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Resistance to crack propagation of alloyed structural and cast steels

K. Bobyliov*, M. K. Leonavičius, M. Šukšta***, A. Krenevičius****, S. Stupak*******
**Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius-40, Lithuania,
E-mail: k.bobyliov@skynet.post.lt*
***Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius-40, Lithuania, E-mail: minleo@fm.vtu.lt*
****Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius-40, Lithuania,
E-mail: marijonas.suksta@fm.vtu.lt*
*****Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius-40, Lithuania, E-mail: akren@fm.vtu.lt*
******Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius-40, Lithuania,
E-mail: stupakas@adm.vtu.lt*

1. Introduction

For maximal usage of strength properties in new and popular structural steels it is necessary to develop such a structural state of a material which could prolong the period of up to crack development and the resistance to crack development under repeatedly changing load. For known types of steel this could be achieved by economical alloying and thermal treatment seeking to develop such properties which could satisfy the performance requirements. During its technological process, every foundry creates some different technological and cooling conditions; therefore the obtained static mechanical properties and the resistance to crack propagation vary significantly. Often large structural elements are cast and then welded. Thermal treatment performed after welding removes residual stresses and changes mechanical properties of the base metal and of the seam. Therefore, it is necessary to know the resistance to crack development and its propagation for both the base and welded seam metals.

The compatibility of strength, durability and resistance to dynamic loads in one material requires additional investigation. In many cases the applicability of a material depends on its indices of impact ductility, brittleness, critical temperature and its resistance to crack development and its propagation. Besides, steels applied for manufacturing of large details in mining and power industry equipment must be both easily machined and welded.

The popular steels AISI 4130 and AISI 4330 are described as alloyed structural steels which obtain better mechanical properties after being thermally treated. They have high indices of strength and cyclic durability. A typical case of AISI 4130 application represents the details of turbines and steam pipelines operating up to 400°C, structural elements of high voltage line supports as well as the deterioration resistant details with a necessary hardness and strength. The resistance of this steel to crack propagation after thermal treatment has been analyzed in [1] with the application of thermodynamical point of view on crack development. The investigation of energetic balance of a loaded system allows treating physical essence of *J*-integral as the criterion of a stable crack increase. Steel AISI 4330 after some improving acquires a considerable strength limit together with a sufficient ductility, high toughness and hardening penetrability. It is used to manufacture high-loaded details working under heavy dynamic load. Such steels are also applied to produce mining industry and transport equipment, especially details rubbing against structural materials made of cast iron [2, 3]. A close equivalent of steel 4130 in GOST system is 30XMA; also close to steel 4330 is the 30XH2MA.

For investigating the properties of cast steel resistance to crack propagation, the steel was selected which in GOST system is denoted as 15Л. Such steels are applied for producing structural elements operating under the conditions of impact loading and abrupt temperature changes, for instance, when producing details for mining industry and casting equipment. Good welding properties allow using them for cast and welded structures, too. During casting these steels are characterized by considerable shape changes and casting defects (shrinkage hollows, porosity, cracking, shape loosing). Therefore it is necessary to know their resistance to cracking.

The aim of this work is to investigate experimentally cracking properties of thermally treated alloyed structural and cast steels and to define empirical dependences of the cracking threshold on material's strength properties; these dependences could be applied for design calculations.

2. Experiment

For experimental investigation each steel samples have been prepared separately.

The investigation deals with 4130M and 4330M alloyed steels which are AISI 4130 and AISI 4330 modifications as well as cast steel plates P, H, T. Plates P and H are of different casting and they were not thermally treated. However, the plate T is treated in this way along the welded seam metal for eliminating residual welding stresses.

Chemical composition of the alloyed structural steels must provide maximum hardening penetrability to obtain the suitable microstructure. Chemical composition of the steels under the investigation is presented in Table 1. The data of the investigated 4130M and 4330M steels differs from that of AISI 4130 and AISI 4330. When comparing with the steel AISI 4130, the plate of steel 4330M possesses less carbon and more manganese, chrome and molybdenum. Correspondingly, the plate of steel 4330M includes less carbon and nickel, but more chrome, manganese and molybdenum. The quantity of sulphur and phosphorus does not exceed the allowable quantities.

