VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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CASTING VOIDS INFLUENCE ON SPHEROID GRAPHITE CAST IRON HIGH-CYCLE FATIGUE STRENGTH

Summary of Doctoral Dissertation

Technological Sciences, Mechanical Engineering (09T)

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General characteristic of the dissertation

Topicality of the problem

Spheroid graphite cast iron is widely used in mining and transport equipment parts production due to high strength and technological properties (Fig. 1, a). Crushing and grinding equipment expected lifetime is 25 years with a possibility to prolong the service life. The production process of some big parts used in this equipment is rather complicated and expensive. Various production defects are inevitable due to production process technological difficulties (Fig 1, b–c). They may be found during non-destructive post-production quality control or during the exploitation. Solidification shrinkage and porosity are among the major sources of casting defects. First, gas porosity is a result of gas bubbles entrapped by the molten metal, when it is poured into the mould. After solidification, voids of a more or less regular shape are formed. Second, shrinkage can be divided into micro-shrinkage or macro-shrinkage, according to the size of voids. Shrinkage voids often are of an irregular shape. Voids appear not only due to casting technology imperfectness, but also due to inevitable significant changes of casting volume in large-size cast elements. These defects influence on element high-cycle fatigue strength should be evaluated before starting the operation of the equipment.

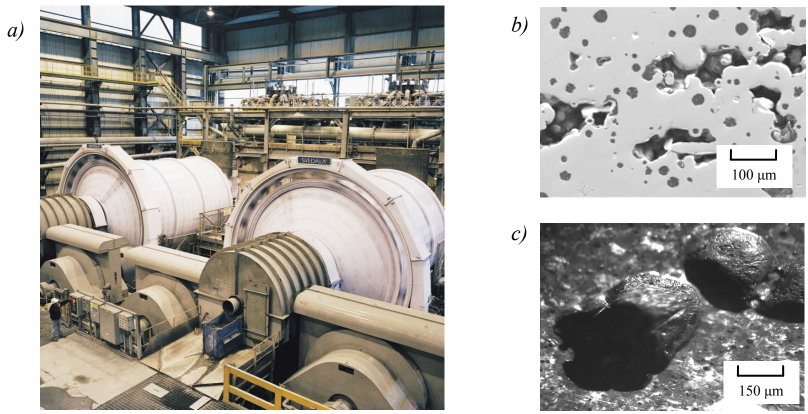

Fig 1. Mineral mining equipment (a), shrinkage voids (b), gas bubbles (c)

Various complex shape voids in big cyclically loaded gear wheels and body parts decrease the cross-section indices, change the mechanical state, often become a crack origin and increase the sensitivity to the negative influence of the environment while being at the surface. Microstructure inhomogeneity is often found in the vicinity of such defects. Several voids in the volume of a part may decrease its strength and to cause the fracture even if the cyclic load is not high enough or after a short-time load only.

Non-destructive control methods permit to detect the casting defects, but big part size makes their usage quite complicated. Safety factor increase often is not substantiated and has negative influence on casting weight and shape optimization. Till now, a calculation method which could evaluate the loss of the cyclic strength and the material fracture process peculiarities is missing. Reasonable evaluation of a danger caused by void is a complex, but still actual problem which would let to decrease large-size equipment production and repair costs. A method which could estimate the part quality rate and its permissible load is needed. It would allow determining the influence of the found casting voids during the production stage or, if the crack develops in the part containing a void, – to predict its growth and to stop it during the operation period.

Aim and tasks of the work

The basic aim of the present work is to estimate the crack appearance and arrest law in spheroid graphite cast iron with voids at very low crack propagation rates evaluating cast iron microstructure, mechanical properties and mechanical state in the vicinity of the void using experimental, analytical and numerical methods and to improve the part with voids fatigue strength calculation method. There are few tasks under consideration:

1. To estimate the investigated spheroid graphite cast iron grades static mechanical properties and cyclic strength rates.
2. To define experimentally the investigated cast iron grades with voids resistance to crack propagation.
3. To estimate the voids influence on the dependency of stress intensity factor range ΔK versus crack propagation rate da/dN, evaluating the alternating specimen cross-section geometrical indices.
4. To make the specimens fracture fractographic analysis and to study the influence of voids on fatigue crack propagation.
5. To investigate the crack-like defect influence on stress intensity factor distribution in the specimen.
6. To propose large-size equipment parts with casting voids fatigue strength calculation method based on specimens with voids experiment test results analysis.

Scientific novelty

Present doctoral dissertation gives to the field of Fracture Mechanics science following results:

1. An original experimental research method is proposed and the influence of casting voids on spheroid graphite iron fatigue strength is estimated experimentally.

2. Fatigue fracture in specimens with defects is studied using optical and electronic microscopy.

3. Stress intensity factor distribution dependence on the crack-like defect size and its position is investigated in the eccentrically loaded specimen using finite element method.

4. Proposed calculation method allows casting voids influence on casting fatigue strength evaluation.

Research methodology includes experimental, analytical and numerical methods. Standard method requirements are modified and applied to material with voids experimental investigation. Analytical and numerical methods based on linear fracture mechanics are used for crack resistance investigation in the vicinity of the defect. Numerical research is made using finite element method.

Practical value

The performed investigations define the cracking threshold decrease in cast iron volumes with shrinkage voids. The calculation method, based on experimental, analytical and numerical research results enables to estimate the fatigue strength of a large-size cast parts with voids.

Defended propositions

1. The highest influence on the stress intensity factor threshold value is made by a congestion of voids and crack mutual position in a part.

2. Voids, detected by non-destructive control methods influence on fatigue strength may be evaluated by experimental, analytical and numerical methods applied in present work.

3. The proposed specified calculation method evaluates the serviceability of the casted element with voids congestion.

The scope of the scientific work. The scientific work consists of 4 chapters, basic results and conclusions, references and 1 annex. The total scope of the present dissertation – 119 pages without annex, 67 pictures, 11 tables, 108 bibliographic sources.

