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Strength of differently cooled cast iron subjected to cyclic loading

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1. Introduction

Increase of equipment and construction element strength, durability and reliability is related to the adoption of rational mechanical properties of a material. A special significance is attached to the material suitability to production of structural elements, which are influenced by a cyclic load. Material should be manufactured in order to meet the conditions of construction cyclic load: it should resist cyclic loads and have good antifriction features at a time. A versatile harmonisation of such features is possible by invoking the well-known consistency and by performing additional research.

For manufacturing mine equipment and transport machines, a high-strength cast iron is used, which is modified during casting. Usually with the help of metallurgical and technological means the composition of cast iron is optimised by using more pure materials and special methods of casting. In the process of changing the casting chemical composition, good casting features are achieved; by regulating the casting cooling rate a structure with spherical graphite is obtained. In the high-strength cast iron, quantity of carbon amounts to 3.2-3.8 %. For high clearance parts, the quantity of carbon may be reduced to 2.7 %, so as to increase casting features. The quantity of alloying elements contributes to the regulation of metallic basis and graphitisation. Thick-wall high-strength cast iron castings have a ferrite or ferrite-pearlite base. In order to have a pearlite structure in such castings, cast iron is alloyed with nickel or copper. The quantity of manganese and silicon is limited to 0.25-0.30 % and 2.0-2.2 % respectively. The quantity of vanadium and chromium is also limited (not more than 0.1 %), as they stimulate formation of carbides. By decreasing the rate of casting cooling a great quantity of ferrite might form. Ferrite reduces mechanical properties, while carbide-phosphide derivatives form on the surfaces of euthectic crystallites [1-5].

Relation between the mechanical properties (obtained by technological means) and resistance to cyclical loads is important for determining the durability of structural elements in the projection phase and during service. Theoretical solutions of evaluation of materials, constructions and technologies should be validated experimentally, by invoking well-known and new criteria of strength and fracture [6, 7].

2. Structure and mechanical properties

Casting of high clearance parts and the following structural formation is related to some problems when obtaining mechanical properties. The available technological means do not warrant structural change for every of them having a small volume. For this reason one should know the structure and mechanical properties, especially in the localised ranges of casting.

Plates prepared for research: one of them cooled by a special regime (cast iron 1), the other one – after casting (cast iron 2). Chemical composition of equal casting plates is alike: C – 3-3.2 %; Si – 1.1 %, Mn – 0.25 %, Mo – 0.23 %; Ni – 0.4 %; Cu – 1.1 %.

Specimens – plates from cast iron 1 and 2 are prepared together with castings. Technology of manufacture corresponds to the manufacturing process of casting parts.

Structure of casting plate is shown in Fig 1. Graphite is in shape of various size flakes, structure matrix is ferrite-pearlite, at some places spherical shape graphite has formed up. On the other plate, graphitization process was regulated during cooling and a structure achieved, the metallic basis of which consists of ferrite-pearlite, while graphite is of spherical shape, as shown in Fig 2.

Uniformity of structure, the same as uniformity of mechanical properties, is significant if the part is under cyclical loads during service. It is well noticed that the size of graphite flakes and globules on different plates are miscellaneous. Dimension of casting cast iron flakes reaches 0.25 mm; a specially cooled grain similar to globule is of 0.06 mm.

From both plates, 8 compact specimens are cut for determining the threshold ΔK_{th}. For determining the mechanical properties, special specimens are prepared. After

