VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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FAILURE RESISTANCE OF HIGH-CYCLE LOADED WELDED JOINTS

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Introduction

Topicality of the problem. The project-based longevity and residual resource of the equipments depends on structural, technological and operational factors. Large-size industrial structures (such as mineral grinding mills, having a drum diameter up to 15 meter) are often made from separate structural elements, which are welded together. In welded structures of large dimensions the technological defects, such as slag inclusions, pores, cracks, poor welding and different types of heterogeneity, are unavoidable. During operation the welded joints are affected by different loads: static, dynamic and cyclical. When operational lifetime of the equipments exceeds 25 years (e.g. mineral grinding mills) due to multiple variable loading (which exceeds more than 10^8 cycles) in the separate localized places the irreversible damages, which becomes growing cracks, are accumulated. To describe the failure process, there must be identified specific parameters: cracking threshold, relationships of crack growth rate and the conditions of complete failure. Especially important parameter is crack stopping conditions. Experimental, analytical and numerical investigations, as well as natural and semi-natural tests should be performed for complex strength evaluation of significant structures, working under high-cycle loading, to make the basis of the existing and developing calculation methodology.

The results of research in the dissertation have been applied in the international programme “The Expansion of Durability of Mining Industry’s Equipment” and can be used to design the mechanisms of considerable dimensions in mining, transport and construction industries and nuclear-powered and wind-powered stations.

Research object. The mechanical state of welded joints in the structural elements is subject to the failure process which begins in the structural elements due to high-cyclic load (stress is lower than the margin of endurance).

Aim and tasks of the work. The main aim of the present work is to examine the regularities of crack‘s formation, growth, end and complete failure influenced by gigacyclic loading; to improve the methods of calculation of welded constructive elements applying the established limiting states of failure of regulated and special samples.

To achieve this aim, the following tasks should be performed:

1. To determine the microstructure of investigated welded joints‘ materials and the indexes of the mechanical properties of constructions.

2. To evaluate the influence of welded seam on the dependence of stress intensity factor range *ΔK* and crack growth rate *da/dN*, in consideration of the position of crack growth plane in regard to the seam.
3. By experiment, analytically and by numerical methods to examine the process of semi-natural specimens high-cyclic failure and to determine limiting states of failure.
4. To make the fractography analysis of compact and semi-natural specimens, distinguishing the stages of failure processes.
5. To suggest the improved methods of intensity calculation of considerable dimensions structural elements that are connected by boundary welding seams and influenced by high-cyclic loading based the analysis of the results of experimental, analytical and numerical tests.

Methodology of research. Experimental, analytical and numerical methods of research as well as comparative analysis were applied in this dissertation. Experiments have been carried out using regulated and applied original research methods. Methods that have been used were based on the regularities of linear fracture mechanics.

Semi-natural welded joints made on the basis of real constructions and CT specimens cut from specially prepared welded plates have been investigated during the experiments, orienting the crack in regard to the steam in different ways.

Scientific novelty. The following scientific novelties to the field of mechanics were disclosed:

1. The influence of welded joint‘s structural position and inhomogeneity to durability has been identified by the research in the high-cyclic sphere of failure process.
2. The limiting states in the welded joint of high-cyclic failure process.
3. Regularities of failure process have been revised by the methods of optical and electron microscopy.
4. The methods of calculation were created and revised, comparing CT specimens and the limiting states of semi-natural specimens in the sphere of gigacyclic loading

Practical value. Research results can be used evaluating the influence of structural and technological factors in the welded joints, thus more precisely predicting the cyclic durability of welded joints. The research results that have been found and the methods of calculation are being applied while designing the new welded structural elements of considerable dimensions subjected to high-cyclic loading.

Defended propositions

1. Obtained comparative cracking threshold results, depending from crack growth and stopping in regard to the welded seam, allow to evaluate fitness of designed constructions with butt joints and to extend service life by changing the location of seam.
2. The assessment of mechanical state of real structural elements is validated by research results of semi-natural specimens resistance to programming cyclic load – the kinetic fatigue diagram, limiting stress intensity factors.
3. Regularities of stress-strain states and failure mechanics can be applied to analyse the failure mechanisms of specific welded joints, crack growth and stopping.
4. Determined values of resistance to cracking, when crack growth rate is close to $5\cdot10^{-12}$ m/cycle, can be used in calculations of welded joints strength and durability, when number of cycles exceeds 10^{8}, in modelling inhomogeneity formations and crack growth.

The scope of the scientific work. The scientific work consists of an introduction, 5 chapters, conclusions, bibliography, list of author publications. The dissertation consists of 110 pages, 77 figures, 41 formulas and 11 tables.

1. Welded Joints‘ Strength and Cyclic Failure Review

The research review of examined problem has been presented in this section.

The strength of welded joints depends on their construction and on the static mechanic properties of joining elements and structural inhomogeneity appearing at the seam‘s environment as well as on various technological defects and running factors. Failure mechanism and position in welded joint changes depending on the loading (static, low-cyclic, high-cyclic). While structural properties and welding technologies are successfully improved, running factors (loading, environmental conditions) are constantly changing and are not always predicted. When durability increases, the cyclic loading of the structural elements of mining industry‘s equipment reaches 10^{9} cycles (gigacyclic sphere). Currently calculated maximum stresses in this sphere are accepted lower than the margin of endurance and are not based on experimental analytical research.

The diagram of cyclic failure processes facilitates to determine the influence of various factors on fatigue crack growth and end. Diagram involves known regularities and diagram‘s analysis gives much information while examining the resistance to high-cyclic loading applying the methods of failure mechanics. To combine the results obtained while testing regulated and semi-natural specimens means to combine and to reason the designed and running requirements.

The standards that are regulating the accomplishment of tests describe the methods of tests until 10^{-10} m/cycle cracks growth rates, because it is agreed that cracks do not grow in smaller rate. Analysis shows that this rate is insufficient determining the failure indexes for those structural elements, which durability exceeds 25 years. In those cases it is purposeful to count the cyclic strength approaching to the rates – 10^{-12} m/cycle.

