



Gediminas PETRAITIS

**INVESTIGATION OF HIGH-CYCLE FATIGUE
CRACK FORMATION AND PROPAGATION
IN LAYERED CAST IRON**

**Summary of Doctoral Dissertation
Technological Sciences, Mechanical Engineering (09T)**

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Vilnius  **2006**

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Gediminas PETRAITIS

**DAUGIACIKLIO NUOVARGIO
PLYŠIŲ SUSIDARYMO IR PLITIMO
SLUOKSNIUOTAJAME KETUJE TYRIMAS**

Daktaro disertacijos santrauka
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1. GENERAL CHARACTERISTIC OF THE DISSERTATION

Topicality of the problem. Modern machines, equipment and structures are designed for the purpose to increase their characteristics to maximum values by reducing weights, production and energy costs but retaining a high duty, effectiveness and longevity. The high-strength cast iron is used for manufacturing the transportation and mining equipment, showed in Fig 1, the mechanical properties of which are improved by special heat and thermo-chemical treatment processes. However, due to large dimensions it is hard to maintain uniform quality of manufacturing processes and different volumes with non-homogeneous matrices may appear. Such volumes can be identified as separate layers and the whole structure termed the layered cast iron. When the equipment longevity exceeds 20–50 years, the crack formation and

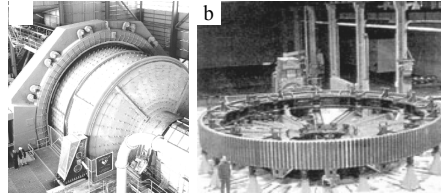


Fig 1. Mineral grinding drum (a), gear (b)

propagation mechanism under high- and hyper-cycle fatigue (number of cycles $10^5 \dots 10^9$) becomes unclear. Modern calculating methods used in the first crack formation stages are insufficiently reasoned. Supposedly, the fracturing changes its character. The crack formation time determines the longevity of the whole structure. Various non-homogeneous formations and defects accelerate the fracturing process. Besides, even at the design stage, it is needed to evaluate the strength of structural elements when the cracks are not formed yet, ie to be able to evaluate the residual strength of the structural element with a crack.

For solving these problems the international program “Increase of cyclic strength and resistance to crack propagation of mining and transport equipment” was organised including their commercial and academic participants in the USA, Australia, France, Germany, Finland as well as the Strength of Materials Department of Vilnius Gediminas Technical University.

Aim and tasks of the work. Using different methods to determine fatigue crack formation and propagation regularities in high-strength layered cast iron under a high-cycle fatigue and to improve the structural element calculation methods.

Methodology of research. Experimental, analytical and numerical methods have been applied in the dissertation. For the experimental testing original and standard methods have been used. The resistance to crack formation and propagation was analysed by a linear fracture mechanics criterion – stress intensity factor. ANSYS was used for numerical analysis.

Research object. The mechanical state emergent during service of the real structural elements of high strength cast iron under high cycle loading.

Scientific novelty

- The investigation deals with a high- and hyper-cycle fatigue of high-strength layered cast iron considering the poor research of fracture process determining factors.
- The fatigue crack formation and propagation factors have been defined for layered high-strength cast iron.

Practical value

- It was established by the investigation that the fatigue crack origin is earlier and propagation rates are higher in volume with technological defects than in the structures without such deflections.
- The obtained results and calculation methods enable to evaluate the strength of large structural elements.

The scope of the scientific work. The dissertation consists of a general characteristic, 5 chapters, conclusions, references and appendices. The overall volume of the dissertation includes 100 pages, 68 figures, 6 tables and 3 appendixes.

Acknowledgment. The author thanks Assoc. Prof. Dr. A. Krenevičius, Assoc. Prof. Dr. M. Šukšta, Manchester University Assoc. Prof. J. Marrow, “Metso Minerals Industries Inc”. Engineering Technologies Director V. Svalbonas and co-workers of VGTU Laboratory of Strength of Mechanics for their kind assistance in experimental testing.

2. STRUCTURE OF THE WORK

The first chapter presents the analysis of scientific investigations in the research field. It shows that there is a lack of research of high-strength layered cast iron subjected to a high-cycle fatigue which prevents the

trustworthy longevity predictions of large dimensions structural elements. Various defects and uneven mechanical state develop during large-dimensions elements manufacturing processes. However, they are unavoidable and have a direct influence on the longevity of structures which influence is almost impossible to appreciate by using modern methods. The influence of different factors in a high-cycle fatigue range is also insufficiently known. Resistance to high-cycle loading is investigated in various aspects by using different fatigue theories and linear fracture mechanics. The experiment testings are still unavoidable for determining critical values of fracture criteria used for design calculations.

The second chapter presents a review of methods and testing equipment used for the experimental investigation. The original and standard methods have been applied. Semi-natural and compact tension (CT) specimens and the loading scheme have been prepared in the manner to repeat the mechanical state of a real structural element. Semi-natural rectangular cross-section specimens with a dross layer were applied to pure bending. The loading programme was tuned to reach the threshold stress intensity by increasing K , and to control the crack propagation until the final breakage. The stress ratio was $r = -0.62$ and the stress alternating range varied from 70 to 280 MPa. The testing equipment enabled a slight movement of semi-natural specimens in the longitudinal direction to prevent the influence of fixation. For measuring crack propagation there were applied methods of non-destructing control – optical, ultrasonic, magnetic luminescence and paint imprint – and enabled to measure crack size in a different manner. Furthermore, the crack sizes were additionally checked by optical microscopy after the specimens' breakage.