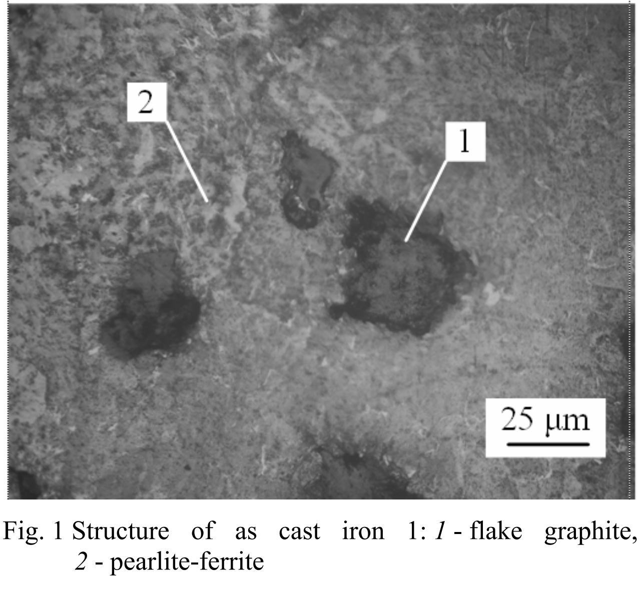

Fig. 1 Structure of as cast iron 1: *1* - flake graphite, *2* - pearlite-ferrite

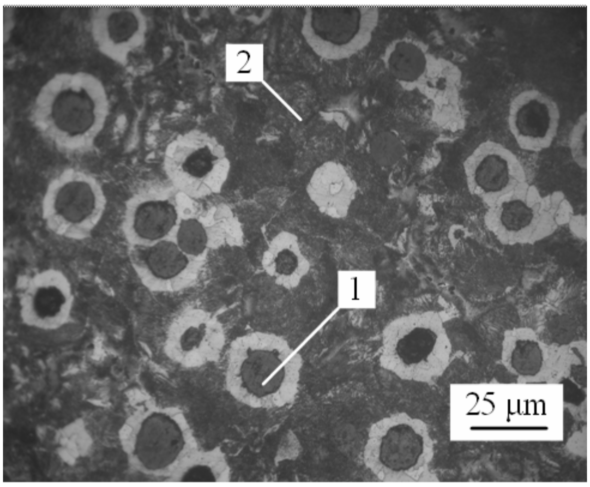

Fig. 2 Structure of cooled cast iron 2: *1* – spherical graphite, *2* - pearlite-ferrite

the experiment, factors of mechanical properties and hardness for every *CT* specimen are provided in Table 1.

Mechanical property factors of specimens from casting plate: hardness 259-281 BHN, tensile strength $\sigma_u = 622\text{-}671$ MPa, yield stress $\sigma_{0,2} = 443\text{-}510$ MPa; percentage of elongation $A_t = 1.81\text{-}2.43$ %.

Mechanical property indexes of specimens from a specially cooled plate: hardness 228-252 BHN, tensile strength $\sigma_u = 684\text{-}727$ MPa; yield stress $\sigma_{0,2} = 454\text{-}467$ MPa; percentage of elongation $A_t = 5.3\text{-}6.2$ %.

As we can see, hardness and mechanical properties for casting and a specially cooled cast iron differ in rather wide limits. It may be influenced by the form of graphite and metallic basis. Nonhomogeneity of structure, separate derivatives of irregular form, inequality of metallic basis in thinner castings decrease mechanical properties of localised places, become flashpoints of crack by operating with cyclical loads.

Table 1

Mechanical properties

Specimen No.	Cast iron 1			Cast iron 2		
	BHN	A_t, %	σ_u/σ_y	BHN	A_t, %	σ_u/σ_y
1	225-235	6.13-6.77	1.57	278	1.8-1.9	1.25
2	244-251	5.5-6.0	1.50	281	1.75-1.9	1.22
3	244-245	5.5-6.0	1.52	266-269	1.85-2.0	1.30
4	242-245	5.6-6.0	1.56	272	1.79-1.84	1.25
5	246-249	5.5-5.8	1.50	266-269	1.85-2.0	1.38
6	248-256	5.0-5.5	1.48	264-267	1.86-2.2	1.44
7	242-254	5.5-6.2	1.45	255-262	1.93-2.4	1.40
8	240-248	5.4-5.9	1.46	259	1.93-2.43	1.42

3. Resistance to cyclical loads

Various works [6-9] try to find a relation between the threshold ΔK_{th} yield stress σ_y, tensile strength σ_u, endurance limit σ_r and other factors. It should be noted that there is no clear correlation between the indexes of mechanical properties and resistance to crack propagation. Threshold ΔK_{th} is also dependent on cycle asymmetry, influence of temperature environment, loads, structural peculiarities of materials and other factors. However, data on the cast iron resistance to crack propagation by operating in cyclical loads is not sufficient. There is special shortage of data about ΔK_{th} dependability on mechanical properties and structure, which can be changed during the process of casting, cooling and heat treatment.