After performing the analysis of research and methods of calculation, it is possible to maintain, that welded joints’ resistance in gigacyclic sphere is not examined sufficiently and present methods of calculation A STME and other are not based by experimental analytical research or there are no such methods at all. In this thesis there is an attempt to base and improve the methods of calculation applying experimental analytical research results.

2. Methodology of Experimental Research

In this section the methods of accomplished experimental research are presented, the preparation of specimens used for research are described, used equipment is introduced, the tests‘ accomplishment techniques of the non-centrical extension of compact specimens and semi-natural specimens resistance to fatigue crack formation and spread, as well as the evaluation methods of cracked specimens' failure conditions are examined.

Regulated and special specimens are used to determine the cyclic failure indexes. Non-centrical extension compact specimens (CT) have been produced to determine the limiting stresses’ intensity factor (cracking threshold) ΔK_{th}. CT specimens (Fig. 1) have been cut from three welded plates (the 1st – without heat treatment; the 2nd – heat treated after the welding and the 3rd – rewelded in the spheres of detected defects). The plates have been made from carbon steel, which static mechanical properties are: ultimate tensile strength $R_m = 416$–428 MPa, lower yield strength R_{eL} = 259–278 MPa, upper yield strength R_{eH} = 274–301 MPa, modulus of elasticity $E = 210$–215 GPa, elongation A = 35–40 %, reduction in area $Z = 67$–75 %. The properties of the weld are: R_m = 440–475 MPa, R_{eL} = 360–370 MPa, R_{eH} = 380–385 MPa, $E = 211$ GPa, A = 34–35 %, $Z = 73$–78 %. Regulated according to the methods of failure research

ASTM E 647-00 and ASTM E 399-83 are revised and adapted for the calculation of long durability. For stress intensity factor calculation following formula is applied:

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

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

Semi-natural specimens, loaded according to programs, corresponding to real structural loading, have been used to restore the mechanical state of real structural elements. The specimen was made from welded cast iron plates, which properties are as follows: conditional yield stress $R_{p0.2}$ = 490–500 MPa, R_m = 817 MPa, E = 175 GPa, A = 2.13 %, Z = 4.94 % and properties of the weld: R_{eH} = 408–469 MPa, R_{eL} = 392–440 MPa, R_m = 529 MPa, E = 209 GPa, A = 25.2 %, Z = 59.4 %.

3. Influence of structural factors on the resistance failure process of welded joint

In this section the analysis of the results of experimental analytical research are presented, as the aim of research has been to examine the influence of structural and technological factors on the welded joint failure process. Seam‘s influence has been evaluated accomplishing the analysis of comparative experimental research, comparing the values of cracking threshold that have been received, as the same crack growth rates were present in the base metal and next to different crack growth planes in regard to the welding seam (Fig. 1).

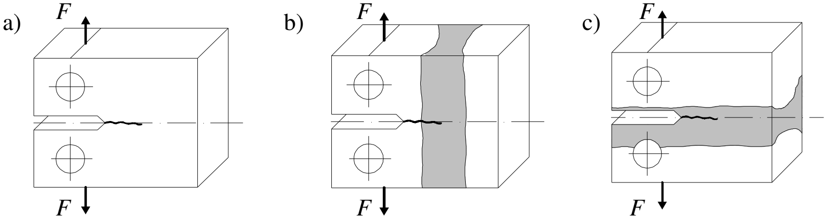

Fig. 1. Scheme of crack propagation in CT specimen: a) basic metal; b) crack is perpendicular to the weld; c) crack is along or near the weld

The limiting stresses' intensity factor (cracking threshold) was established in the case of stress ratio $r \approx 0.05$. The diagrams of crack growth rate versus the range of stress intensity factor were compiled and cracking threshold ΔK_{th} values have been defined, that allow to determine the general trends of the influence of seam on failure process.

Cracking threshold in the specimens of all three welded plates of base metal varies within the limits of: ΔK_{th} = 6.8–9.1 MPa·m$^{1/2}$ when crack growth rate $v = 10^{-10}$ m/cycle and ΔK_{th} = 5.8–9.0 MPa·m$^{1/2}$ when $v = 10^{-11}$ m/cycle.

In the specimens of plate without heat treatment, when fatigue crack growth is perpendicular to the weld, established cracking threshold is: ΔK_{th} = 14–20 MPa·m$^{1/2}$ at crack growth rate $v = 10^{-10}$ m/cycle and ΔK_{th} = 13.6–20.2 MPa·m$^{1/2}$ at $v = 10^{-11}$ m/cycle (Fig 2a). Cracking threshold in the same plate when crack is along or near the weld is ΔK_{th} = 6.9–8.3 MPa·m$^{1/2}$ at $v = 10^{-10}$ m/cycle and ΔK_{th} = 5.9–8.1 MPa·m$^{1/2}$ at $v = 10^{-11}$ m/cycle (Fig 2b).

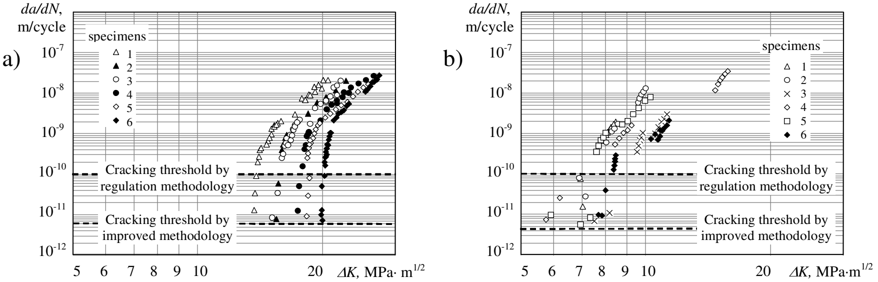

Fig. 2. Crack growth rate versus the range of stress intensity factor in specimens of the plate without heat treatment: a) crack is perpendicular to the weld; b) crack is along or near the weld

Investigation results showed that crack growth plane in regard to the seam notably changes the values of cracking threshold.