1. Spheroidal graphite iron application and cyclic strength problem overview

This chapter is dedicated to state-of-the-art review. Spheroid graphite cast iron industrial application actualities and problems are overviewed together with defects appearance causes and mechanisms. Fatigue crack appearance and propagation in spheroid graphite iron is discussed using linear fracture mechanics. Existing cyclic strength calculation methods imperfectness is analysed. Dissertation aims and tasks are formulated.

2. The methodic of the experimental research

The second chapter covers experimental research methodology presenting an original experiment method used for specimen containing voids high-cycle fatigue strength research. Technical data of used testing equipment are presented. In order to obtain the cracking threshold standard test method (ASTM E-647-00) is modified and applied for eccentrically loaded specimens (CT) with voids experimental research. The proposed experiment implementation and result data post-processing modification enables to estimate the voids influence on the cracking threshold.

One of the basic quantitative crack resistance indices is cracking threshold limit stress intensity factor range ΔK_{th}. The performed research is remarkable due to the fact that the obtained values of the limit stress intensity factor range are obtained at lower, than standard method requires, crack propagation rates. They are decreased down to $v \approx 5\cdot10^{-12}$ m/cycle in order to obtain the cracking threshold corresponding to longer part lifetime (over 25 years of operation). For stress intensity factor calculation following formula is applied:

$$\begin{cases} K = \dfrac{F}{B\cdot\sqrt{W}}, \\ f(\lambda) = \left[(2+\lambda)/(1-\lambda)^{3/2}\right]\varphi(\lambda),\ \lambda = a/W, \\ \varphi(\lambda) = 0.866 + 4.64\lambda - 13.32\lambda^2 + 14.72\lambda^3 - 5.6\lambda^4, \end{cases} \tag{1}$$

where F is tension force, B – specimen width, W – specimen base length; a – crack length.

Spheroid cast iron plates of different grades (one – of austempered cast iron, another – of pearlitic cast iron) were prepared for experimental investigation. These plates were cast in France and Australia foundries together with big parts used in mining equipment production, so the chemical composition of the plates and their mechanical properties fully respects the ones obtained in real castings. 3 CT specimens without voids and 3 specimens containing voids were prepared for austempered cast iron investigation. Respectively, 6 and 3 specimens were made of pearlitic cast iron plate. Total cycle number for austempered cast iron specimens varies from 11.4 to 20.3 mln cycles, for pearlitic cast iron – from 10 to 19.6 mln cycles.

Fatigue fracture process in specimens with voids replicates fatigue crack growth peculiarities in the real cast structural elements. The difference in the cracking threshold values between specimens with and without voids becomes a data base for following analytical and numerical investigation.

3. Casting voids influence on crack appearance and propagation experimental research

The results of cast iron with voids fatigue strength experimental research and their analysis are presented. The influence of microstructure and other factors on specimens with voids cracking threshold and crack propagation had been analyzed. The difference in experimental investigation results for cast iron with and without voids had been discussed.

Austempered cast iron shows a typical microstructure with matrix known as "ausferrite" which contains of acicular ferrite and austenite mixture. The matrix contains irregular size shrinkage microvoids. Structure in the vicinity of the defect has some anomalies, like attached globules (Fig 2, a–d).

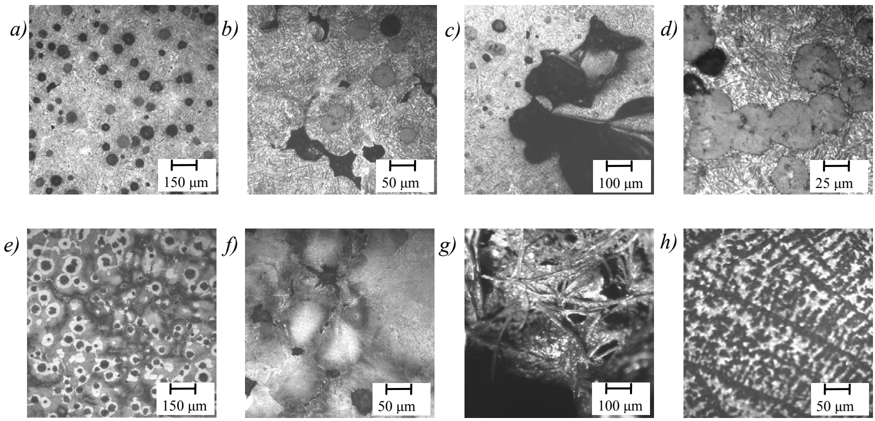

Fig 2. Cast iron microstructure: austempered ductile iron (a–d); pearlitic cast iron (e–h)

The pearlitic cast iron matrix consists of pearlite. Graphite inclusions are surrounded by a ferrite layer, creating typical spheroid graphite microstructure – so called "bull's eye". Matrix also contains small size shrinkage voids, mostly in the intercellular space together with carbides (Fig 2, e–g). A dendrite type microstructure anomaly is found in the vicinity of the voids (Fig 2, h). Static mechanical properties were estimated using cylindrical tension specimens (Table 1). According to estimated mechanical properties, the investigated pearlitic cast iron is similar with EN-GJS-500-7, while austempered cast iron – with EN-GJS-1000-5.

Table 1. Cast iron static mechanical properties rates

Cast iron grade	E, GPa	$\sigma_{0.2}$, MPa	σ_u, MPa	A, %	BHN
Austempered	147...152	649...673	933...995	1.8...2.4	356…364
Pearlitic	191...194	380...405	490...515	2.8...3.0	210…240

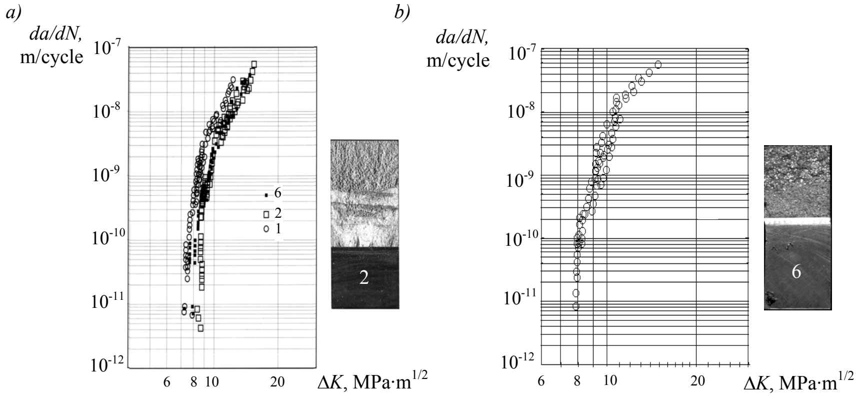

Fig 3. Stress intensity factor range vs. crack growth rate for material without voids: austempered cast iron (a) pearlitic cast iron (b)

It was estimated (Fig 3) that the cracking threshold at lower then 10^{-10} m/cycle obtained in austempered cast iron specimens with voids are significantly lower (difference makes from 6% to 15%) then in specimens without voids (Table 2).