Table 1

Investigated steels chemical composition

Steel	Component, Wt. %						
	C	Mn	Cr	Ni	Si	Mo	Cu
4130M	0.22-0.24	0.98-1.00	1.14-1.18	0.06-0.08	0.15-0.30	0.32-0.36	0.10-0.12
4330M	0.24-0.26	0.90-0.94	1.04-1.06	1.16-1.18	0.65-0.70	0.40-0.42	0.10-0.12
Cast	0.05-0.06	0.84-0.86	0.10-0.12	0.020-0.22	0.38-0.40	0.05-0.06	0.34-0.36

Each steel tension samples were prepared seeking to define their static mechanical properties. Table 2 presents the indices of steel mechanical properties.

Table 2

Indices of mechanical properties

Sample	BHN	σ_u , MPa	σ_y , MPa	Z, %
4130M	285-299	927-948	768-786	58.8-59.9
4330M	282-292	882-912	760-782	37.5-39.5
Plate P	144-152	422-432	266-276	68.6-69.4
Pate H	140-148	426-438	268-282	71.6-73.5
Plate T	120-124	410-432	262-278	72.7-73.2

Steel specimens with different properties were selected for the experiments. Hardness varies from 120 up to 299 BHN, ultimate strength σ_u – from 410 up to 948 MPa. Yield strength σ_y varies from 262 MPa for cast steel up to 786 MPa for steel 4330M. The properties of steels 4130M and 4330M are similar, excepting the percentile reduction of area Z. The indices of plates P, H and T differ slightly, though slight influence of thermal tempering could be noticed in plate T.

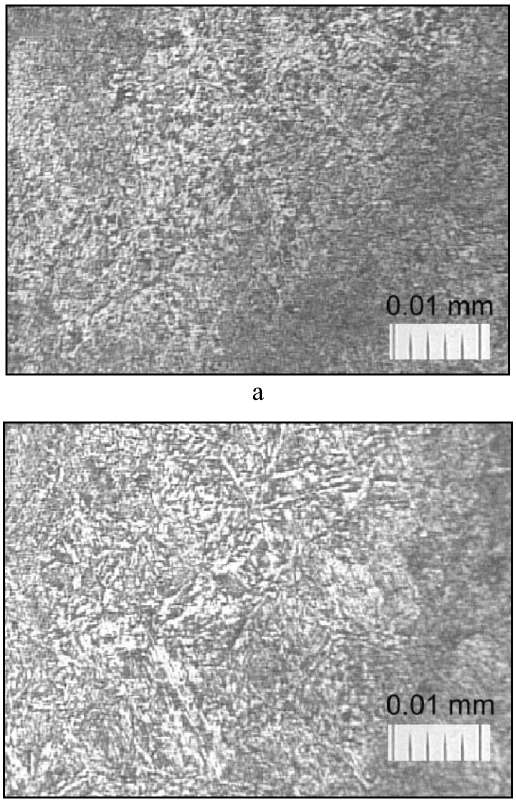
It is known [3] that during a multi cyclic loading, especially in the area of small amplitudes, the magnitude of cyclic plastic strain zone at the top of the increasing crack is of the size of the structural and sub-structural elements, and this fact predetermines the extraordinary sensitivity of disintegration process to the material structure. Therefore the steel structure differences which are not important for estimating strength indices may become important when analyzing the durability indices.

The microstructure of the samples of thermally treated steels 4130M and 4330M is presented in Fig. 1. It corresponds to the usual microstructure of normalized alloyed structural steels [4]. It consists of identical mixture of small grain (No8- 9) ferrite and bainite.

It should be mentioned that the grain size for steel 4330M samples is finer and there is less of ferrite. It could be explained by a larger amount of alloying elements as well as by the place chosen to take a sample in the casting. The sample closer to the surface acquires a finer structure of martensite.

The microstructure of the samples of cast steel is presented in Fig. 2. It is similar for all three plate samples and consists of an identical mixture of ferrite and pearlite. The grain size of cast steels is a little coarser comparing to the samples of thermally treated alloyed steels

For defining the indices of cyclic resistance to cracking and for producing kinetic diagrams of crack development, the methods of ASTM E 647-00 have been applied. Compact samples (CT) were cut out of steel plates under the investigation with a slot orientated differently to the plate axes. For producing diagrams, 4-6 compact samples of each material were tested.



a

b

Fig. 1 Microstructure of thermally treated alloyed structural steel 4130M (a) and 4330M (b): bainite (dark), ferrite (light)