In the specimens of rewelded plate, when crack is perpendicular to the weld, cracking threshold is ΔK_{th} = 23–27 MPa·m$^{1/2}$ at $v = 10^{-10}$ m/cycle and ΔK_{th} = 20–28 MPa·m$^{1/2}$ at $v = 10^{-11}$ m/cycle. Whereas in the same plate, when crack grows along the weld, established cracking threshold in 5 specimens: ΔK_{th} = 8.9–12.6 MPa·m$^{1/2}$ at $v = 10^{-10}$ m/cycle and ΔK_{th} = 7.6–12 MPa·m$^{1/2}$ at $v = 10^{-11}$ m/cycle.

Cracking threshold in the specimens of heat treated plate, when crack is along or near the weld, varies within the limits: ΔK_{th} = 7.6–8.2 MPa·m$^{1/2}$ at $v = 10^{-10}$ m/cycle and ΔK_{th} = 6.4–8.0 MPa·m$^{1/2}$ at $v = 10^{-11}$ m/cycle (Fig. 3).

In Fig. 4 different plates‘ cracking threshold limits are presented, when crack spreads along the welding seam (through the seam itself or very close to it). Obtained limiting stress intensity factor values at the crack growth rate from 10^{-10} m/cycle to $5 \cdot 10^{-11}$ m/cycle show the smallest resistance of specimens without heat treatment to cracking. While resistance of specimens from rewelded plate to cracking is the largest.

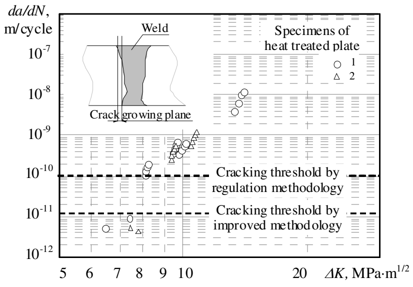

Fig. 3. Crack growth rate versus the range of stress intensity factor when crack is along or near the weld

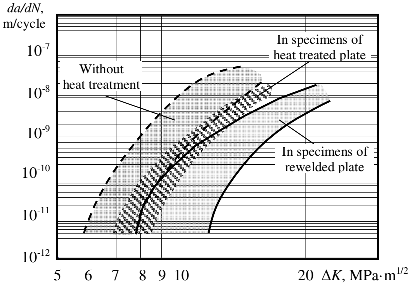

Fig. 4. Boundaries of the crack resistance of differently obtained welds, when crack is along or near the weld

In Fig. 5 more interesting CT specimens‘ fractures are shown. In Fig. 5a a specimen is shown, in which a slot has been made perpendicularly to the seam.

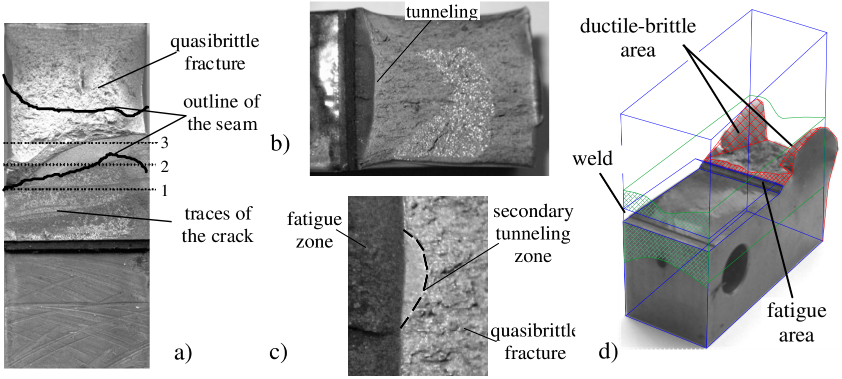

Fig. 5. Fracture surface of the specimen: a) when crack grows perpendicular to the weld (1, 2, 3 – crack’s depths are indicated); b) with tunneling effect; c) increased area with secondary tunnelling features; d) as crack growth is initiated along the welding seam

The values were determined: as crack was growing through the base metal (ΔK_{th} = 18.4 MPa ·m$^{1/2}$); through transitional layer (ΔK_{th} = 20.1 MPa ·m$^{1/2}$); through seam‘s metal (ΔK_{th} = 20.0 MPa ·m$^{1/2}$), when growth rate was 10^{-10}–$7 \cdot 10^{-12}$ m/cycle. The achieved result showed that the seam, in the initial moment as the crack was going through the base metal, reduced the crack opening, increased ΔK values and changed the mechanism of failure.

In Fig. 5b a specimen fracture has been shown, in which the crack grows along the seam through heat affected zone. A unique secondary tunnelling effect has been observed in this specimen (Fig. 5c highlighted), emerged as two-axial deformation state was present in a localized zone, which changed the crack front.

The analysis of fractures, that was made with optical means and with the help of SEM had corrected the state of deformation of stresses, impact of seam on failure mechanism and highlighted the peculiarities of failure process. Tunnelling and secondary tunnelling zones change the one of the notions of failure mechanics – the dimension of specimen. Achieved ΔK–da/dN dependencies provide marginal parameters ΔK_{th} and show the complexity of failure process in welded joints.

4. Experimental research analysis of the resistance of semi-natural welded joints to high-cyclic loading

In the section the results of experimental, analytical and numerical research are presented, while the aim of research is to examine the welded specimens, prepared according to real constructions’ engineering technology and resistance to programmable loading.