Table 2. Investigated cast iron grades cracking threshold ΔK_{th}, MPa·m$^{1/2}$

Cast iron	With defect		No defect	
	10^{-10} m/cycle	< 10^{-11} m/cycle	10^{-10} m/cycle	< 10^{-11} m/cycle
Austempered	5.5…7.7	5.3…7.2	7.4…8.7	7.2…8.6
Pearlitic	6.3…7.9	-	8.0…8.2	7.8…7.9

Significant difference is in specimen 5 where the crack front is also more curved (Fig 4). This means that microstructural inhomogeneity is a significant factor influencing the cracking threshold.

After passing the defect, the cracking threshold values are similar to ones obtained in material with no defect. The biggest difference in values estimated before and after the void is found in the austempered cast iron specimen with the smallest void (3 % of the cross-section). This allows concluding that the area of the void is not the only factor influencing on the cracking threshold. Analytical and numerical researches were made in order to make the crack propagation in specimen with voids mechanism more clear.

Comparing specimen with voids tests results to ones of non-defective specimens, it was noticed, that the cracking threshold value difference at $da/dN = 10^{-10}$ m/cycle makes from 1.3 to 25 %. In order to investigate this difference, additional analytical research has been done.

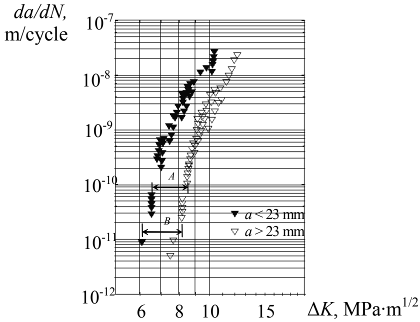

Fig 4. Austempered cast iron specimens with void ΔK – *da/dN* dependency

Fractographic analysis shows that the voids significantly complicate the fracture process; the crack front becomes curved, secondary cracks propagate in the vicinity of the defect, fracture mechanism and modes alternates (Fig 5). Due to microstructure inhomogeneity, crack growth acceleration is found in most part of the samples.

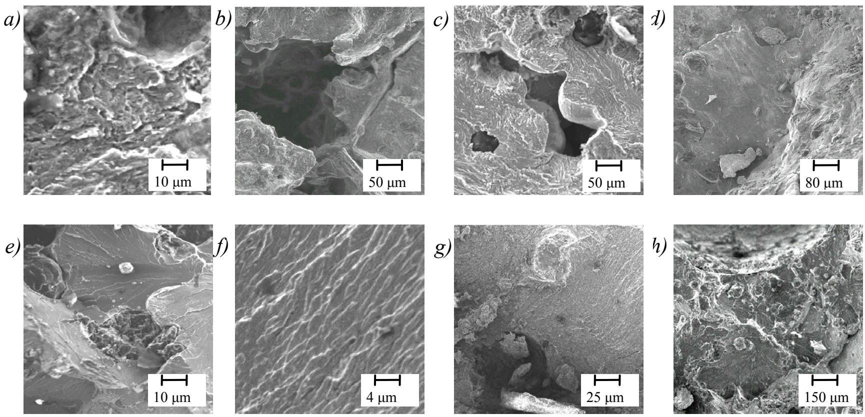

Fig 5. SEM fractographs: austempered cast iron (a–d); pearlitic cast iron (e–h)

General crack propagation mechanism in areas is cleavage. The detected microstructure anomalies (dendrites, carbides) decrease the material resistance to crack propagation. The fatigue striations together with rare intergranular fracture were found in the vicinity of the void. Fractographic analysis shows that the crack growth here was not sudden. Hence, the void here had not become the primary reason of a fracture.

4. Crack-like defect influence on stress intensity factor analytical and numerical research

This chapter presents defect influence analytical and numerical research and its results analysis. Cross-section with voids geometrical indices calculation method is proposed. An analytical investigation of stress intensity factor in defective specimen is presented. The cyclic strength difference in specimens with and without voids and the influence of the last on these values is researched analytically. Casting with voids high-cycle fatigue strength calculation method is proposed, taking into consideration design and verification issues.

The presented analytical investigation is performed basing on a void's negative influence on the geometrical indices of a specimen's cross-section. The calculation scheme is presented on Fig 6. Real cross section (with assumption of defects) moment of inertia is calculated by formula:

$$I_{zd} = I_{st} + A_{st}\left(y_c - y_{st}\right)^2 - \left(\sum I_{di} + \sum A_{di}\left(y_c - y_{cd_i}\right)^2\right). \qquad (2)$$

When the distance between the cross-section center and the most distant point ($y_{\max}$) is obtained, the modulus of resistance is calculated:

$$W_{zd} = \frac{I_{zd}}{\left|y_{\max}\right|}. \qquad (3)$$

The analysis of performed specimen fracture with defects calculations (Fig 6) shows that voids reduce the area of the cross-section up to 10%, the moment of resistance – up to 26%.