The standard testing methodology of CT specimens have been changed: the threshold stress intensity factor was determined at the crack propagation rates around 10^{-12} m/cycle, ensuring crack size measurement in a number of cycles. For experimental material analysis the analytical and numerical (ANSYS) methods have been applied.

The third chapter presents the research of high-strength cast iron used for manufacturing the supporting elements of minerals and cement clinker grinding machines with dross layer that remains inside the large dimension castings after manufacturing. This layer has worse mechanical properties and resistance to fatigue crack formation and propagation.

In the base layer showed in Fig 2, the graphite is spherical in shape. In the transitional layer the graphite is in shape of flakes. The dross layer consists of flake and plate graphite, inserts, cavities and non-homogeneous formations.

The mechanical properties of the base and dross layers differed considerably: basic metal $\sigma_{pr}=228$ MPa, $\sigma_{0,2}=328$ MPa, $\sigma_u=507$ MPa, $E=177$ GPa, $\psi=3,8\%$ and $\delta=5,5\%$. The mechanical properties of dross layer are as follows: $\sigma_{pr}=150$ MPa, $\sigma_{0,2}=218$ MPa, $\sigma_u=233$ MPa, $E=145$ GPa, ψ or $\delta < 1\%$.

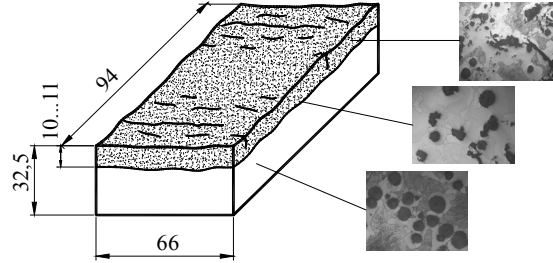


Fig 2. Testing section of specimens and microstructures

The loading program and the fatigue crack size are shown in Fig 3. The overall number of cycles for specimen 1 was $3,1 \cdot 10^8$ and for specimen 2 – $2,5 \cdot 10^8$ cycles.

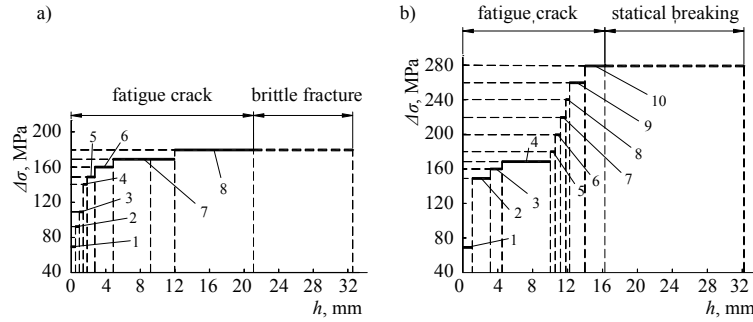


Fig 3. Loading program and crack propagation dependences on stress range:
a – specimen 1, b – specimen 2

The stress intensity factor K_I for rectangular cross-section specimen in pure bending case was calculated according to the ASME:

$$K_I = \sigma \sqrt{\pi a} f(\alpha), \quad (1)$$

where σ – maximum stress in process zone; a – crack length; $f(\alpha)$ – geometry function:

$$f(\alpha) = 1,122 - 1,40\alpha + 7,33\alpha^2 - 13,08\alpha^3 + 14,0\alpha^4, \quad (2)$$

where α – the ratio of the crack size a to the specimens width W .

The dependencies of crack growth rate versus the maximum stress intensity factor are shown in Fig 4.

To determine the stress intensity range threshold ΔK_{th} the CT specimens were tested. The dependences of crack growth rate versus the stress intensity factor range were determined and showed in Fig 5. The threshold of dross layer is $\Delta K_{th} = 7,7 \text{ MPa}\cdot\text{m}^{1/2}$. The threshold of base metal is $\Delta K_{th} = 9,3 \text{ MPa}\cdot\text{m}^{1/2}$.

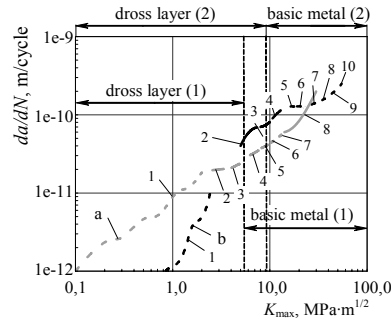


Fig 4. Crack growth rates vs maximum stress intensity factor: a – specimen 1, b – specimen 2 (1–10 – numbers of program loading cases)

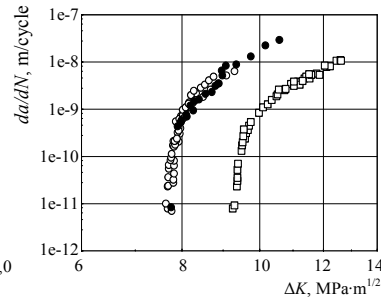


Fig 5. Crack growth rate vs stress intensity factor range (○, ● – dross layer, □ – basic metal)

The numerical analysis was performed by ANSYS finite element program. The investigated model is shown in Fig 6. For an accurate stress intensity factor determination, a special element was employed. The middle points were mowed by 0,5 of length to the crack tip. In the near crack tip regime a special finite element mesh was proceeded and is shown in Fig 7.