From cast iron 1 and 2, compact tensile specimens (*CT*) have been produced. According to the standard ASTM E 647-00 methodology, 8 casting and 8 specially cooled plate specimens (62.5×60×24), having a special notch were tested. During the cyclical load a crack was grown up and propagation rate was decreased by a decreasing power. Range of stress intensity factor was calculated according to the formula

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

where $\lambda = a / W$ (2)

$$f(\lambda) = \left[\left(2+\lambda\right)/\left(1-\lambda\right)^{3/2}\right]\times$$
$$\times\left(0.866 + 4.64\lambda - 13.32\lambda^2 + 14.72\lambda^3 - 5.6\lambda^4\right) \tag{3}$$

Stress intensity factor range $\Delta K = K_{max} - K_{min}$; stress ratio $R = F_{min} / F_{max} = K_{min} / K_{max}$.

K_{min} and K_{max} are minimum and maximum stress intensity factor in the cycle of loading.

Nominal stress in the crack tip

$$\sigma = F / A + M / Z = \left(F / B\right)\left[\left(4W + 2a\right)/\left(W - a\right)^2\right] \tag{4}$$

or $\sigma = \left(2F / B\,W\right)\left(2+\lambda\right)/\left(1-\lambda\right)^2$ (5)

where F is axial force; bending moment $M = F\left[a + \left(W - a\right)/2\right]$; area of netto cross-section $A = \left(W - a\right)B$; section modulus $Z = \left|\left(W - a\right)^2 B\right|/6$

The size of limit stress intensity factor ΔK_{th} was determined, while cycle asymmetry factor is $r \approx 0.05$.

Dependence of ΔK_{th} on crack propagation rate are provided in Figs. 3, 4. We may see that values of threshold fluctuate between rather wide limits and are different for cast iron 1 and 2.

According to the regulating methodology [10, 11], dependability of stress intensity factor range ΔK on crack propagation rate is determined when the rate is less than $v < 10^{-8}$ m/cycle. In order to predict and expand durability, one should know the limit stress intensity factor range ΔK_{th} on lesser rates.

An experimental research is performed so as to get data on ΔK_{th} values, when crack propagation rate approaches 10^{-10} m/cycle, 10^{-11} m/cycle and 10^{-12} m/cycle.

It is worth knowing for the projection durability security that the threshold correlates with mechanical properties of materials. For this reason an analysis is accomplished concerning the threshold ΔK_{th} (by various crack propagation rates), on the one side, and hardness, tensile strength ratio, conditional yield stress ratio, percentage of elongation on the other one.

Table 2

Threshold stress intensity factor range and crack propagation rates

Specimen No	$\sigma_u/\sigma_{0,2}$	Threshold stress intensity factor range at crack propagation rates, MPa·m$^{1/2}$		
		$1\cdot10^{-10}$ m/cycle	$1\cdot10^{-11}$ m/cycle	$1\cdot10^{-12}$ m/cycle
Cast iron 1				
1	1.57	9.21	9.27	8.23
2	1.50	9.1	8.78	–
3	1.57	10.9	10.8	10.49
4	1.56	9.51	9.39	–
5	1.50	10.6	9.4	9.68
6	1.48	9.51	8.9	8.44
7	1.45	9.5	8.2	–
8	1.46	9.74	8.48	9.05
Cast iron 2				
1	1.25	7.45	8.24	–
2	1.22	8.6	8.4	
3	1.30	9.1	8.6	–
4	1.25	9.0	8.39	8.08
5	1.38	8.52	7.14	–
6	1.44	8.23	7.11	6.83
7	1.40	7.2	6.97	–
8	1.42	7.3	7.19	6.86