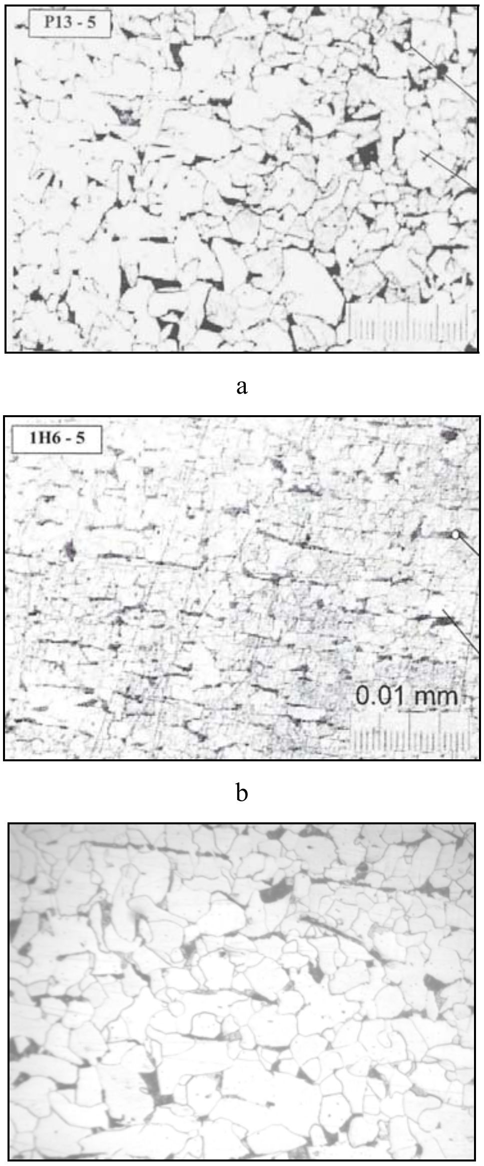
For calculating the interval ΔK of stress intensity coefficient, formula [5] was applied

$$\Delta K = \frac{\Delta F}{BW^{1/2}} f\left(\lambda\right) \tag{1}$$

here ΔF is load interval; B is sample thickness; W is base length of the sample; $f(\lambda)$ is geometrical function.

The stress intensity threshold magnitude ΔK_{th} was established in the case of stress ratio $r \approx 0.09$. Kinetic fatigue diagrams of thermally treated steel samples are presented in Fig. 3.

The values of cracking threshold vary in rather wide limits and are similar for both steels. For steel 4130M, the stress intensity threshold limit value ΔK_{th} =7-8.5 MPa·m$^{1/2}$; for steel 4330M ΔK_{th} =7.1-9.0 MPa m$^{1/2}$.



a

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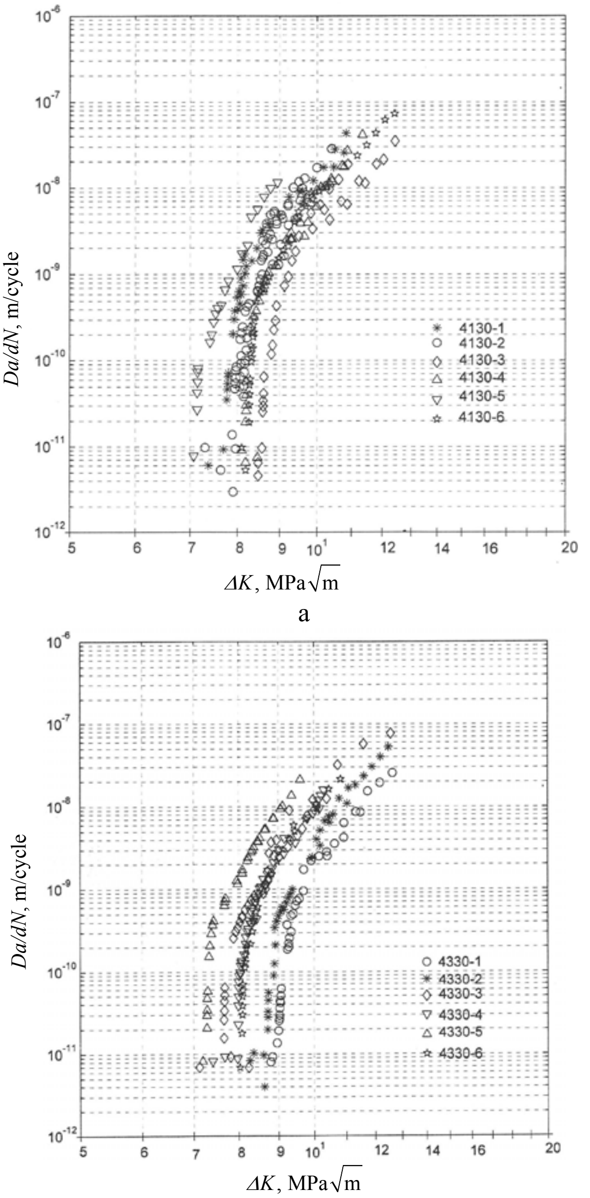
c