When investigating the finite element model, the stress-strain field for particular loading and crack length have been determined. The crack size and the loadings were taken from the experimental investigation. The crack tip concentration element has been changed according to the crack

size. The finite element mesh was regenerated for each loading and crack size case.

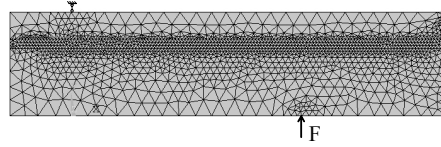


Fig 6. Finite element model mesh

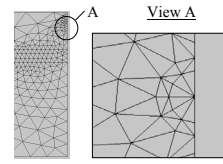


Fig 7. Finite element mesh at stress concentration

The experimentally-analytically and numerically obtained crack propagation dependences on stress intensity factor are shown in Fig 8 a and b. By comparing the experimental-analytical results with numerical ones it is clear that as the loading increases, the differences increase too. For explaining the differences of such notices the fractographic analysis was performed (Figs 9, 10). It showed the zigzag crack propagation path. The crack initiation site “fish eye” has been discovered in the surface layer; and lots of defects on the fatigue surface of dross layers which have distorted the fracturing process. Fatigue surface of basic metal and brittle fracture were determined as characteristic.

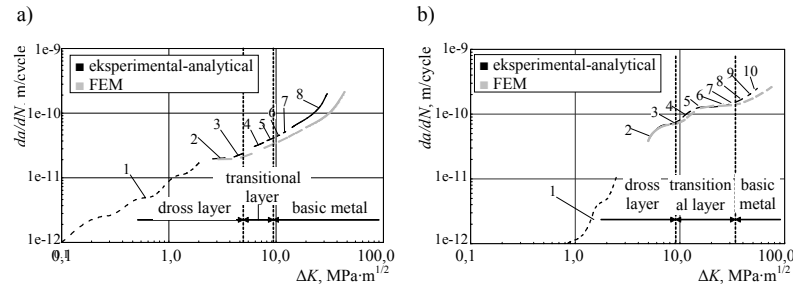


Fig 8. Crack growth rates vs maximum stress intensity factor in specimen 1 (a) and in specimen 2 (b)

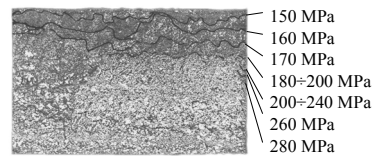


Fig 9. Fracture

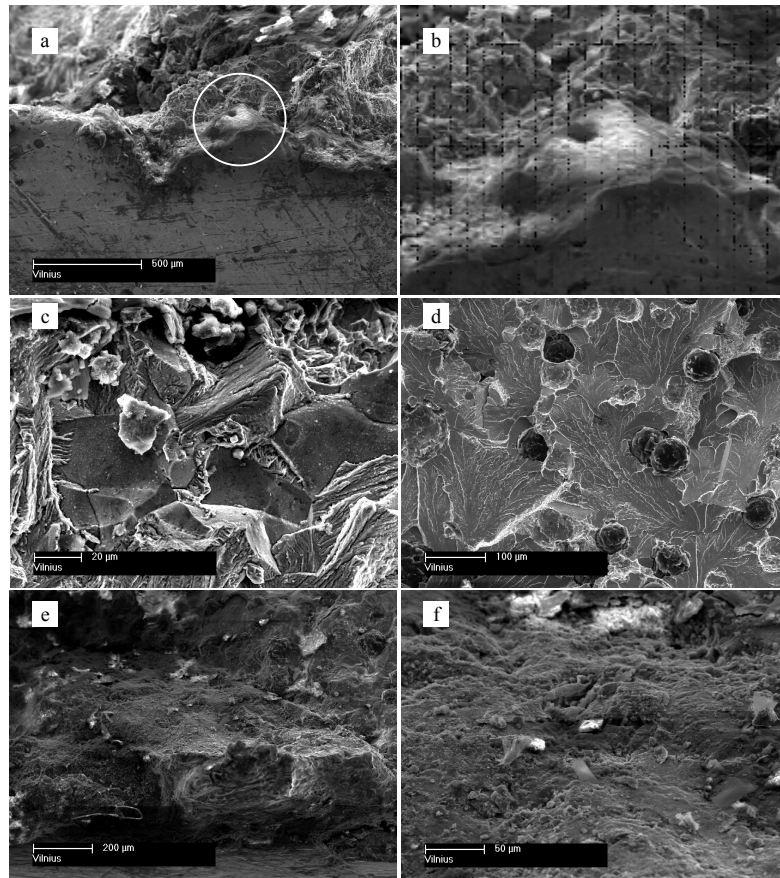


Fig 10. SEM fractography: a – fracture initiation site (“fish eye”), b – enlarged view, c – fatigue (intergranular failure), d – cleavage, e, f – microstructural defects on fatigue surface

There is a need for structural elements under the cyclic loading to determine the crack non-propagating conditions after the origin of the fatigue crack. The use of the fracture mechanics in this case is pointed to calculation of K_{th} . This parameter enables us to find the stress at which the further crack propagation in present structural elements stopps. The threshold stress intensity factor at different stress ratios is connected with the formula

$$\Delta K_{th} = \Delta K_{th0} (1-r)^\gamma; \quad (3)$$

here ΔK_{th} – the threshold stress intensity factor range, for positive stress ratio r , ΔK_{th0} – threshold stress intensity factor range when $r = 0$, γ – factor determined by material properties.