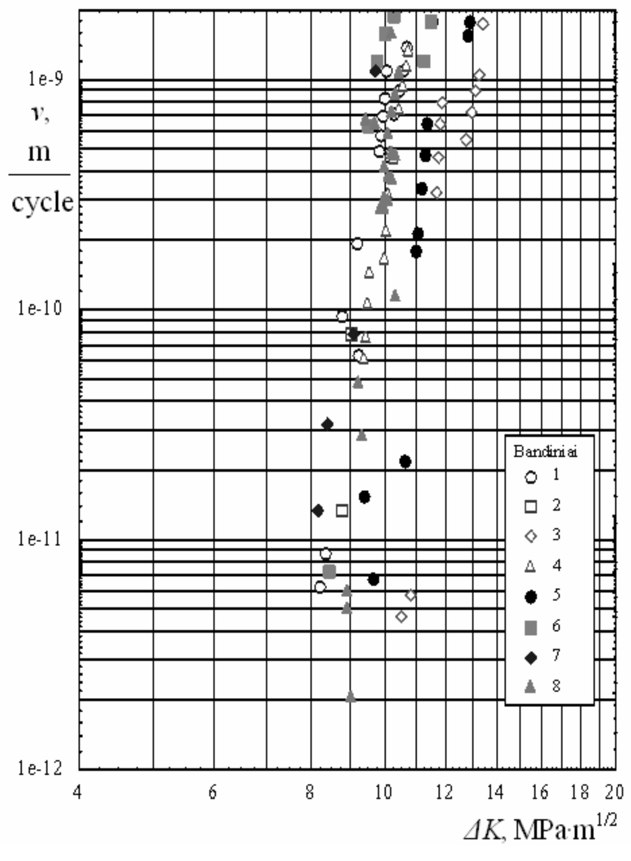

Fig. 3 Stress intensity factor range ΔK dependencies on crack propagation rates for specially cooled cast iron

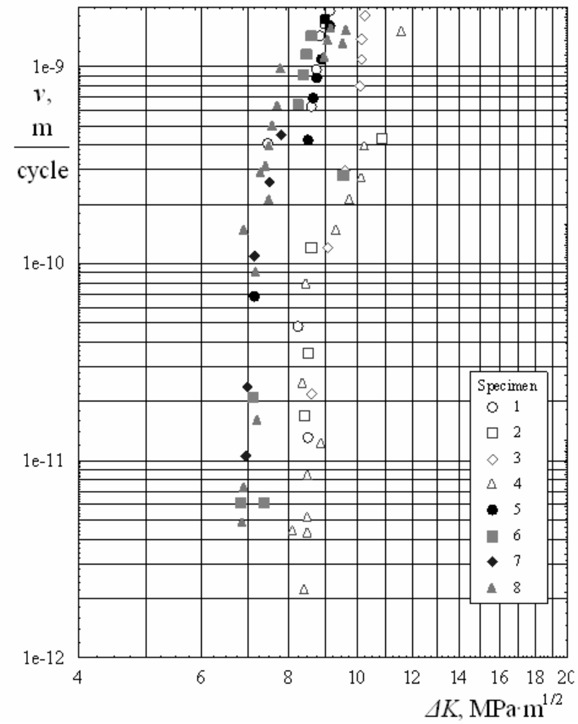

Fig. 4 Stress intensity factor range ΔK dependencies on crack propagation rates for cast iron