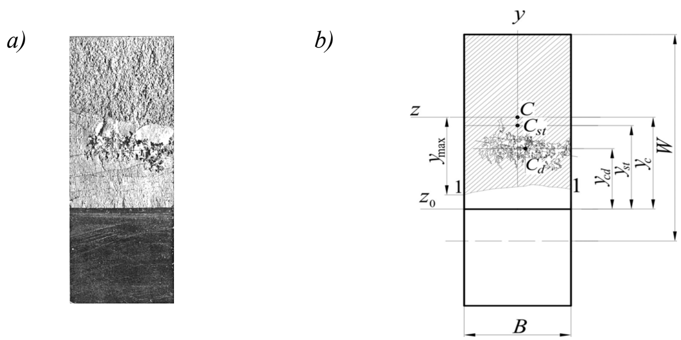

Fig 6. Austempered cast iron specimen fracture and geometrical indices calculation scheme

Higher defect influence on the cross-section indices is obtained in the early stage of crossing the defect. Cross-section with voids geometrical indices and tests results comparison show that void size is not the only factor which influences the cracking threshold. Microstructure inhomogeneity in the vicinity of a defect and mechanical state alternation are also important. The performed analysis of the specimens with voids geometrical indices allows making a conclusion that the voids significantly decrease the cross-section area A_d and the modulus of resistance W_d. These two indices are essential for nominal stress in the eccentric tension specimen crack tip. Nominal tension stress in the defective specimen can be calculated by formula:

$$\sigma_d = \frac{F}{A_d} + \frac{M}{W_d} = \frac{2F}{BW}\frac{2+\lambda}{(1-\lambda)^2}. \quad (4)$$

Nominal stress in the crack tip of a specimen with voids is higher due to lower cross-section indices. Defective specimen cross-section area A_d and the moment of resistance W_d can be calculated applying the presented method. The stress intensity factor for a specimen with voids can be estimated by formula:

$$K_d = 0.5\sigma_d W^{1/2}(1-\lambda)^{1/2}\varphi(\lambda). \quad (5)$$

When the cracking threshold is reached and the crack stops to propagate and keeping in mind the alternating force:

$$\Delta K_{thd} = 0.5\Delta\sigma_{thd} W^{1/2}(1-\lambda)^{1/2}\varphi(\lambda), \quad (6)$$

where ΔK_{thd} – cracking threshold for the material with voids; $\Delta\sigma_{thd}$ – limit threshold stress in the crack tip.

Applying formula (5), experimentally obtained values of ΔK can be post-processed and new stress intensity factor values ΔK_d are estimated, which reflects the variable influence of voids. New corrected values are estimated and marked on the *da/dN* – ΔK dependency. Applying this method to pearlitic cast iron specimens with voids (7, 8, 9) test results, a corrected *da/dN* – ΔK diagram is obtained (Fig 7). Obtained corrected values are similar to ones estimated for pearlitic cast iron without voids: post-processed ΔK_{thd} = 8.2...8.4 MPa·m$^{1/2}$; cast iron with no voids ΔK_{thd} = 8.0...8.2 MPa·m$^{1/2}$. This confirms the conclusions formed after austempered cast iron specimen test results analysis: voids influence on the stress intensity factor is not limited by the decreasing geometrical indices.

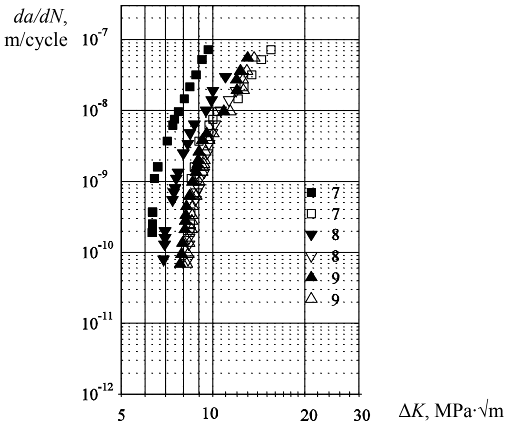

Fig 7. Pearlitic spheroid graphite iron specimens 7, 8, 9 with voids stress intensity factor range versus crack growth rate: ■,▼, ▲ – experimentally obtained values; □, ∇, Δ – corrected values obtained by formula (4.6)

Numerical investigation of a crack-like defect influence on stress intensity factor distribution in CT specimen was performed using FEM software ANSYS. The calculations schemes are presented on Fig 8. After analyzing the fracture of the austempered cast iron specimen, an assumption was made that total dimensions of the defect on fracture surface do not exceed 10×6 mm and the distance to the notch tip is 10 mm. Few typical crack length values (a = 18.8, 19.8, 22.8 and 25.8 mm) were chosen alongside a few reference points (A, B, C and D) in which SIF was supposed to be indicative.

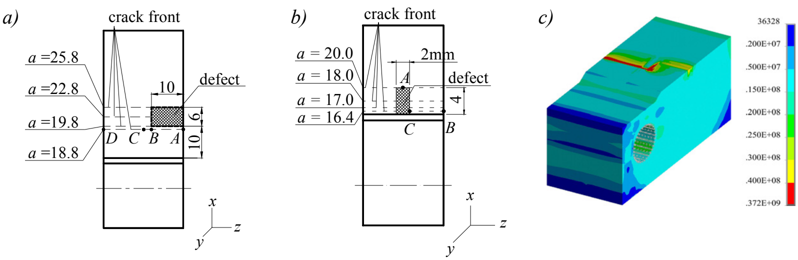

Fig 8. Numerical investigation calculation schemes (a, b) and Von Mises stress distribution when crack length a = 19.8 mm (c)

Different numerical approaches were used for SIF values calculation: first – using crack surface displacements obtained by FEM; second – using J-integral.

The SIF calculation method using crack surface displacements obtained by FEM was used because it gives accurate results, using a model with a relatively small number of degrees of freedom. The essential feature of this method is the usage of the special singular elements, where middle nodes are skewed in the crack tip direction. This technology allows us to use the benefits of the HRR-singularity in the crack tip described in non-linear fracture mechanics, using the linear fracture mechanics approach. Stress intensity factor is calculated according to formula:

$$K_I = \lim_{r \to 0} \left[v_i(r,\theta) \frac{2G}{\widetilde{v}_i(\theta)} \sqrt{\frac{2\pi}{r}} \frac{1}{1+\mu} \right], \tag{7}$$

where G is shear modulus, v_i is notch displacement, r is distance between the node and the crack tip, θ is degree to the crack plane, v is Poisson ratio, $\mu = \frac{1-\nu}{1+\nu}$ for plane stress state or $\mu = \frac{1}{1-\nu}$ for plane strain state.