The threshold stress intensity factor range at $r = 0$ can be calculated by

$$\Delta K_{th0} = \frac{\Delta K_{th}}{(1-r)^\gamma}. \quad (4)$$

Threshold stress intensity factor $\Delta K'_{th}$ for any stress ratio may be expressed as

$$\Delta K'_{th} = \Delta K_{th} \left(\frac{1-r}{1-r_{th}} \right)^\gamma; \quad (5)$$

here r – present stress ratio, r_{th} – stress ratio at which the threshold stress intensity factor was determined.

The allowable stress in accordance with threshold stress intensity factor is expressed by the known equation

$$K = \sigma \sqrt{\pi a} f(\alpha). \quad (6)$$

The stress range according to the threshold stress intensity factor evaluating stress ratio can be calculated as follows:

$$\Delta \sigma'_{th} = \frac{\Delta K_{th}}{\sqrt{\pi a}} \left(\frac{1-r}{1-r_{th}} \right)^\gamma f(\alpha). \quad (7)$$

Equation (7) is valid when $r > 0$. For real structural elements can be the cases when $r < 0$. Then the K_{max} is used more frequently. Interdependence of these two parameters can be expressed as

$$K_{max} = \frac{\Delta K}{1-r}. \quad (8)$$

The stress ratio influences the fracturing character. This is associated by the crack closure phenomena and effective stress intensity factor K_{eff} . Besides, for the high-strength cast iron, the limit strength under tension and compression differs ($3\sigma_{ut} \approx \sigma_{uc}$). The influence of stress ratio on cast iron crack formation and propagation is unclear and insufficiently investigated. The maximum stress that accords with threshold stress intensity range is expressed by the following formula:

$$\sigma_{\max,th} = \frac{\Delta K_{th}}{\sqrt{\pi a}} \frac{(1-r)^\gamma}{(1-r)^{1+\gamma}} f(\alpha). \quad (9)$$

In this case operating stress range equals the maximum stress per cycle: $\Delta\sigma_{th} = \sigma_{\max,th}$.

By the way, the stresses in layered materials are distributed in a different manner than in a homogeneous material. If an investigated structural element is of a rectangular cross-section, the stresses dependence on layers must be mentioned:

$$\sigma_{\max,th} = \frac{M_{\max} E_i}{\sum_{i=1}^n E_i I_i}. \quad (10)$$

By using equations 9, 10, the ΔK_{th} was recalculated and equals – for the dross layer – $8,1 \text{ MPa}\cdot\text{m}^{1/2}$, basic metal – $9,8 \text{ MPa}\cdot\text{m}^{1/2}$. Dependences shown in Figs 8 a and b were recalculated and are shown in Fig 11.

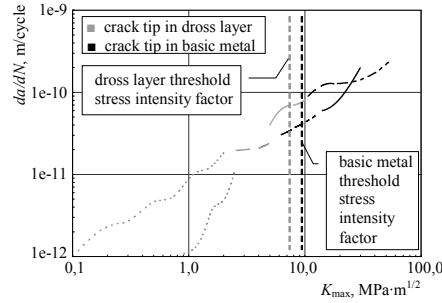


Fig 11. Recalculated crack growth rate diagram vs threshold stress intensity factor

In Fig 12 we can see that cracks to the left of the threshold stress intensity factors can be classified as short cracks. The cracks are called as long as the plastic deformation appears at the crack tip and the linear fracture mechanics dependences become valid. When the long cracks appear in the material, ie $a > a_i$, their propagation becomes dependent on the process zone size ρ^* which is respectively dependent on material microstructure and is much more bigger than the microstructural grain size. Then the crack propagation depends on two parameters: the stress value in local sites and the plastic zone size, which is also associated with plastic hardening phenomena at the crack tip. When the precracking size exceeds the long crack size $\rho^* > a_i$, the cracks are termed as non propagating ones. When the crack length exceeds the long crack length, the sensitivity to microstructure decreases and the crack closure becomes more influential. Crack closure phenomena have a great influence on crack propagation kinetics under the near threshold regime. By increasing the material strength, the influence of crack closure decreases. Below the threshold stress intensity factor the crack on its way must overcome every grain (defect) separately, and the cracks get a zigzag path. Due to this the influence of I mode decreases and the influence of II mode increases. Besides, it is important to note that the crack length increases with zigzag crack path that needs an additional energy and is a stopping factor. So the crack path changes the crack threshold stress intensity factor.

The fifth chapter gives the heat treated high-strength cast iron with non-homogeneous non-affected volumes research.

To improve the microstructure, normalisation is mostly applied. During this process, it is necessary to get microstructures with the pearlite matrix, but usually some part of ferrite remains. It is mild and undesirable. Therefore it is much more difficult to control the cooling temperature of large-size products. It is necessary to know the microstructure, mechanical properties and the resistance to crack propagation after casting and heat treatment. Two sorts of globular iron have been tested.

The microstructure of GI (globular iron) cast and normalised iron is shown in Fig 12. The microstructure of SGI (spheroidal graphite iron) cast and normalised iron is shown in Fig 13.