Fig. 2 Microstructure of cast steel samples P (a), H (b) and T (c): pearlite (dark), ferrite (light)

It was noticed when performing investigations that in some steel 4130M samples (for instance, 4130-2) the cracking threshold ΔK_{th} depends on the crack depth. The stress state and structural non-homogeneity change the disintegration mechanism and influence crack front. For checking this phenomenon, additional investigations have been performed (Fig. 4). In supplementary tests the influence of crack depth on the cracking threshold ΔK_{th} is small and that means that the structure of these samples is homogeneous.

Kinetic fatigue diagrams of samples of cast steel are presented in Fig. 5.

The values of the cracking threshold were defined: plate P – ΔK_{th} = 6.6-8.8 MPa·m$^{1/2}$, plate H - ΔK_{th} = 6.9-8.6 MPa·m$^{1/2}$, plate T - ΔK_{th} = 5.7-7.8 MPa·m$^{1/2}$. It was noticed, when analyzing the results of cast steel samples, that a considerable distribution of ΔK_{th} is characteristic for many samples when *da/dN* ratio does not exceed 10^{-10} m/cycle limit. Plates of a different cast have a different resistance to crack formation and propagation.



a

b

Fig. 3 Crack development kinetic diagram of compact samples of steel 4130M (a) and 4330M (b)

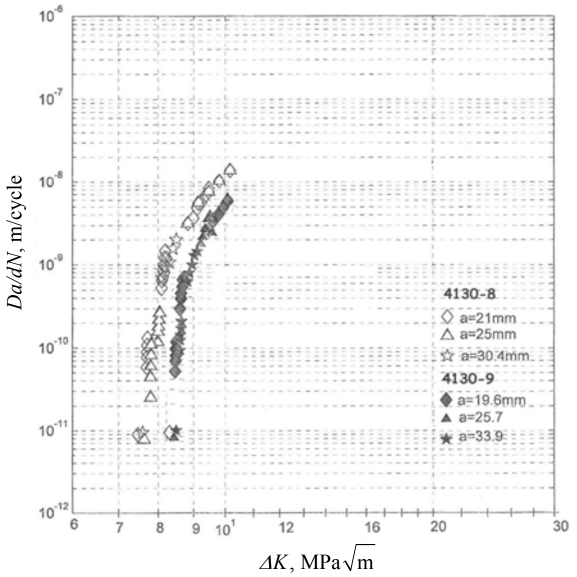
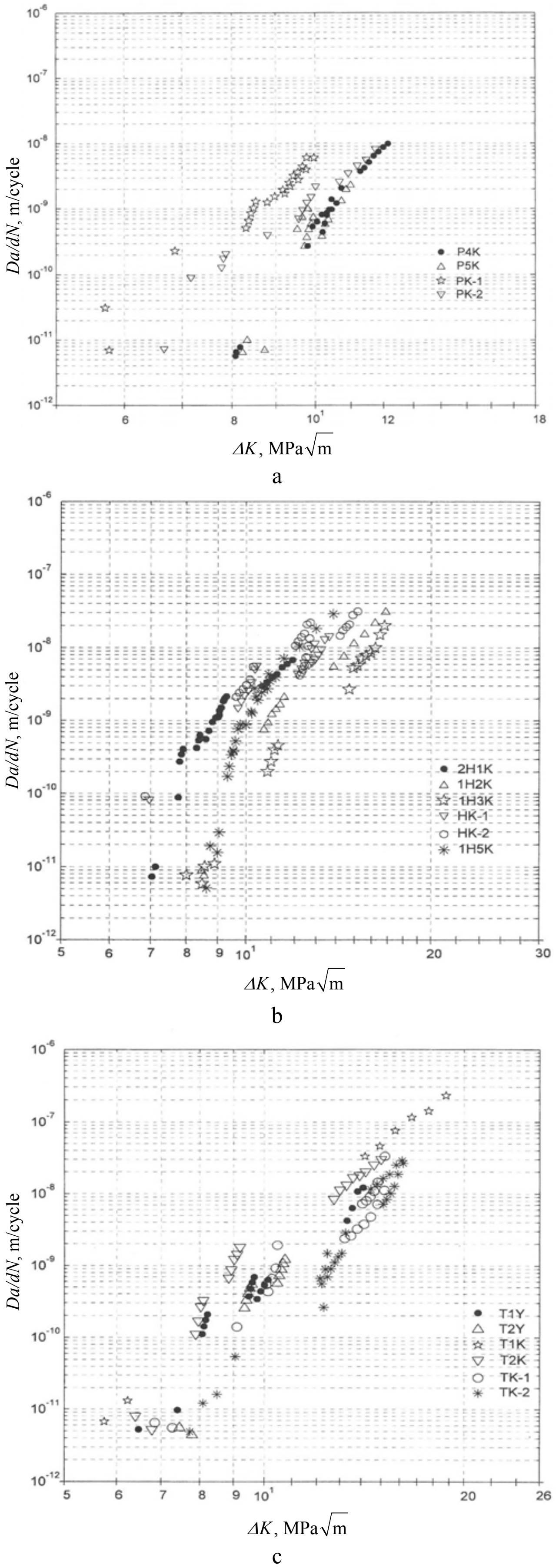