For J-integral calculation a following formula was used:

$$J = \int_\Gamma W \mathrm{d}y - \int_\Gamma \left(T_x \frac{\delta u_x}{\delta x} + T_y \frac{\delta u_y}{\delta x} \right) \mathrm{d}s \,, \tag{8}$$

where W – deformation potential energy; T_x, T_y – traction vectors along x and y axes, respectively.

Because each elements layer is rather thin, so stress intensity factor (SIF) can be estimated according plane stress assumption using next formula:

$$K = \sqrt{J \cdot E} \,, \tag{9}$$

where E – modulus of elasticity.

In order to validate the created FE model, a comparison with analytical result for a model without defect had been made. Numerically obtained results for a CT model without defect demonstrates high similarity comparing to analytically solved model (the difference makes no more than 1.1%). The obtained by different methods results of calculations are presented on Fig 9. The difference caused by defect can be obviously seen in the positions when crack length is, respectively, 18.8, 19.8 and 22.8 mm. This creates the conditions for curved crack front appearance. The highest stress intensity factor is obtained in point C when crack length is 22.8 mm. The difference of values between the model with defect and the model without defect disappears when crack length reaches 25.8 mm.

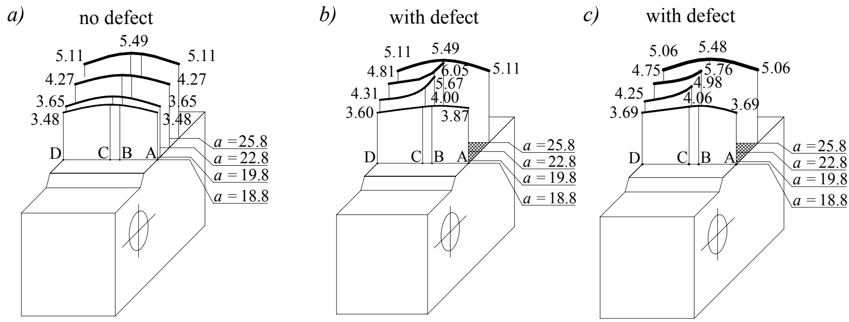

Fig 9. Stress intensity factor distribution obtained in specimen without defect (a), with defect (b) (using crack front displacement) and with defect using *J*-integral (c)

For stress intensity factor distribution calculation in the specimen with central defect (4×2 mm) was used a scheme presented on Fig 8, b. Relative crack depth *h/h'* varies from 0.4 to 4 mm. Stress intensity factor values dependency in points A, B, C on *h/h'* is presented on Fig 10. Natural tests results are given for comparison purposes only. Values obtained by FEM, using *J* integral calculated by different integrations paths, show that defect has an influence on the stress intensity factor. The most considerable influence is found in front edge of defect, point *A* (Fig 8, b). For comparison, a similar calculation by geometrical indices is also shown. Though values obtained by geometrical indices simulation are comparable to FEM simulation results, it is necessary to notice that they are not sensitive to strain state triaxility and stress concentration (that's why values in points *B* and *C* are equal).

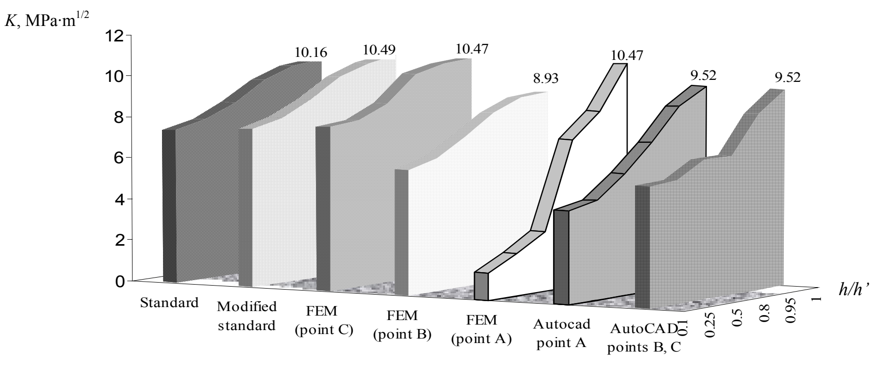

Fig 10. Stress intensity factor vs. relative crack depth *h/h'*

Various defects significantly complicate fatigue strength calculations. The evaluation of voids and crack in engineering calculations is rather complicated and forces to use higher safety factors and, hence, to increase the weight of the part. Using the fracture mechanics laws in fatigue strength calculations, the critical stress value (which relies with crack non-propagation) is desired to find. On the other side, a critical crack value may be estimated if the stress distribution in the part is known.

For a structure element containing defect a following crack non-propagation condition can be written:

$$\Delta K_I([\sigma],[l],R,t) \le [\Delta K_d] = \frac{\Delta K_{thd}}{n_K}. \tag{10}$$

The limit stress intensity factor range depends on stress rate, crack size, cycle asymmetry, temperature and other factors. Evaluating this and performed research results, for mineral grinding equipment parts fatigue strength calculation a formula defining a cracking threshold in a part with a shrinkage void is proposed:

$$\Delta\sigma'_{thd} = 0.5\sigma_{thd} W^{1/2}(1-\lambda)^{1/2}\varphi(\lambda)(1-R)^{\gamma}. \tag{11}$$

In fatigue strength calculations, the experimentally defined average or minimal stress intensity factor range ΔK_{thd} can be applied. In order to expand the fatigue life calculations, the minimal value $\Delta K_{th\ min}$ established at crack propagation rate close to 10^{-12} m/cycle should be involved.

Mineral mills productivity depends on permissible load which relies with detected defects size and quantity. During the operation, the equipment is periodically examined using non-destructive control methods in order to detect the propagating cracks to define their propagation rates. The results are used for fatigue life calculations.