Of all plates compact tension specimens (CT) have been made. The values of mechanical properties have been defined; they are presented in Table 1. The hardness of GI cast iron is 250–277 BHN, normalised – 228–256 BHN, and hardness of SGI cast iron – 289–311 BHN, the normalised one – 290–311 BHN. In the process of heat treatment, hardness has changed slightly. For determining the threshold stress

intensity factor range ΔK_{th} , from GI and SGI cast irons compact tension CT specimens were cut.

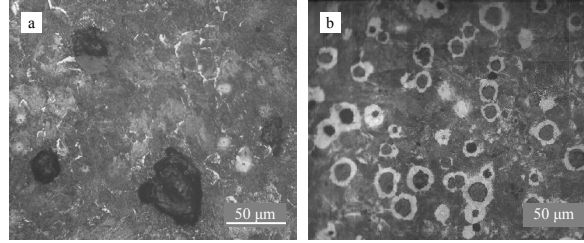


Fig 12. Structures of GI cast iron: a – cast, b – normalised

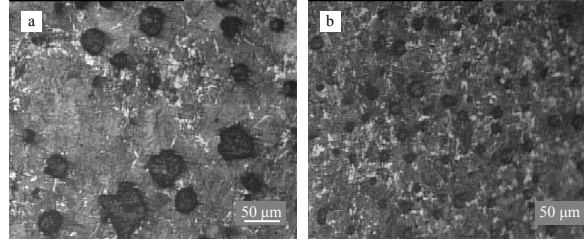


Fig 13. Structures of SGI cast iron: a – cast, b – normalised

Table 1. Mechanical properties

Cast iron		$R_{p0,2}$, MPa	R_m , MPa	A , %
GI	cast	443 - 503	622 - 671	1,80 - 2,43
	normalised	454 - 467	684 - 727	6,13 - 10,3
SGI	cast	630 - 634	863 - 933	3,70 - 6,70
	normalised	607 - 621	862 - 882	3,60 - 4,00

The mechanical properties of each CT specimen were used to define the dependence between threshold and yield and ultimate strength ratio ($R_m/R_{p0,2}$). According to the ASTM E 647-00 methods, 8 specimens of cast iron, 8 specimens of normalised GI cast iron and 4 cast and 4 normalised SGI cast iron specimens have been tested (frequency to 30 Hz, stress ratio $r \approx 0$). Crack growth rate versus stress intensity factor range diagrams of fatigue have been compiled and the stress intensity factor range ΔK defined. Besides, the threshold stress intensity factor was determined at the crack propagation rates around 10^{-12} m/cycle, as mentioned above. The crack growth rate versus stress intensity factor range fatigue diagram of specimens of GI cast iron is shown in Fig 14 a. The crack growth rate

versus stress intensity factor range fatigue diagram of normalised cast iron is presented in Fig 14 b. The threshold $\Delta K_{th} = 6,5 - 8,6 \text{ MPa}\cdot\text{m}^{1/2}$; for normalised cast iron $\Delta K_{th} = 8,2 - 10,3 \text{ MPa}\cdot\text{m}^{1/2}$. The crack growth rate versus stress intensity factor range fatigue diagram of specimens of SGI cast iron is presented in Fig 15 a and normalised cast iron - in Fig 15 b. The threshold for cast iron $\Delta K_{th} = 8,0 - 9,6 \text{ MPa}\cdot\text{m}^{1/2}$; for normalised cast iron $\Delta K_{th} = 8,7 - 9,8 \text{ MPa}\cdot\text{m}^{1/2}$. The presented data show that normalisation increases the resistance to crack initiation and propagation.

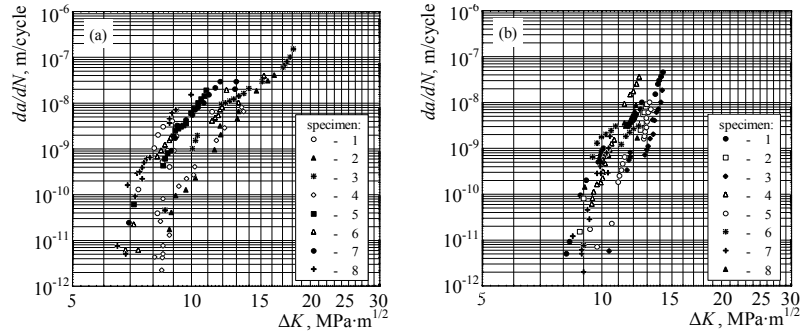


Fig 14. Crack growth rate vs stress intensity factor range of GI iron:
a – cast iron, b – normalised iron

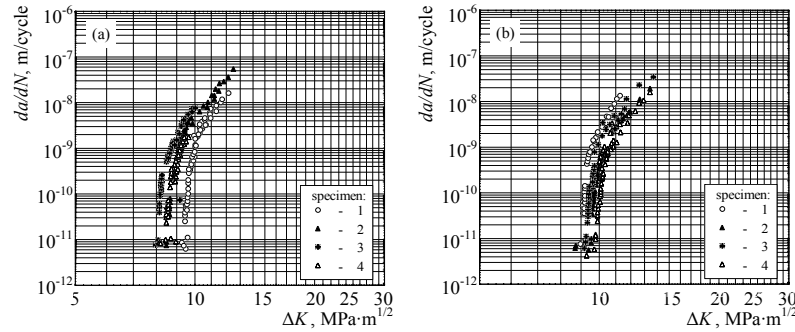


Fig 15. Crack growth rate vs stress intensity factor range of SGI iron:
a – cast, b – normalised

Having defined the indices of resistance to crack propagation, it is possible to choose such safety coefficients which can guarantee the application of non-uniform material for producing of important details too.