Fig. 4 Kinetic diagrams of crack development. Additional investigations on steel 4130M



a

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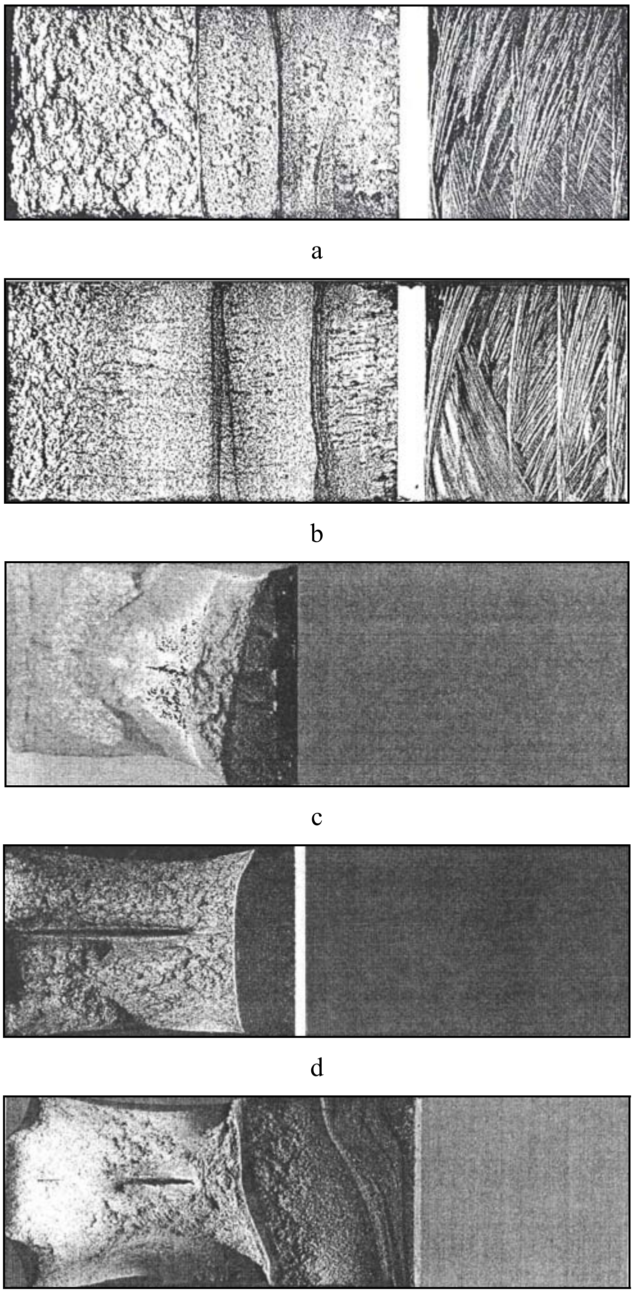
Fig. 5 Kinetic diagrams of crack development. Compact samples of P (a), H (b) and T (c) plates