The welded cast iron specimen of rectangular cross-section was cyclically tested to determine the indexes of resistance to high-cyclic loading (Fig. 6). The history of the program loading is shown in Fig. 7. The experiment started from a low stress, lower than the “long” cracks nonpropagating threshold. The development of crack origin was fixed after 130 million cycles in 150 MPa stress change interval. It is interesting that under the stress σ_{max} = 42.8 MPa, σ_{min} = –26.2 MPa (cycle asymmetry r = –0.62) the specimen passed 100 million cycles, but the initial cracking was not fixed. This loading history corresponds to the real loading of structure elements. Some crack origins, i.e. the development of the defectoscopy picture, was detected at $\Delta\sigma$ = 120 MPa. The formation of crack has emerged in the environment of subsurface defect. The crack formation was not found before the experiment while examining the specimen with ultrasonic, turbulent currents and luminescence magnetic methods. Only after the experiment, several inhomogeneity formations were determined when the analysis of fracture with optical means and with the help of SEM was made. Failure process has begun from one of them. Subjected to cyclically variable stresses even more focuses have appeared, which united forming a macro crack. It is interesting to note, that small abrasions after the abrasive treatment of the seam in the initial loading period did not became the focuses of crack.

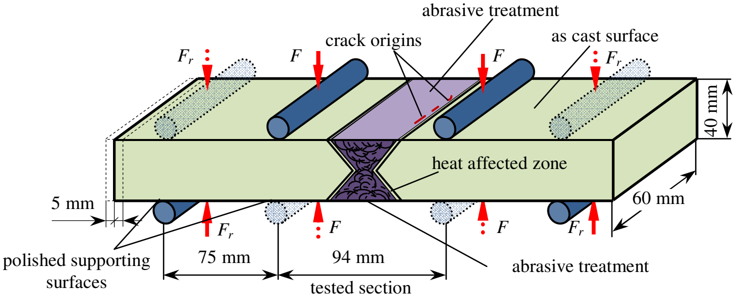

Fig. 6. Scheme of semi-natural specimen

The parameters of the curve (kinetic fatigue diagram) define the resistance of the material to a cyclic loading. According to the experimental data obtained (crack depth – number of cycles) the kinetic diagrams are designed (Fig. 8) applying 3 different formulas for K calculation:

1) Anderson:

$$K_{\mathrm{I}} = \frac{M}{B\sqrt[3]{W}} f\left(\frac{a}{W}\right), \tag{2}$$

2) Tada, Paris, Irwin:

$$K_{\mathrm{I}} = \frac{6M}{tW^2}\sqrt{\pi a}\, f\left(\frac{a}{W}\right), \tag{3}$$

3) ASTME:

$$K_{\mathrm{I}} = \sigma\sqrt{\pi a}\, f(\alpha). \tag{4}$$

In these formulas M is bending moment, B and t is specimen width, W is thickness, σ is maximal stresses and a is crack size; $f\,(a/W)$ and $f\,(\alpha)$ are dimensionless geometry function.

According to some calculations, kinetic diagrams are made (crack growth rate – stress intensity factor) in Fig. 8.

In the figure we can see that all the formula applied give similar results.

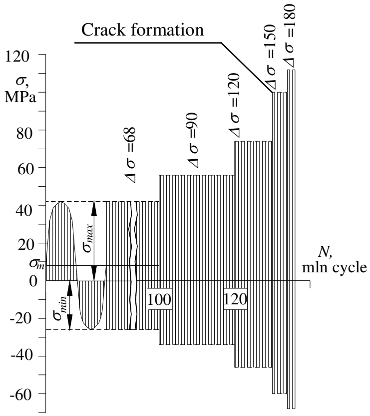

Fig. 7. Loading history diagram

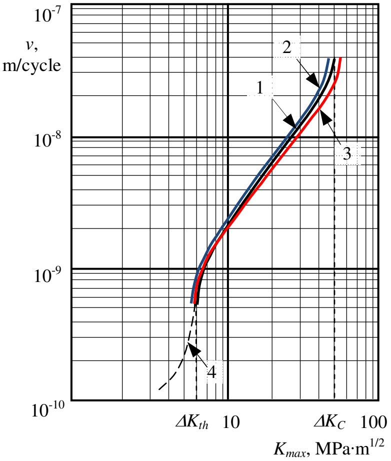

Fig. 8. Kinetic diagram of fatigue:
1 – Anderson; 2 – Tada, Paris, Irvine;
3 – ASTME, 4 – short cracks

The straight part of the definited kinetic fatigue diagram is by Paris and Erdogan formula described:

$$\frac{da}{dN} = C(\Delta K)^n , \tag{5}$$

where $\frac{da}{dN}$ – crack growth rate; $\Delta K = K_{max} - K_{min}$ – stress intensity factor range per loading cycle; C ir n – constants, obtained from experimental data ($c = 1 \cdot 10^{-10}$ and $n = 1.6$).

FEM method was used for additional analysis of crack growth. The geometry, material and loading of model under investigation (located at the moment of crack origin) were analogical as in the experimental research. Models with the crack peak present at variable depth were examined. In Fig. 9. the *von Misses* stresses field was presented beside crack peak (0.22 mm distance up to the base metal). The numerical research is also contributing to the results of experiment and showing that, when the crack peak approaches the base metal, due to difference of properties and loading, notably bigger stresses occur in base metal than in seam metal, and the rate of crack growth increases in the base metal due to cyclical loading.

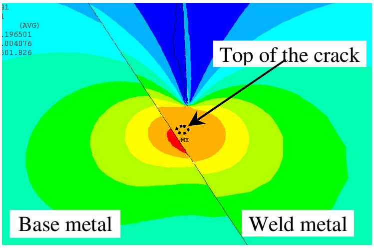

Fig. 9. Distribution of *von Mises* stresses near top of the crack

The total impact of stresses σ_x and σ_y determines that crack growth plane makes some angle with cross-section plane.