Resistance to crack initiation and propagation depends directly on microstructure formations (inclusions, cavities, slide belts, defects of production and service). After statistical analysis by using the linear regression method the linear dependence between ΔK_{th} and mechanical properties ratio $R_m/R_{p0,2}$ was established and showed in Fig 16:

$$\Delta K_{th0} = 5,1 \frac{R_m}{R_{p0,2}} + 1,3. \quad (11)$$

The obtained correlation coefficient equals 0,62. We can see that for the cast GI and SGI irons there are bigger deflections from the obtained dependence.

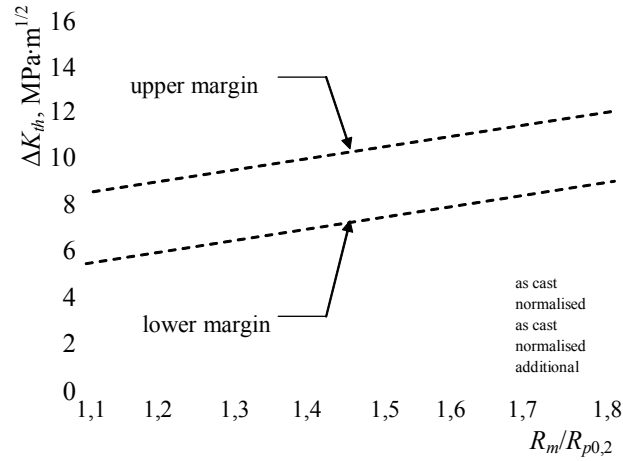


Fig 16. Dependence between ΔK_{th} and $R_m/R_{p0,2}$

For the investigated material it is possible to draw two approximation lines which include all experimentally obtained values:

$$\Delta K_{th0} = 5,1 \frac{R_m}{R_{p0,2}} + 2,7, \quad (12)$$

$$\Delta K_{th0} = 5,1 \frac{R_m}{R_{p0,2}} + 0,059. \quad (13)$$

The threshold stress intensity factor ΔK_{th} also depends on asymmetry, temperature, environment effect, overloading, non-homogeneity and other factors. The investigations disclose the increase of threshold ΔK_{th} and fatigue crack growth rate under the change of stress ratio from 0 to 0,9. Under conditions of larger stress ratios ($r > 0,6 - 0,7$), the fracture process changes: its mechanism starts approaching the static fracture. Because the crack during the loading process remains all the time open, the threshold ΔK_{th} and fatigue crack growth rate in a uniform stress intensity factor range becomes more independent of asymmetry. When the stress change is negligible ($r > 0,9$), the cyclic fracture becomes more approximate to static fracture. Under conditions of a negative symmetry, its impact on the threshold stress intensity range ΔK_{th} considerably decreases; it is influenced by crack closing. Under conditions of a negative cycle asymmetry, the compressive stresses are often neglected, considering that $K_{min} = 0$ and $\Delta K = K_{max}$.

The stress ratio changes under service conditions in rather large ranges and influences the crack propagation. When calculating real structures, it is necessary to make corrections in stress states, in dimensions, stress concentration and surface conditions. For practical calculations of ΔK_{th} , when assessing the stress ratio r :

$$\Delta K_{th} = \Delta K_{th0}(1 - r)^\gamma ; \quad (14)$$

here ΔK_{th0} is the threshold stress intensity factor range at $r = 0$; γ is coefficient dependent on the material and fluctuates from 0,5 up to 1.

Considering the experimental data and performed analysis, it is possible to get equations that are suitable for structural elements and investigated cast irons. It is possible to write:

$$\Delta K_{th} = \left(5,1 \frac{R_m}{R_{p0,2}} + 1,3 \right) (1 - r)^\gamma . \quad (15)$$

If there is a crack of the length $2l$ on the surface of a detail, the crack development will be stopped, when the limit stress interval correspondent to ΔK_{th} does not exceed $\Delta \sigma_{th}$ calculated by formula

$$\Delta \sigma_{th} = \frac{\Delta K_{th}}{Y \sqrt{2l}} . \quad (16)$$

By rearranging formula (15) and (16) we can get the stress range which accords to threshold stress intensity factor range ΔK_{th} :

$$\Delta \sigma_{th} = \frac{\left(5,1 \frac{R_m}{R_{p0.2}} + 1,3 \right) (1-r)^\gamma}{Y \sqrt{2l}} . \quad (17)$$

The expression obtained may be used for calculating the strength of cyclically loaded large-size details, which remains non-homogeneous after casting and heat treatment processes. To validate the eq (17) for details from cast iron with another stress ratio an additional analysis based on experiments is necessary.