Large-size gear wheels (3–12 m in diameter) and body parts with shrinkage voids can be reduced and only the element’s part containing defect is being investigated. The voids on gear surface are not admissible. After the stress existing in this volume is clear, it is separated and modeled as a plate or a volume with a void. Two problems can be separated:

- Fatigue strength estimation in design calculations, when a detected void danger to element fatigue strength should be estimated; the safety factor is calculated.
- Fatigue strength calculation for equipment being in service: the aim of the calculations is to define the load which would allow to arrest the

propagating crack. In addition, the limit crack size which complies with sudden fracture can be established.

The analytical calculation possibilities are limited due to complex geometrical shape limitations. For proposed calculation the schemes presented on Fig 11 are being used. A void may be found in a volume or on the surface of the element. The principal stress is defined in the vicinity of the void together with void section area.

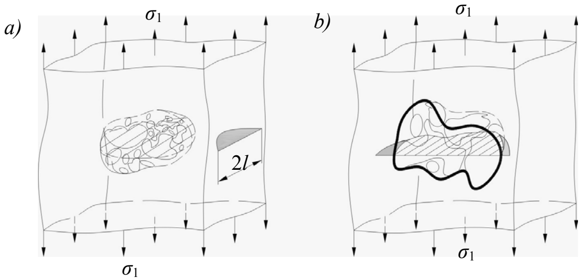

Fig 11. Shrinkage voids in the volume (a) or at the surface (b)

The stress intensity factor range in the vicinity of the void:

$$\Delta K_I = c\Delta\sigma_0\sqrt{\pi\sqrt{A_d}}\,. \tag{12}$$

Applying this formula, one can verify if the void do not become an origin of the crack:

$$c\sigma_0\sqrt{\pi\sqrt{A_d}} \le 0.5\sigma_{th\,d}W^{1/2}(1-\lambda)^{1/2}\varphi(\lambda)(1-R)^{\gamma}\,. \tag{13}$$

Finally, the area of the void in the structural element should not exceed:

$$A_d \le \frac{1}{16\pi^2c^4}\left(\frac{\Delta\sigma_{th\,d}}{\Delta\sigma_0}\right)^4[W(1-\lambda)]^2[\varphi(\lambda)]^4(1-R)^{4\gamma}. \tag{14}$$

On the other hand, when the crack which length is $2l$ is detected on the surface of the element, its non-propagation equation is proposed:

$$\Delta\sigma \le \Delta\sigma_{th\,d} = \frac{0.5\Delta\sigma W^{1/2}(1-\lambda)^{1/2}\varphi(\lambda)(1-R)^{\gamma}}{Y\sqrt{2l}}. \tag{15}$$

Proposed formulae can be applied in large-size mining equipment elements fatigue life calculations. It is important to apply a similarity principle, thus a wider experimental result data based is needed.

Applying FEM, J-integral or ΔK can be calculated with lower sensitivity to complex geometrical shape of the model, defining the safe state of the element. Accordingly to the crack and defect shape, a model with singular or rectangular elements in the vicinity of the void is created.

General conclusions

1. Structural elements with casting voids quality evaluation requires to perform stresses and mechanical state in the vicinity of the defect and additional experimental researches. Performed investigation shows that present calculation methods need to be improved together with experimental research standard methods, taking account of design, production technology and operation factors, estimating the voids and cracks by applying fracture mechanics criterions, analytical and numerical methods.
2. Standard test method is improved and applied to specimen with casting voids research and limit stress intensity factor range (cracking threshold) estimation, so that the obtained results would be applicable in casting with defects longevity prolongation calculations.
3. Obtained results demonstrate that the void size is not the only factor influencing on the limit stress intensity factor range decreasing. The cracking threshold also depends on void‘s place in the casting, microstructure inhomogeneity and the mechanical state in the vicinity of the void.
4. The results show that cracking threshold decreases together with crack propagation rate: for austempered cast iron ΔK_{th} = 7.4...8.7 MPa·m$^{1/2}$ at $v = 10^{-10}$ m/cycle and ΔK_{th} = 7.2...8.6 MPa·m$^{1/2}$ at $v = 10^{-11}$ m/cycle and lower; respectively, for pearlitic iron ΔK_{th} = 8.0...8.2 MPa·m$^{1/2}$ and ΔK_{th} = 7.8...7.9 MPa·m$^{1/2}$.
5. The stress intensity factor range versus crack growth rate dependency and fractographic analysis show that void shape, size and inhomogeinic structure have influence on crack shape and size.
6. Experimental results show that the cracking threshold in the material with defects varies: for austempered cast iron ΔK_{thd} = 5.3...7.2 MPa·m$^{1/2}$ at $v \approx 5\cdot10^{-12}$ m/cycle and ΔK_{thd} = 5.5...7.7 MPa·m$^{1/2}$ at $v = 10^{-10}$ m/cycle; for pearlitic cast iron ΔK_{thd} = 6.3…7.9 MPa·m$^{1/2}$ at $v = 10^{-10}$ m/cycle. These values are up to 28 % lower comparing to values obtained in cast iron with no defects.
7. Numerical research shows that the stress intensity factor increases by 1.5 time comparing to the model without defect. The defect on the surface is more dangerous than the on inside.
8. The complex precised high-cycle fatigue strength estimation method for cast elements with voids, based on analytical and numerical stress intensity

factor calculation and experimental research results, is proposed. The obtained limit stress intensity factor range ΔK_{thd} values may be applied in mining equipment spheroidal cast iron elements cyclic strength design and verification calculations.

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Konstantin Bobyliov was born in Vilnius on July 25, 1977.

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LIEJIMO TUŠTUMŲ ĮTAKA STIPRIOJO KETAUS DAUGIACIKLIAM STIPRUMUI

Mokslo problemos aktualumas

Stiprusis ketus yra plačiai taikomas kalnakasyboje ir transporto įrenginių gamyboje dėl savo aukštų stipruminių ir technologinių savybių. Rūdos malūnų ir smulkintuvų projektinis ilgaamžiškumas yra 25 metai su galimybe pratęsti resursą. Tokių įrenginių atskirų didelių matmenų detalių (būgnų, atramų) gamybos procesas yra sudėtingas ir brangus. Neišvengiamas technologinio proceso padarinys – įvairūs defektai, kurie išryškėja neardančios kontrolės metu arba tik eksploatacijos metu. Tuštumos liejinyje yra ne tik liejinio technologijos netobulumas, bet ir didelio liejinio problema, kurią reikia įvertinti pradedant įrenginio eksploatavimą.