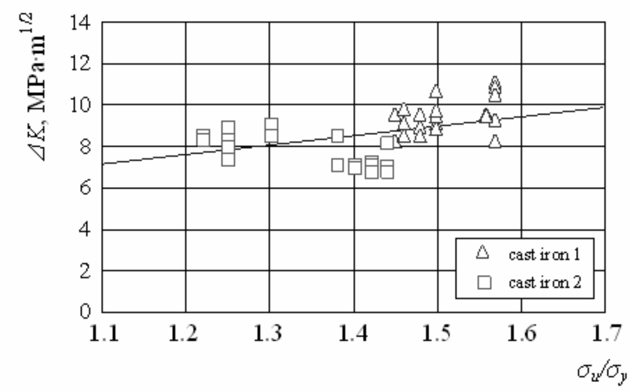

Fig. 5 Stress intensity factor range ΔK dependencies on ratio σ_u/σ_y

Table 2 presents threshold values determined for the crack propagation rate reaching 10^{-10}; 10^{-11} and 10^{-12} m/cycle. According to the data provided in Figs. 3, 4 and Table 2, a dependence between σ_u/σ_y (tensile strength and yield stress ratio) and limit stress intensity factor ΔK_{th} are presented. This dependence is shown in Fig. 5.

Linear dependence is described by function:

$$\Delta K_{th} = 4.396\frac{\sigma_u}{\sigma_y} + 2.405 \qquad (6)$$

where σ_u is tensile strength; σ_y is yield stress.

Correlation factor 0.506 is little and shows a tendency rather than a regularity.

Threshold stress intensity factor range dependence on cast iron percentage of elongation A_t (relative elongation of the specimen) is shown in Fig. 6.

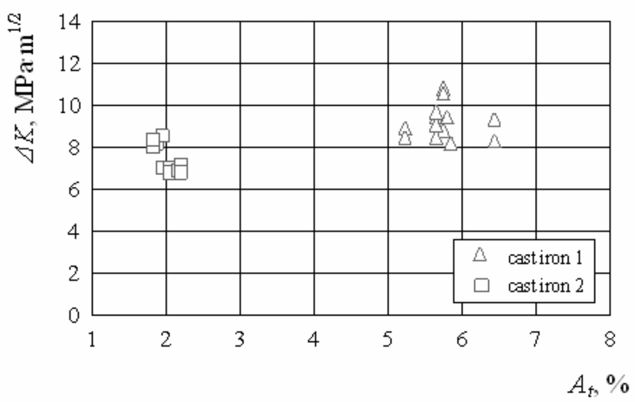

Fig. 6 Threshold stress intensity factor range ΔK_{th} dependence on plasticity factor A_t

The provided data show that in case of an increase elongation, the threshold is also increase marginally.

Relation between the threshold and compact specimen hardness BHN is shown in Fig. 7.

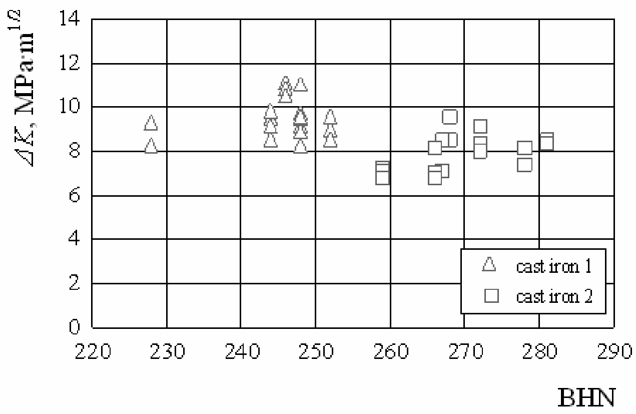

Fig. 7 Stress intensity factor range ΔK dependence on hardness

We can see that hardness of specially cooled cast iron 228-256 BHN is less than of casting cast iron hardness 255-281 BHN. However, no significant relation between hardness and threshold has been observed.

The investigation had approved the proposition, that for improving of mechanical properties, it may be adapted various heat or thermo-chemical treatment processes. The technology of castings cooling is constituent part of this process. In consequence it is possible to increase the hardness, plasticity and ultimate strength. Unfortunately one of the heat treatment imperfections for large or complicated configuration castings lay therein some locations the microstructures and defects may remain unaffected or under-unaffected. This influences threshold stress intensity factor range under cyclic loading. For increase of materials resistance for crack formation and propagation it is needed an additional investigation and analysis for determination of its relation with mechanical properties.