Conclusions

On the basis of the performed investigation the following conclusions have been drawn:

1. After the analysis of references it is possible to state that the mechanisms of crack formation and propagation in high-strength cast iron with technological deflections subjected to a high-cycle loading have not been sufficiently investigated yet. Those have not allowed the predictions of a true service time of large structural elements.
2. The original experimental methodology matched better the real structural element loading and enabled to monitor the fatigue crack formation and propagation under a high-cycle loading. The change of the regulated methods allowed obtaining the results of high-cycle loading.
3. The fractographic analysis revealed that zigzag fatigue crack path was formed due to the many initiation sites on the specimens' surfaces and in the surface layer (fish eye). The further crack propagation is dependent on non-homogeneous microstructure of dross layer.
4. It was determined by experiments that threshold stress intensity factor range of basic metal was $\Delta K_{th} = 9,8 \text{ MPa} \cdot \text{m}^{1/2}$ and dross layer $\Delta K_{th} = 8,1 \text{ MPa} \cdot \text{m}^{1/2}$ and differs 1,2 times.
5. The experimental analytical investigation of heat treated cast iron showed that in large dimension elements the effect of heat treatment process in non-uniform and volumes of non-homogeneous microstructures with different properties are retained.

6. It was determined by experiments that heat treatment enlarges the strength of GI cast iron to fatigue crack propagation up to 22 % and enlarges the strength to crack propagation of SGI cast iron up to 6 %.
7. The obtained relation between ΔK_{th} and $R_m/R_{p0.2}$ have been employed for calculating the structural elements of high-strength cast iron containing various casting and heat treatment deflections.

Published works on the topic of the dissertation

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1. Leonavičius, M.; Petraitis, G.; Krenevičius, A.; Šukšta, M.; Stupak, S. Investigation of High-Cycle Fatigue of Cast Iron with Porous Layer Near Threshold ΔK_{th} . *Kovove Materialy*, Vol 43, No 5, 2005, p. 348–357. ISSN 0023-432X . (ISI).
2. Petraitis, G.; Leonavičius, M. Threshold K_{th} Investigation of High-Cycle Fatigue of Cast Iron with Porous Layer. *Mechanika*, Vol 48, No 4, Kaunas: Technologija, 2004, p. 25–28. ISSN 1392-1207. (INSPEC).
3. Leonavičius, M.; Šukšta, M.; Stupak, S.; Petraitis, G. Experimental Investigation of Cyclic Bending Strength of Cast Iron with Dross Layer. *Mechanika*, Vol 43, No 5, Kaunas: Technologija, 2003, p. 13–18. ISSN 1392-1207.

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4. Petraitis, G.; Leonavičius, M.; Stupak, S. Cast Iron with Different Structures Strength to Cyclic Loading. In: Proceedings of the International Conference “Mechanika – 2005”, held in Kaunas on 7–8 April, 2005 (Tarptautinės konferencijos „Mechanika–2005“, įvykusios Kaune 2005 m. balandžio 7–8 d., mokslinių pranešimų rinkinys). Kaunas: Technologija, 2005, p. 51–55 (in Lithuanian). ISBN 9955-09-850-3.
5. Petraitis, G.; Šukšta, M.; Stupak, S.; Leonavičius, M. Analytical Investigation of Two-Layer Cast Iron Strength for high-Cycle Bending. In: Proceedings of the International Conference “Mechanika–2004”, held in Kaunas on 1–2 April, 2004 (Tarptautinės konferencijos „Mechanika–2004“, įvykusios Kaune 2004 m. balandžio 1–2 d., mokslinių pranešimų rinkinys). Kaunas: Technologija, 2004, p. 115–119 (in Lithuanian). ISBN 9955-09-630-6.

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About the author

Gediminas Petraitis was born in Vilnius, on 14 of January 1978.

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DAUGIACIKLIO NUOVARGIO PLYŠIŲ SUSIDARYMO IR PLITIMO SLUOKSNIUOTAJAME KETUJE TYRIMAS

Mokslo problemos aktualumas. Šiuolaikinės mašinos, įrenginiai ir konstrukcijos kuriamos siekiant maksimaliai pagerinti jų charakteristikas, mažinant jų masę, gamybos, priežiūros ir energijos sąnaudas, tačiau išlaikant didelį darbo efektyvumą, našumą, patikimumą bei ilgaamžiškumą. Transporto ir kalnakasybos įrenginių gamyboje naudojamas stiprusis ketus su rutuliniu grafitu, kurio fizikinės mechaninės savybės gerinamos specialiomis liejimo ir termocheminio apdorojimo technologijomis. Tačiau dėl konstrukcijų elementų didelių gabaritų sunku išlaikyti technologinių procesų kokybę ir detalėse gali susidaryti įvairaus tūrio nevienalyčių terpių. Tokias vietas galima laikyti atskirais sluoksniais, o tokį ketų – sluoksniuotuoju. Kai įrenginiai naudojami 25–50 metų, neaiškus plyšio susidarymas ir plitimas daugiacyklio ir hipercyklio nuovargio srityje (ciklų skaičius $N \approx 10^5 \dots 10^9$). Dabartiniai skaičiavimo metodai, naudojami pirmajame pažeidimų kaupimosi etape, yra nepakankamai pagrįsti. Manoma, kad keičiasi irimo mechanizmas, laikas iki nuovargio plyšio atsiradimo lemia visos konstrukcijos darbo laiką, o įvairūs nevienalyčiai dariniai ir defektai skatina irimo procesą. Jau

projektavimo stadijoje reikia žinoti stiprumą, jeigu atsiras plyšiai, t. y. vertinti tolesnį konstrukcijos darbą su plyšiu.

