evident for the quenched 23G2SAF steel where the brittle character of the fracture predominates to temperatures higher than the operating ones.

One of the recent tendencies in evaluating the structural materials is the determination of such parameters which characterize the brittle fracture resistance in the presence of defects. The advantage of the K_{Id} parameter as compared to the standard mechanical characteristics regarding the evaluation of the material behaviour is the fact that it provides a possibility to establish any quantitative relation between existing stresses, defects shape and size and the material resistance to the unstable development of such defects. Fig.2a-f shows the variation of the brittle fracture resistance (K_{Id}, K_{IJd}) for the tested steels in the temperature range. A characteristic feature of steels is the low temperature at which the fracture is purely brittle, i.e. it occurs under the conditions of plane deformation. In the temperature range from -60°C to -20°C the ductile fracture progresses with the development of a plastic zone at the crack tip, resulting in an increase of the K_{Id} values. The K_{Id} calculation is is corrected for the presence of a plastic zone by the introduction of effective crack length, a_{eff} .

The 17G2SAF steels are interesting with their behaviour after heat treatment. High temperature tempering widens brittle fracture temperature range increasing the K_{Id} values at the same time. The investigations carried out for determining the critical temperature of brittleness show that the energy required for the crack propagation at $T > T_{cr}$ decreases and this reflects the fracture behaviour.

Fig.3 a-f shows the temperature relationship at yield stress under the above conditions. The experimental results clearly show tendency of reducing steel sensitivity to load rate by increasing the strength characteristics, i.e. with an increment of the strength characteristics of steels of low and moderate yield stress ($R_e <$ 750 MPa) the difference between static yield stress and dynamic yield stress of heat treated steels decreases but it has been found out that the experimental values of R_e^d are more scattered. Fig.4 shows a comparison of the R_e^d values calculated through relations (1) and (2).

The results clearly show that it is possible to determine accurately only the area of pure brittle fracture, T_{cr1}.T_{cr2} values vary as a function of their determination criterion, e.g. T_{cr1} value determined by a 50 % plastic component of the fracture surface outlines the area of quasi brittle and plastic fracture. But the variation of the criterion for T_{cr1} determination, say by KCV

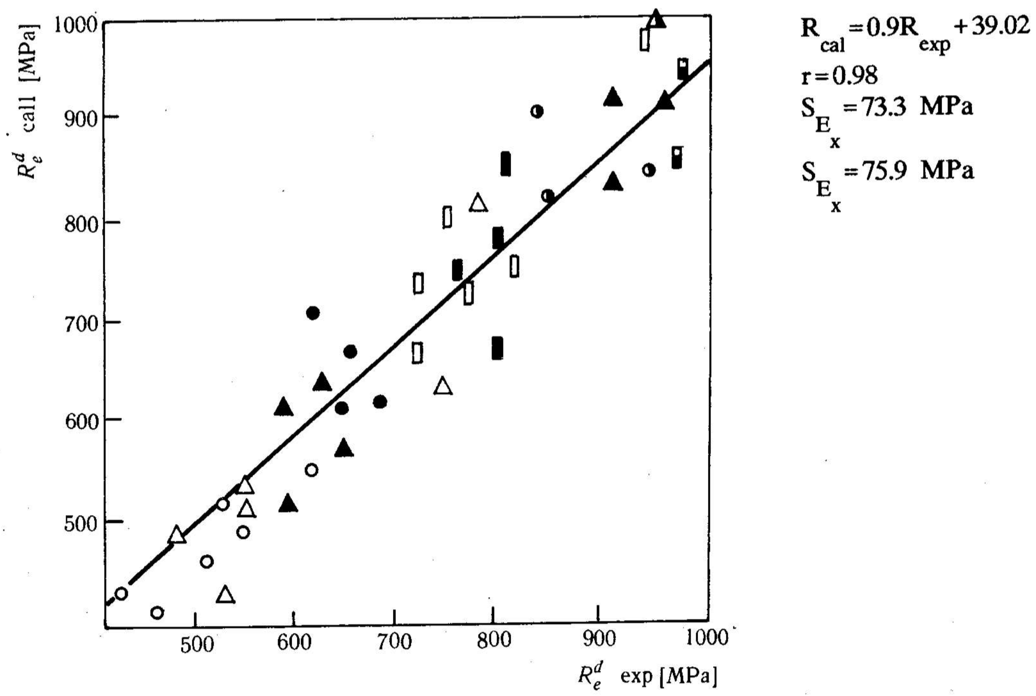

Fig.4. Correlation between the R_e values obtained experimentally and empirically, correlation coefficient r=0,99.

Table3. Critical temperature values of brittleness according to criteria used

Material	Condition	T_{cr_1}	T_{cr_2}	T_{cr}^{50}	$T_{cr_{35}}^{KCV}$	$T_{cr_{20}}^{KCV}$
Steel		°C	°C	°C	°C	°C
* 10G2SAF	normalized	-25	-60	-7	-38	-70
17G2SAF	normalized	-25	-45	-18	-42	-70
	quenched	-17	-62	-32	-38	-60
	martempered	-20	-20	-40	-57	-70
23G2SAF	quenched	-	-20	-	-40	-70
	martempered	-	-20	-20	-60	-70

values (low alloy structural steel standard shows Charpy energy values of 35 J/cm^2 and 20 J/cm^2) sharply reduces the quasi brittle fracture area and draws T_{cr1} closer to T_{cr2} , i.e. to the pure brittle fracture area Table 3. We have to point out that this is rather comparative approach as the T_{cr2} values show the fracture behaviour in the presence of plane deformation at the crack tip and T_{cr1} is specified by a physically non-determined value such as impact toughness. Special techniques have been developed for T_{cr1} determination, where as basic criteria are considered simultaneously the energy for the specimen fracture and the part of the plastic component of the fracture surface [7]. This work presents the T_{cr} values, determined using the above techniques and the critical temperature values obtained using the common diagrams of the investigated steel dynamic characteristics.

Conclusions

1. The behaviour of SAF-type nitrogen-alloyed structural steels has been examined at a dynamic load ($\dot{K}$ = 2,5 x 10^5MPa $m^{\frac{1}{2}}s^{-1}$).

2. The steel dynamic, energetic and structural characteristics (KCV, R^e_d, K_{Id}, %B) have been determined as a function of the test temperature (from -100°C to + 20°C).

3. The critical temperatures of brittleness which specify the areas of respective fracture behaviour have been determined on the basis of the obtained results.

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