Tuštumos (įvairios formos ertmės) didelių matmenų cikliškai apkraunamuose krumpliaračiuose ir korpusinėse detalėse mažina skerspjūvio geometrinius rodiklius, atsparumą statinėms ir ciklinėms apkrovoms, pakeičia mechaninį būvį, tampa plyšių atsiradimo židiniais, o būdami paviršiuje – didina jautrumą išorinės aplinkos neigiamiems veiksniams. Šalia tokių ertmių pastebimas ir struktūros nevienalytiškumas. Įvairaus dydžio tuštumų sankaupa detalės tūryje gali taip sumažinti konstrukcijos elemento stiprumą, kad jis suirs nepasiekęs reglamentuojamos ciklinės apkrovos ar apkrovus jį tik vieną kartą.

Neardančios kontrolės metodai leidžia aptikti liejimo defektus, tačiau dideli liejinių gabaritai sunkina kontrolės metodų taikymą. Atsargos koeficientų didinimas dažnai yra nepakankamai pagrįstas ir daro neigiamą įtaką liejinio masės ir formos optimizavimui. Skaičiavimo metodikų, kurios leistų įvertinti konstrukcinio elemento ciklinio stiprumo sumažėjimą ir atsižvelgtų į medžiagos irimo proceso specifiką, nepakanka. Pagrįstas tuštumų keliamo pavojaus įvertinimas yra sudėtingas, bet aktualus, nes leistų sumažinti didelių gabaritų įrenginių gamybos ir remonto išlaidas. Reikalingas toks elementų tinkamumo eksploatacijai ir apkrovimo nustatymo metodas, kuris galėtų įvertinti gamybos metu aptiktų liejimo tuštumų įtaką, o jeigu plyšys atsirado įrenginį eksploatuojant – nusakyti ir sustabdyti jo plitimą. Eksploatavimo metu atsirandantys kalnakasybos įrenginių elementų lūžiai rodo atliekamų stiprumo, patikimumo ir ilgaamžiškumo problemų tyrimų svarbą. Jų sprendimui sudarytas tarptautinis projektas.

Darbo tikslas ir uždaviniai

Pagrindinis darbo tikslas – eksperimentiniais, analitiniais ir skaitiniais tyrimais nustatyti plyšio susidarymo ir sustojimo dėsningumus stipriajame ketuje su tuštumomis esant labai mažam plyšio plitimo greičiui, įvertinant stipriojo ketaus mikrostruktūrą, mechanines savybes ir mechaninį būvį liejimo tuštumų aplinkoje ir patobulinti konstrukcijų elementų skaičiavimo metodiką.

Darbo tikslui pasiekti reikia spręsti šiuos uždavinius:

1. Nustatyti tiriamų stipriojo ketaus rūšių atsparumo statinei ir ciklinei apkrovai rodiklius.
2. Eksperimentais nustatyti skirtingų stipriojo ketaus rūšių su liejimo tuštumomis atsparumą pleišėjimui.
3. Įvertinti liejimo tuštumų įtaką įtempių intensyvumo koeficiento intervalo ΔK ir plyšio plitimo greičio da/dN priklausomybei, atsižvelgiant į kintančius bandinio skerspjūvio geometrinius rodiklius.
4. Atlikti bandinių lūžių fraktografinę analizę ir ištirti liejimo tuštumų poveikį nuovarginio plyšio plitimui.
5. Ištirti plyšio pavidalo defekto įtaką įtempių intensyvumo koeficiento pasiskirstymui bandinyje su defektu.
6. Pasiūlyti stambiagabaričių konstrukcinių elementų su liejimo tuštumomis stiprumo skaičiavimo metodiką, pagrįstą bandinių su tuštumomis tyrimų rezultatų analize.

Mokslinis naujumas

Rengiant disertaciją buvo gauti šie nauji mokslui irimo mechanikos rezultatai:

1. Sukurta originali eksperimentinio tyrimo metodika, remiantis kuria įvertintas liejimo tuštumų sankaupų poveikis stipriojo ketaus daugiacikliam stiprumui.
2. Optinės ir elektroninės mikroskopijos ir kitais neardančios kontrolės metodais ištirtas nuovarginis irimas bandiniuose su tuštumomis.
3. BEM ištirtas įtempių intensyvumo koeficiento pasiskirstymas necentrinio tempimo bandinyje įvertinant defekto dydį ir padėtį.
4. Pasiūlyta skaičiavimo metodika įvertina tuštumų liejinyje įtaką cikliniam stiprumui.

Tyrimų metodika

Darbe naudoti eksperimentiniai, analitiniai bei skaitiniai tyrimo metodai. Eksperimentiniams bandymams atlikti reglamentuojami metodai pakeisti ir pritaikyti medžiagos su tuštumomis tyrimams. Tiriant atsparumą plyšio plitimui, naudojami analitiniai ir skaitiniai metodai, pagrįsti tiesinės irimo mechanikos dėsningumais. Skaitinė analizė atliekama remiantis baigtinių elementų metodu. Tuštumų sankaupa nagrinėjama kaip plokščias plyšio pavidalo defektas.

Ginamieji teiginiai

1. Įtempių intensyvumo koeficiento ribinėms reikšmėms įtaką turi tuštumų sankaupos ir plyšio padėtis konstrukcijų elemente.
2. Sukurta patikslinta daugiaciklio stiprumo skaičiavimo metodika įvertina konstrukcinių elementų su liejimo tuštumų sankaupa

tinkamumą eksploatacijai.

3. Neardančios kontrolės metodais aptiktų defektų įtaką cikliniam stiprumui galima įvertinti darbe naudotais eksperimentiniais, analitiniais ir skaitiniais metodais.