5. Analysis application of welded joints failure process

In this section the revision of the methods of calculation of welded joints is given, evaluating the influence of inhomogeneity formations that occurred in the welding process to high-cyclic strength. It is agreed, that fatigue cracks do not occur, if the following condition is satisfied:

$$\Delta K_1 \leq [K_I] = \frac{\Delta K_{th}}{n_K}, \qquad (6)$$

where ΔK_I (permissible) and ΔK_{th} (marginal) parameters of failure mechanics; n_K – assurance factor. When $n_K = 1$, critical crack length l_c is achieved, corresponding to the permissible (estimated) stresses size, but when $n_k > 1$ – safe crack size $[l] < l_c$.

In Fig. 10 the location of origin and spread of crack in the specimen was presented and inhomogeneity formations were detected in the specimen's fracture. Subsurface defects were ascribed to the cracks that spread according to the regularities of short crack growth. Due to the differences of defects it is difficult to determine value *K*. Therefore, inhomogeneity forms should be schematized, allowing to receive the bigger resistance assurance. The combination of defects is being applied while schematizing the crack which has the form of ellipse, semi-ellipse or quarter ellipse. Two alongside inhomogeneity formations should be combined and examined as one bigger defect, if the minimum distance between the defects is smaller than the biggest dimension of the smaller defect.

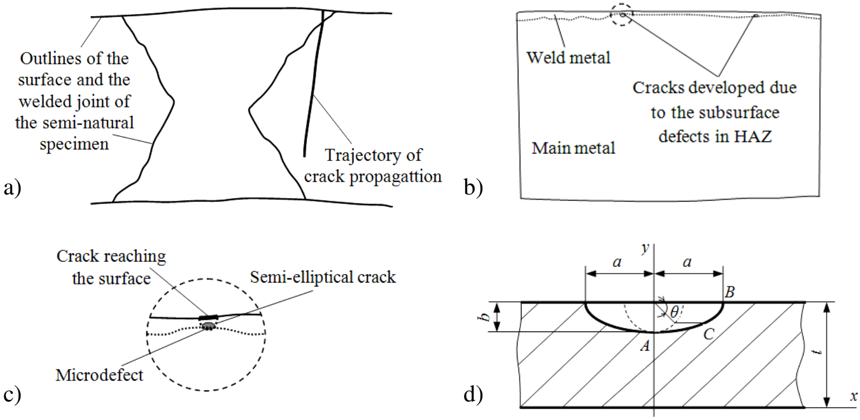

Fig. 10. The fracture scheme of the semi-natural specimen and defect schematization: a) the trajectory of crack propagation in a semi-natural specimen; b) a schematic view of the fracture, c) the enlarged view of the location of the crack region formation; d) the calculating model of semi-elliptical surface crack

In Fig. 11 schematization of failure process is being shown, which involves semi-natural specimen kinetic fatigue curve, marginal states of CT specimens, conditional zone of short cracks and the sphere of crack origin. In our case, subjected to programmable cyclic loading, the period of crack origin made approximately 80% from the total number of cycles. Known or supposed defects – dislocations, vacancies, different strength crystallites and the like – are shown in this period; as well as inhomogeneity formations, which could be imagined as localized volumes, in which the stresses and deformations are increased. These localized volumes have lower strength, their accidental position determine the accidental initial form and front of crack.

Stated crack‘s geometry is close to semi-ellipse crack (Fig. 10d), subjected to extension stresses $\sigma_z^\infty = \sigma$, therefore, the approximation formula can be used to calculate stress intensity factor:

$$K = \sigma\sqrt{\pi b / Q_0}\, F_1 , \tag{7}$$

depending from $(b/a, b/t, \theta)$, $(0 \le b/a \le 2, 0 \le \theta \le \pi, b/t < 1{,}25(b/a + 0{,}6)$, when $0 \le b/a \le 0{,}2$, $b/t \le 1$, when $0{,}2 \le b/a \le 2$).

where σ – stresses; a, b, t, θ – geometrical parameters, F_1, Q_0 – values are determined according to empirical formulas, subject to b/a relation.

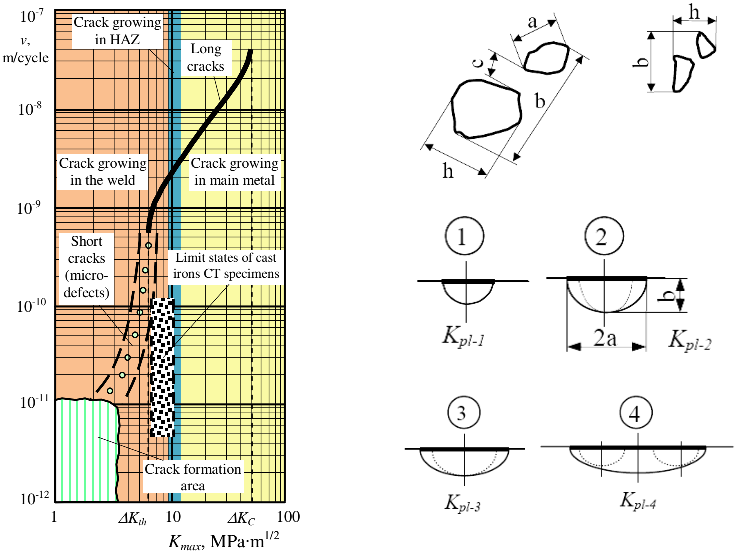

Fig. 11. Schematization of failure process: a) generalized kinetic fatigue curve; b) scheme of combination of defects and cracks: 1–3 – the formation stage of semi-ellipse cracks; 4 – combination of two semi-ellipse cracks

Having applied analytical expressions (7), stress intensity factor was calculated, having the initial fatigue crack appeared due to subsurface defect and reaches $K \approx 2.51$ MPa·m$^{1/2}$ (at $\Delta\sigma = 150$ MPa, as crack depth is $b = 0.7$ mm and length is $2a = 1.1$ mm). Several values of intercalary crack sizes K and assurance factors, calculated according to formula (6), are presented in Table 1.