Šių problemų sprendimui sudarytas tarptautinis projektas „Kalkakasybos ir transporto įrenginių lietu ir virintinių komponentų ciklinio stiprumo ir atsparumo plyšėjimui tyrimas“, kuriame dalyvauja JAV, Australijos, Prancūzijos, Vokietijos, Suomijos firmos ir universitetai bei Vilniaus Gedimino technikos universiteto Medžiagų atsparumo katedra.

Darbo tikslas. Pagrindinis darbo tikslas – įvairiais tyrimais nustatyti plyšių susidarymo ir plitimo dėsningumus stipriajame sluoksniuotajame ketuje daugiacyklio apkrovimo atveju ir patobulinti konstrukcijų elementų skaičiavimo metodiką.

Tyrimų metodika. Darbe panaudoti eksperimentiniai, analitiniai bei skaitiniai metodai. Eksperimentams pritaikyti originalūs ir reglamentuojami tyrimų metodai. Atsparumas plyšių atsiradimui ir plitimui įvertintas tiesinėje irimo mechanikoje naudojamu kriterijumi – įtempimų intensyvumo koeficientu. Skaitinei analizei panaudota ANSYS programa.

Tyrimų objektas. Stipriojo ketaus mechaninis būvis, atsirandantis realiuose konstrukcijos elementuose technologinio gamybos proceso ir eksploatacijos metu, veikiant daugiacykliam apkrovimui, susidarius ir plintant plyšiui.

Mokslinis naujumas

- Darbas skirtas stipriojo sluoksniuotojo ketaus nuovargio irimui daugiacyklio ir hipercyklio apkrovimo srityje, kurioje irimo procesus nusakantys veiksniai mažai žinomi.
- Nustatyti plyšio atsiradimo rodikliai ir plitimo dėsningumai daugiacyklio apkrovimo veikiamame stipriajame sluoksniuotajame ketuje.

Praktinė vertė

- Tyrimais nustatyta, kad daugiacyklio ir hipercyklio apkrovimo atveju nuovargio plyšiai stipriojo sluoksniuotojo ketaus technologiškai pažeistuose sluoksniuose atsiranda ir plinta greičiau nei sluoksniuose be defektų ir termiškai apdorotame ketuje.

- Gauti tyrimų rezultatai ir skaičiavimo metodika leidžia įvertinti didelio gabarito konstrukcijų stiprumą.

Darbo apimtis. Darbą sudaro bendra darbo charakteristika, 5 skyriai, išvados, literatūros sąrašas, publikacijų sąrašas ir priedai. Bendra disertacijos apimtis – 100 puslapių, 68 iliustracijos, 6 lentelės ir 3 priedai.

Išvados

1. Išnagrinėjus literatūrą, galima teigti, kad daugiacyklio nuovargio plyšių atsiradimo ir plitimo mechanizmai sluoksniuotajame ketuje mažai žinomi ir neleidžia patikimai numatyti didelio gabarito konstrukcijų ilgaamžiškumo.
2. Pritaikyta originali eksperimentinių tyrimų metodika leido atkurti realių konstrukcijų elementų apkrovimą bei leido stebėti nuovargio plyšio atsiradimą ir plitimą daugiacyklio nuovargio srityje. Panaudojus pakeistą reglamentuojamą bandymo metodiką gauti daugiacyklio ir hipercyklio apkrovimo bandymo rezultatai.
3. Fraktografinė bandinių iš sluoksniuotojo ketaus (su liejimo procesų netobulumais) analizė parodė, kad sudėtingą plyšio fronto trajektoriją lėmė židiniai, susidarę skirtinguose paviršiaus pjūviuose ir židiniai popaviršiniuose sluoksniuose („žuvies akis“). Tolimesniam plyšio plitimui didelę įtaką turi nevienalytė specialiojo sluoksnio struktūra.
4. Eksperimentais nustatyta, kad pagrindinio metalo $\Delta K_{th} = 9,8 \text{ MPa} \cdot \text{m}^{1/2}$ ir specialiojo sluoksnio $\Delta K_{th} = 8,1 \text{ MPa} \cdot \text{m}^{1/2}$ ribinis įtempimų intensyvumo koeficientas (plyšėjimo slenkstis) skiriasi 1,2 karto.
5. Terminiškai apdoroto stipriojo ketaus eksperimentinis analitinis tyrimas parodė, kad didelio gabarito gaminiuose terminio apdorojimo procese struktūra pakeičiama ne visame liejinio tūryje, išlieka įvairaus dydžio ir formos grafitas, o atskiros zonos turi skirtingas mechanines savybes.
6. Eksperimentiniais bandymais nustatyta, kad terminis apdorojimas iki 22,5 % padidino GI ketaus atsparumą nuovargio plyšių plitimui ir iki 6 % padidino SGI ketaus atsparumą plyšių plitimui.
7. Gauta ΔK_{th} ir santykio $R_m/R_{p0,2}$ priklausomybė naudojama cikliškaai apkraunamų kalnakasybos įrenginių elementų iš stipriojo ketaus su nevienodo mechaninio būvio zonomis projektiniam stiprumo skaičiavimui.

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HIGH-CYCLE FATIGUE CRACK FORMATION AND PROPAGATION IN LAYERED CAST IRON

Summary of Doctoral Dissertation

Technological Sciences, Mechanical Engineering (09T)

Gediminas Petraitis

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