Disertacijos struktūra ir apimtis

Disertaciją sudaro: bendroji darbo charakteristika, žymėjimų sąrašas, 67 paveikslai, 11 lentelių, keturi skyriai, pagrindiniai darbo rezultatai ir išvados, 2 priedai. Darbo apimtis yra 119 puslapių, neįskaitant priedo. Disertacijoje panaudoti 108 literatūros šaltiniai.

Pirmasis skyrius skirtas literatūros apžvalgai. Jame apžvelgiama stipriojo ketaus pramoninio naudojimo aktualijos ir problematika, aptariamos defektų atsiradimo priežastys ir pobūdis. Pasitelkus tiesinės irimo mechanikos dėsningumus, nagrinėjamas nuovarginio plyšio atsiradimo ir plitimo procesas stipriajame ketuje esant daugiaciklei apkrovai. Analizuojami esamų ciklinio patvarumo skaičiavimo metodikų trūkumai. Skyriaus pabaigoje formuluojamos išvados ir konkretizuojami disertacijos uždaviniai.

Antrajame skyriuje pristatoma originali eksperimento metodika bandinių su tuštumomis daugiaciklio stiprumo tyrimui. Siūlomi eksperimento atlikimo ir rezultatų apdorojimo patobulinimai leidžia nustatyti tuštumų poveikį pleišėjimo slenksčiui.

Trečiajame skyriuje pateikiami atliktų eksperimentinių analitinių tyrimų rezultatai ir jų analizė. Pateikiama skerspjūvių su tuštumomis geometrinių rodiklių skaičiavimo metodika. Pateikiama detali fraktografinė lūžių analizė.

Ketvirtajame skyriuje aprašomi analitiniai bei skaitiniai defektų įtakos tyrimai ir jų rezultatų analizė. Pasiūlyta metodika liejinių su tuštumomis daugiaciklio stiprumo skaičiavimui, nagrinėjant projektinį ir eksploatavimo atvejus.

Pagrindiniai darbo rezultatai ir išvados

1. Atlikus literatūros analizę nustatyta, kad daugiaciklio stiprumo skaičiavimo metodikos konstrukcijų elementams su liejimo tuštumų sankaupa trūksta. Vystomoms skaičiavimo metodikoms pagrįsti reikia patikslinti ir patobulinti eksperimentinio tyrimo reglamentuojamus metodus, atsižvelgiant į konstrukcinius, technologinius ir eksploatavimo veiksnius, įvertinti tuštumas ir plyšius naudojant irimo mechanikos kriterijus, analitinius ir skaitinius metodus.

2. Ribiniam įtempių intensyvumo koeficientui (pleišėjimo slenksčiui) nustatyti taikoma reglamentuojama metodika yra pakeista ir pritaikyta bandinių su liejimo tuštumomis tyrimui taip, kad gaunami rezultatai būtų pritaikyti lietų detalių su realiais defektais ilgaamžiškumo didinimui.

3. Gauti rezultatai rodo, kad tuštumų dydis nėra vienintelis rodiklis, turintis įtaką ribinio įtempių intensyvumo koeficiento intervalo mažėjimui.

Pleišėjimo slenkstis taip pat priklauso ir nuo tuštumų padėties skerspjūvyje, mikrostruktūrinio netolygumo bei mechaninio būvio tuštumų aplinkoje.

4. Rezultatai rodo, kad pleišėjimo slenkstis medžiagoje mažėja, jeigu mažėja plyšio plitimo greitis: austemperizuotam ketui ΔK_{th} = 7,4...8,7 MPa·m$^{1/2}$ prie $v = 10^{-10}$ m/ciklą ir ΔK_{th} = 7,2...8,6 MPa·m$^{1/2}$ prie $v = 10^{-11}$ m/ciklą ir mažiau; atitinkamai, perlitiniam ketui ΔK_{th} = 8,0...8,2 MPa·m$^{1/2}$ ir ΔK_{th} = 7,8...7,9 MPa·m$^{1/2}$.

5. Plyšio plitimo greičio ir įtempių intensyvumo koeficiento intervalo priklausomybės bei fraktografinė analizė rodo, kad plyšio fronto formai ir plyšio dydžiui įtakos turi tuštumos forma, dydis ir nevienalytė struktūra.

6. Gauti rezultatai rodo, kad pleišėjimo slenkstis medžiagoje su tuštumomis kinta: austemperizuotam ketui ΔK_{thd} = 5,3...7,2 MPa·m$^{1/2}$ prie $v \approx 5 \cdot 10^{-12}$ m/ciklą ir ΔK_{thd} = 5,5...7,7 MPa·m$^{1/2}$ prie $v = 10^{-10}$ m/ciklą; stipriajam perlitiniam ketui ΔK_{thd} = 6,3…7,9 MPa·m$^{1/2}$ prie $v = 10^{-10}$ m/ciklą. Šios reikšmės iki 28 % mažesnės lyginant su reikšmėmis medžiagoje be defektų.

7. Skaitinio tyrimo rezultatai rodo, kad įtempių intensyvumo koeficientas defekto aplinkoje didėja 1,5 karto lyginant su modeliu be defekto. Paviršiuje esantis defektas yra pavojingesnis už esantį detalės viduje.

8. Siūloma kompleksinė liejinių su tuštumų sankaupa ciklinio patvarumo skaičiavimo metodika, pagrįsta tikslesniais analitiniais ir skaitiniais įtempių intensyvumo koeficiento nustatymo metodais ir eksperimentinio tyrimo rezultatais. Gautos ribinės įtempių intensyvumo koeficiento ΔK_{thd} reikšmės gali būti naudojamos kalnakasybos įrenginių elementų iš stipriojo ketaus projektiniam ir tikrinamajam ciklinio stiprumo skaičiavimui.

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CASTING VOIDS INFLUENCE ON SPHEROID GRAPHITE CAST IRON HIGH-CYCLE FATIGUE STRENGTH

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

Konstantin Bobyliov

LIEJIMO TUŠTUMŲ ĮTAKA STIPRIOJO KETAUS DAUGIACIKLIAM STIPRUMUI

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