Received values are compared with ΔK_{th} (cracking threshold), determined using CT specimens and threshold determined using the help of kinetic fatigue curve.

Average and minimum ΔK_{thS} values can be used to calculate welded structural elements with small hardly detected welding defects. When predicted equipment‘s exploitation is more than 25 year, it is recommended to use

$\varDelta K_{th\_min}$ in the calculations of durability This marginal index is being determined experimentally, when crack growth rate v becomes close to 10^{-12} m/cycle.

Table 1. Stress intensity factors and factors of safety

$\varDelta\sigma$, MPa	σ_{max}, MPa	K, MPa·m$^{1/2}$	n
150	93.0	2.51	1
120	74.4	2.01	1.25
90	55.8	1.51	1.66
68	42.2	1.14	2.2

In the stresses intensity factors determination formulas for ellipse and semi-ellipse crack we apply the condition of non-spread, with the aim that inner welding element or inhomogeneity formation would not become the focus of crack:

$$\varDelta K_{1max} \le \varDelta K_{thSD}\,, \tag{8}$$

where $\varDelta K_{thSD}$ – cracking threshold value of structural element with welding defects.

The made analysis allows to determine exploitation stresses, determining assurance factor and comparing with received programmable loading results.

General conclusions

1. The scientific research thesis analysis of welded joints of exploited and designed mining industry's equipment shows that the carried out theses in the sphere of resistance to high-cyclic (>10^8 cycles) loading are not enough in order to validate the methods of the calculation of strength and durability of those equipment, which durability exceeds 25 years.
2. The investigations of resistance to high-cyclic (>10^8 cycle) failure of compact non-centrical extension (CT) specimens and semi-natural specimens were carried out in order to compare cracking threshold values. Regulated cracking threshold's determination methodology has been changed, reducing growth rate till $5{\cdot}10^{-12}$ m/cycle in order that the determined values would be applied to the calculations of bigger durability.
3. The investigation of structural factors influence on the resistance failure process of welded joint revealed that the front trajectory of formed crack is subjected to seam's and heat affected zone, and seam position changes failure mechanism and cracking threshold value.

4. Having tested 35 CT specimens from 3 welded steel plates (the 1st – without heat treatment; the 2nd – heat treated and the 3rd – rewelded), dependencies of crack growth rate versus the range of stress intensity factor were made and it was determined that next to the rate $5 \cdot 10^{-12}$ m/cycle, the smallest marginal stresses intensity factor's values (ΔK_{th} = 5.9–9.0 MPa·m$^{1/2}$) were received in base metal; when crack was growing along the seam (ΔK_{th} = 6.1–10.5 MPa·m$^{1/2}$), and the biggest stresses intensity factor (ΔK_{th} = 13.6–20.2 MPa·m$^{1/2}$) was determined as crack spread perpendicularly to the seam. Results show that cracking threshold perpendicularly to the seam is twice as big as along the seam.

5. The experimental research of semi-natural welded specimens according to programmable loading in gigacyclic (>10^8 cycle) sphere has shown that the crack focus for stresses close to exploitation occurred beside subsurface defect and emerged to the surface, whereas stresses state, the surface irregularities and metal structure influence further growth.

6. Fractography analysis revised the regularities of failure process, and showed that in a qualitative seam (without defects) there are inevitable inhomogeneity formations in heat affected zone, which become crack focuses and influence the durability of the whole construction.

7. Applied calculation methodology of welded joints cyclical strength (interpolating endurance limit) is not validated, therefore it has been changed to calculation method, which evaluates the inhomogeneity formations (not detected before tests) and obtained regularities of failure process.

8. Researches have shown that by evaluating the inevitable inhomogeneity formations, very small (1x1,5 mm), compared with dimensions of mineral mills (>10 m) and very small compared to the welded seam length (>30 m), at the design stage, longevity will exceed 25 years.

List of Published Works on the Topic of the Dissertation
In the reviewed scientific periodical publications

Stonkus, R.; Leonavičius, M.; Petraitis, G. Stupak, S. 2011. High-cyclic failure analysis of welded cast iron plates, *Mechanika* 2(17): 120–125. ISSN 1392-1207 (Thomson ISI Web of Science).

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In the other editions

Stonkus, R.; Leonavičius, M. 2010. The high cyclic failure analysis of welded joints of CT specimens, *Diffusion and Defect Data Part B: Solid State Phenomena*, Vol.165: 183–188. ISSN 1012-0394 (ISI Proceedings)

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DAUGIACIKLIŠKAI APKRAUTŲ SUVIRINTŲJŲ JUNGČIŲ ATSPARUMAS IRIMUI

Mokslo problemos aktualumas. Įrenginių projektinis ilgalaikiškumas ir liekamasis resursas priklauso nuo konstrukcinių, technologinių ir eksploatacinių veiksnių. Didelių gabaritų pramoninės konstrukcijos (pvz. kalnakasyboje naudojami mineralų malūnai, kurių skersmuo iki 15 metrų) dažnai gaminamos iš atskirų konstrukcinių elementų, kurie vėliau suvirinami. Didelio tūrio suvirintose konstrukcijose neišvengiami technologiniai defektai: šlako intarpai, poros, įtrūkimai, neįvirinimai ir įvairaus pobūdžio nevienalytiškumai. Eksploatacijos metu suvirintosios jungtys apkraunamos įvairiomis apkrovomis: statinėmis, dinaminėmis ir ciklinėmis. Kai įrenginių eksploatacijos trukmė siekia ≥25 metus (pvz. mineralų smulkinimo malūnai), dėl daugkartinių kintamų apkrovų (kurios siekia virš 10^8 ciklų) atskirose lokalizuotose vietose susikaupia negrįžtami pažeidimai, kurie tampa plintančiais plyšiais. Irimo procesui apibūdinti reikia nustatyti specifinius parametrus: plyšėjimo slenkstį, plyšio plitimo greičio priklausomybes ir visiško suirimo sąlygas. Ypač svarbus parametras – plyšio sustojimo sąlygos. Kompleksiniam svarbių konstrukcijų, dirbančių daugiaciklėje srityje, atsparumo įvertinimui reikia taikyti eksperimentinius, analitinius ir skaitinius tyrimus, natūrinius ir pusiau natūrinius bandymus tam, kad būtų pagrįstos esamos ir tobulinamos skaičiavimo metodikos.