Fractographic analysis of thermally treated steel samples showed that the surfaces of fractures of steel 4130M and 4330M samples (Fig. 6, a, b) are characteristic for alloyed structural steels. They are of a brittle character and the traces of disintegration inside the grain could be noticed. Such disintegration takes place when intergranular bonds because of some reasons (polluted intergranular layers, presence of secondary phases, segregation of alloying additives, etc.) are weaker than the structural grains. At the beginning of a fatigue crack formation it is possible to observe many cracking foci, which at the depth of 1-5 mm join to the main crack. In the cracks, pits could be seen, formed in the place of cavities and around them in the place of crest connections. Also, some signs of chemical macro inconsistency are seen – graphite inclusions formed by thermal treatment.



a

b

c

d

e

Fig. 6 Compact samples CT fractures (a, b - thermally treated steels 4130M, 4330M; c, d, e - cast steel plates P, H, T respectively)

Fractures of cast steel samples (Fig. 6, c, d, e) are of a more ductile character. The samples include visible traces of plastic deformations. The fatigue field is smaller than that of the alloyed steels. The fracture in an abrupt disintegration field is non-crack uniform. Along the crack development direction, a shearing crack of 1-2.5 mm width appears; at its end or nearby, the field of fragile grain rupture is seen.

3. Analysis of indices of mechanical properties and resistance to cracking

In fracture mechanics the general expression of stress intensity is [3]

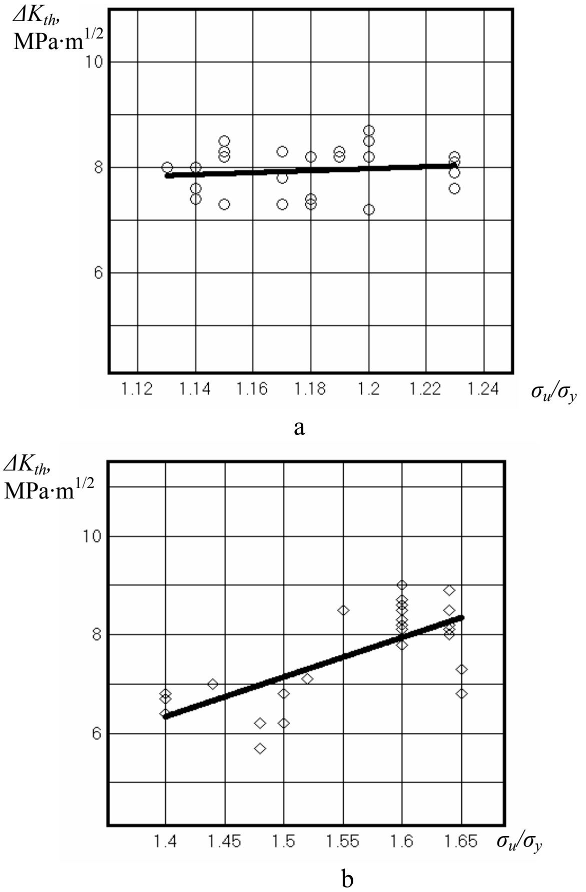
$$K_{\mathrm{I}} = Y\sigma\sqrt{a + a_o} \tag{2}$$

here Y is geometric factor; σ is stresses; a is crack size; a_0 is the size of structural defect.

When $a = 0$, $\sigma = \sigma_R$ (durability strength), $K_{\mathrm{I}} = \Delta K_{th}$ we obtain the stress intensity threshold

$$\Delta K_{th} = Y\sigma_R\sqrt{a_o} \tag{3}$$

In different works [3, 6], efforts are made to find the dependence between the crack threshold ΔK_{th}, yield strength σ_y, ultimate strength σ_u and other indices.



a

b

Fig. 7 ΔK_{th} and σ_u/σ_y experimental data and its regression line (a - alloyed steel; b - cast steel)

Using the obtained experimental data, the dependences ΔK_{th} and their linear regression equations on the ultimate and yield strength ratio σ_u/σ_y have been estimated. For alloyed steels this dependence is of such a shape

$$\Delta K_{th} = 1.9869\frac{\sigma_u}{\sigma_y} + 5.5904 \tag{4}$$

The graph of this function and its experimental data are shown in Fig. 7, a.