4. Conclusions

1. Casting and specially cooled cast iron research show that cast iron of the same chemical composition has a different structure, hardness, factors of mechanical properties and resistance to cyclic load.

2. It is determined that a threshold stress intensity factor range for casting cast iron is ΔK_{th}=6.8-9.0 $\text{MPa}\sqrt{\text{m}}$, a specially for the cooled cast iron – ΔK_{th}=8.2-10.9 $\text{MPa}\sqrt{\text{m}}$, when crack propagation rate diminishes from 10^{-10} m/cycle to10^{-12} m/cycle.

3. The threshold depends on σ_u / σ_y (determined dependability), cast iron structure and elasticity.

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SKIRTINGAI AUŠINTŲ KETŲ STIPRUMAS VEIKIANT CIKLINĖMS APKROVOMS

Reziumė

Straipsnyje pateikiami lietų ir specialiai aušintų ketų daugiaciklio nuovargio eksperimentinio ir analitinio tyrimo rezultatai. Žinoma ketaus rūšis liejimo procese modifikuota tam, kad gauti geresnes mechanines savybes ir atsparumą plyšio susidarymui ir plitimui. Nustatyti mechaninių savybių rodikliai rodo, kad specialus aušinimas pakeičia struktūrą, padidina plastiškumą ir suvienodina takumo ir stiprumo ribas. Lieto ketaus struktūra turi įvairaus dydžio dribsnių ir rutuliukų pavidalo grafitą, kuris po specialaus aušinimo įgauna rutulinę formą, sumažėja, suvienodėja dydžiu bei susmulkėja visa struktūra. Išbandžius kompaktinius necentrinio tempimo CT bandinius nustatyti įtempimų intensyvumo koeficientų ribiniai intervalai priklausomai nuo tokių mechaninių savybių rodiklių: kietumo, plastiškumo ir stiprumo bei takumo ribų santykio. Pasiūlyta ΔK_{th} ir mechaninių savybių rodiklių priklausomybės analitinė išraiška gali būti panaudojama cikliškai apkraunamų didelio gabarito detalių stiprumo skaičiavimui.

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STRENGTH OF DIFFERENTLY COOLED CAST IRON SUBJECTED TO CYCLIC LOADING

Summary

The paper presents the results of experimental and analytic investigation of cyclic fatigue of a common and a specially cooled cast iron. A well-known type of cast iron was modified by casting to receive better mechanical properties and strength to formation and propagation of crack. Established indices of mechanical properties show that a special cooling modifies structure, enhances plasticity and equalises limits of yield stress and tensile strength. The structure of cast iron includes graphite flakes of various size. Graphite of a specially cooled cast iron is of spherical shape, lesser size and are equalised by size. By trying compact tensile specimens CT limit ranges of stress intensity factor were established depending on following factors of mechanical properties: hardness, elasticity, and mechanical properties ratio ratio. An analytic expression of ΔK_{th} and factors of dependence on mechanical properties were proposed may be applied to calculations of strength of cyclic load high clearance parts.

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ЗАВИСИМОСТЬ ЦИКЛИЧЕСКОЙ ПРОЧНОСТИ ЧУГУНА ОТ ПРОЦЕССА ТИПА ОХЛАЖДЕНИЯ

Резюме

В настоящей работе приведены результаты иследования литых и специально охлаждених чугунов на многоцикловую усталость. Известные марки чугунов в процесе литья модифицированы для улучения механических свойств и многоцикловой прочности. Установлены механические свойства показывают, что специальное охлаждение улучшает структуру, увеличивает пластичность и прочность. После испытания компактных образцов получены пороговые коэфициенты интенсивности напряжений. На основе экспериментальных даных приведены зависимости между пороговыми коэфициентами интенсивности напряжений и твердостью, пластичностью и отношением между пределом прочности и текучести позволили получить аналитическое выражение порогового коэфициента интенсивности напряжений для расчета циклически нагруженых деталей конструкций больших габаритов.

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