Disertacijoje gauti tyrimų rezultatai pritaikyti tarptautinėje programoje „Kalnakasybos įrenginių ilgaamžiškumo didinimas“ ir gali būti panaudoti kalnakasybos, transporto, statybos, atominės ir vėjo jėgainių energetikos stambiagabaritiniams įrenginiams projektuoti.

Tyrimų objektas. Suvirintųjų jungčių mechaninis būvis, susidarantis konstrukcijos elementuose, kuriuose dėl apkrovos daugiacikliškumo (įtempiai žemiau patvarumo ribos) prasideda irimo procesas.

Darbo tikslas ir uždaviniai*.* Darbo pagrindinis tikslas – ištirti plyšio susidarymo, plitimo, sustojimo ir visiško suirimo dėsningumus, veikiant gigacikliam apkrovimui, patobulinti suvirintų konstrukcinių elementų skaičiavimo metodiką taikant nustatytus reglamentuojamų ir specialių bandinių suirimo ribinius būvius.

Darbo tikslui pasiekti reikia spręsti šiuos uždavinius:

1. Nustatyti tiriamų suvirintųjų jungčių medžiagų mikrostruktūrą ir statinių mechaninių savybių rodiklius.
2. Įvertinti suvirinimo siūlės įtaką įtempių intensyvumo koeficiento intervalo ΔK ir plyšio plitimo greičio da/dN priklausomybei, atsižvelgiant į plyšio plitimo plokštumos padėtį siūlės atžvilgiu.
3. Eksperimentiškai analitiškai ir skaitiniais metodais ištirti pusiau natūrinių bandinių daugiaciklio suirimo procesą ir nustatyti irimo ribinius būvius.
4. Atlikti kompaktinių ir pusiau natūrinių bandinių fraktografinę analizę, išskiriant suirimo procesų etapus.
5. Pasiūlyti patobulintą didelių gabaritų konstrukcinių elementų, kurie sujungti sandūrinėmis suvirinimo siūlėmis ir veikiami daugkartinėmis ciklinėmis apkrovomis, stiprumo skaičiavimo metodiką, pagristą eksperimentinių bandymų, analitinių ir skaitinių tyrimų rezultatų analize.

Tyrimų metodika. Disertacijoje taikomi eksperimentiniai, analitiniai ir skaitiniai tyrimo metodai bei lyginamoji analizė. Eksperimentai atlikti naudojantis reglamentuojamais bei pritaikytais originaliais tyrimų metodais. Naudojami metodai pagrįsti tiesinės irimo mechanikos dėsningumais.

Eksperimentų metu buvo tiriami realių konstrukcijų pagrindu pagaminti pusiau natūriniai suvirinti sujungimai bei iš specialiai paruoštų suvirintų plokščių išpjauti CT bandiniai, įvairiai orientuojant plyšį siūlės atžvilgiu.

Mokslinis naujumas. Rengiant disertaciją buvo gauti šie mechanikos inžinerijos mokslui nauji rezultatai:

1. Suirimo proceso daugiaciklėje srityje tyrimu nustatyta suvirintosios jungties padėties konstrukcijoje ir nevienalytiškumo įtaka ilgalaikiškumui.
2. Daugiaciklio suirimo proceso ribiniai būviai suvirintoje jungtyje.
3. Patikslinti suirimo proceso dėsningumai optinės ir elektroninės mikroskopijos metodais.
4. Sukurta patikslinta skaičiavimo metodika, lyginant CT bandinių ir pusiau natūrinių bandinių ribinius būvius gigaciklėje apkrovimo srityje.

Praktinė vertė. Tyrimų rezultatai gali būti naudojami įvertinant konstrukcinių ir technologinių veiksnių įtaką suvirintose jungtyse, tiksliau prognozuoti suvirintųjų jungčių ciklinį ilgalaikiškumą. Gauti tyrimų rezultatai ir skaičiavimo metodika pritaikoma projektuojant naujus didelių gabaritų konstrukcijų suvirintus elementus, kurie veikiami daugkartinėmis ciklinėmis apkrovomis.

Ginamieji teiginiai

1. Gauti palyginamieji plyšėjimo slenksčių rezultatai, priklausomai nuo plyšio plitimo ir stabdymo padėties siūlės atžvilgiu, leidžia įvertinti projektuojamų konstrukcijų su sandūrinėmis jungtimis tinkamumą ir prailginti eksploatacijos laiką, keičiant siūlės padėtį.
2. Realių konstrukcijų elementų mechaninio būvio įvertinimą pagrindžia pusiau natūrinio bandinio atsparumo programiniam cikliniam apkrovimui tyrimo rezultatai – kinetinė nuovargio diagrama, ribiniai įtempių intensyvumo koeficientai.
3. Įtempių deformacijų būvio ir irimo mechanikos dėsningumus galima taikyti nagrinėjant specifinių suvirintųjų jungčių irimo mechanizmą, plyšio plitimą ir stabdymą.

4. Nustatytas atsparumo plyšėjimui reikšmes, esant plyšio plitimo greičiui artimam $5 \cdot 10^{-12}$ m/ciklą, galima pritaikyti suvirintųjų jungčių stiprumo ir ilgalaikiškumo skaičiavimams, kai ciklų skaičius viršija 10^8, modeliuojant nevienalytiškumo darinius ir plyšio plitimą.