The value of correlation coefficient $r = 0.14$. Thus, it is not possible to state that there exists dependence between ΔK_{th} and σ_u/σ_y. By the disposition of experimental results in the graph it is clear that no other more valuable correlative dependence could be determined. For design calculations of steels, arithmetical mean value of the obtained ΔK_{th} values could be applied; it is equal to $\Delta K_{th,\,m} = 7.93$ MPa·m$^{1/2}$. The dispersion of results is small, the variation coefficient amounts to $v = 5.7\%$.

The equation of linear regression for cast steels is

$$\Delta K_{th} = 8.032\frac{\sigma_u}{\sigma_y} - 4.9043 \tag{5}$$

The experimental data and the graph of regression equation function are presented in Fig. 7, b. The correlation coefficient $r = 0.70$. Such value shows a rather strong and important linear dependence. The regression equation obtained may be applied to ΔK_{th} design calculations.

4. Conclusions

1. For cast steels, a considerable dependence of stress intensity threshold on crack depth has been found. It shows an insufficient homogeneity of the cast material.

2. The dependence of alloyed steels ΔK_{th} on their strength indices is insignificant. For design calculations it is possible to apply arithmetic mean of the obtained ΔK_{th} values.

3. The dependence of cast steels ΔK_{th} on their strength indices is significant. For design calculations it is possible to use the defined linear dependence.

References

1. **Nguyen-Duy, P., Bayard, S.** Fracture toughness of 4130 quenched and tempered steel.-ASME. J. of Engineering Materials and Technology, v.103, No1, p.57-63.
2. **Calister, W.D.** Fundamentals of materials science and Engineering: An interactive e. text. Willey, 2000.-552p.
3. **Трощенко В.Т.** Деформирование и разрушение металлов при многоцикловом нагружении.-Киев: Наукова думка, 1981.-343с.
4. **Франценюк И.В., Франценюк Л.И.** Альбом микроструктур чугуна, стали, цветных металлов и их сплавов.-Москва: ИКЦ «Академкнига», 2004. -192с.
5. **ASTM E 647-00.** Standard test method for measurement of fatigue crack growth rates. Annual Books of ASTM Standards, 2002, v.0301, p.615-657.
6. **Leonavičius, M., Šukšta, M., Stupak, S., Petraitis, G.** Experimental investigation of cyclic bending

strength of cast iron with dross layer.-Mechanika.- Kaunas: Technologija, 2003, Nr.5(43), p.13-18.

K. Bobyliov, M.K. Leonavičius, M. Šukšta,
A. Krenevičius, S. Stupak

LEGIRUOTŲJŲ KONSTRUKCINIŲ IR LIEJAMŲJŲ PLIENŲ ATSPARUMAS PLEIŠĖJIMUI

Reziumė

Tiriamas termiškai apdorotų konstrukcinių legiruotųjų ir liejamųjų plienų atsparumas pleišėjimui. Nustatytos pleišėjimo slenksčio priklausomybės nuo plieno stiprumo rodiklių. Šią priklausomybę galima taikyti liejamųjų plienų projektiniams skaičiavimams. Ištirta plyšio gylio įtaka pleišėjimo slenksčiui.

K. Bobyliov, M.K. Leonavičius, M. Šukšta,
A. Krenevičius, S. Stupak

RESISTANCE TO CRACK PROPAGATION OF ALLOYED STRUCTURAL AND CAST STEELS

Summary

The resistance to crack propagation of thermally treated alloyed structural ant cast steels is investigated. The dependences between cracking threshold and steel's strength indices is estimated. For cast steels, it could be applied in design calculations. The influence of crack depth on cracking threshold has been investigated.

К. Бобылёв, М.К. Леонавичюс, М. Шукшта,
А. Кренявичюс, С. Ступак

ТРЕЩИНОСТОЙКОСТЬ ЛЕГИРОВАННЫХ КОНСТРУКЦИОННЫХ И ЛИТЕЙНЫХ СТАЛЕЙ

Резюме

Исследуется трещиностойкость термически обработанных легированных конструкционных и литейных сталей. Установлены зависимости между порогом трещиностойкости и механическими свойствами стали. Для литейных сталей выявленная зависимость может использоваться в проектировочных расчетах. Исследовано влияние глубины трещины на порог трещиностойкости.

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