Darbo struktūra ir apimtis. Disertaciją sudaro įvadas, 5 skyriai ir rezultatų apibendrinimas. Bendra disertacijos apimtis yra 110 puslapių, tekste panaudotos 41 numeruotos formulės, 77 paveikslai ir 11 lentelių.

Įvade apibrėžta tyrimų sritis ir aktualumas, aprašyta mokslo krypties problema, suformuluotas darbo tikslas ir iškeltieji uždaviniai, paminėti naudoti tyrimo metodai, aptartas darbo naujumas ir originalumas, paaiškinta rezultatų praktinė vertė. Pirmame skyriuje apžvelgiami moksliniai darbai, glaudžiai susiję su disertacijos tematika, pateikiama daugiaciklio stiprumo suvirintuose komponentuose aktualijos ir problematika. Skyriaus pabaigoje formuluojamos išvados ir konkretizuojami disertacijos uždaviniai. Antrajame skyriuje pateikta tyrimų metodika. Aprašyta bandymų metodų esmė, taikymas, eksperimentų atlikimas bei rezultatų apdorojimo metodai. Trečiajame skyriuje pateikiami atliktų eksperimentinių analitinių tyrimų, kuriais siekta ištirti konstrukcinių veiksnių įtaką suvirintosios jungties suirimo procesui, rezultatai ir jų analizė. Ketvirtajame skyriuje tiriamas suvirintųjų bandinių, paruoštų pagal realią konstrukcijų gamybos technologiją ir veikiamų apkrovomis, atitinkančiomis realių konstrukcijos elementų apkrovimą, atsparumas irimui, pateikiami gautų tyrimų rezultatai bei jų aptarimas. Penktajame skyriuje, atlikus detalią analitinio ir skaitinio tyrimo rezultatų analizę, pasiūlyta patobulinta suvirintų konstrukcinių elementų skaičiavimo metodika.

Bendrosios išvados

1. Eksploatuojamų ir projektuojamų kalnakasybos įrenginių suvirintųjų jungčių mokslo tiriamųjų darbų analizė rodo, kad atsparumo daugiacikliam ($>10^8$ ciklų) apkrovimui srityje atliktų darbų nepakanka tam, kad būtų galima pagrįsti stiprumo ir ilgalaikiškumo skaičiavimo metodikas tų įrenginių, kurių ilgalaikiškumas viršija 25 metus.

2. Irimo proceso ir plyšėjimo slenksčio reikšmių palyginimui atlikti kompaktinių necentrinio tempimo (CT) bandinių bei pusiau natūrinių bandinių atsparumo daugiacikliam ($>10^8$ ciklų) irimui tyrimai. Reglamentuojama plyšėjimo slenksčio nustatymo metodika pakeista mažinant plitimo greitį iki $5 \cdot 10^{-12}$ m/ciklą, siekiant pritaikyti nustatytąsias reikšmes didesnio ilgalaikiškumo skaičiavimams.

3. Konstrukcinių veiksnių įtakos suvirintosios jungties atsparumo suirimo procesui tyrimas atskleidė, kad suformuoto plyšio fronto trajektorija yra

veikiama siūlės ir terminio poveikio zonos: keičiasi irimo mechanizmas, susidaro įstrižas arba iškraipytas plyšio frontas, pasireiškia dvigubo tuneliavimo efektas ir kinta (didėja arba mažėja) plyšėjimo slenksčio dydis.

4. Išbandžius 35 CT bandinius iš suvirintų 3-jų plieno plokščių (be terminio apdirbimo; po terminio apdirbimo; pervirintos), sudarytos plyšio plitimo greičio ir įtempių intensyvumo koeficiento priklausomybės bei nustatyta, jog prie greičio, artimo $5{\cdot}10^{-12}$ m/ciklą, mažiausios ribinio įtempių intensyvumo koeficiento reikšmės $\Delta K_{th} = 5{,}9–9{,}0$ MPa·m$^{1/2}$ gautos pagrindiniame metale; plyšiui plintant išilgai siūlės $\Delta K_{th} = 6{,}1–10{,}5$ MPa·m$^{1/2}$, o didžiausias įtempių intensyvumo koeficientas $\Delta K_{th} = 13{,}6–20{,}2$ MPa·m$^{1/2}$ nustatytas plyšiui plintant statmenai siūlei. Rezultatai rodo, kad plyšėjimo slenkstis statmenai siūlei yra dvigubai didesnis nei išilgai siūlės.

5. Pusiau natūrinių suvirintų bandinių eksperimentinis tyrimas pagal programinį apkrovimą gigaciklėje ($>10^8$ ciklų) srityje parodė, kad esant įtempiams, kurie artimi eksploataciniams, plyšio židinys susidarė ties nevienalyčiu dariniu ir iškilo į paviršių, o tolimesnį plitimą lemia įtempių būvis, paviršiaus nelygumai ir metalo struktūra.

6. Fraktografinė analizė patikslino suirimo proceso dėsningumus ir parodė, kad kokybiškoje siūlėje (be defektų) yra neišvengiamų nevienalytiškumo darinių ir jų sankaupų terminio poveikio zonoje, kurie tampa plyšio židiniais ir įtakoja visos konstrukcijos ilgalaikiškumą.

7. Taikoma suvirintųjų jungčių ciklinio stiprumo skaičiavimo metodika (interpoliuojant patvarumo ribą) yra nepagrįsta, todėl ji pakeista skaičiavimo metodu, įvertinančiu nevienalytiškumo darinius (neaptiktus prieš bandymus) ir gautus suirimo proceso dėsningumus.

8. Atlikti tyrimai parodė, kad projektavimo stadijoje įvertinus neišvengiamus nevienalytiškumo darinius, labai mažus (1x1,5 mm) palyginti su mineralų malūnų gabaritais (>10 m) ir labai mažus palyginti su virintinės siūlės ilgiu (>30 m), ilgaamžiškumas viršys 25 metus.

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FAILURE RESISTANCE OF HIGH-CYCLE
LOADED WELDED JOINTS

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

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