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INTEGRITY ASSESSMENT OF AN AIRCRAFT CYLINDER ASSEMBLY WITH A CRACK

OCENA INTEGRITETE GLAVE VALJA Z RAZPOKO V LETALSKEM MOTORJU

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The repeatability of the air-cooled piston engine cylinder assembly failure due to a crack in the cylinder head, as well as its severity from the aspect of crew and passenger safety were the main motives for our research. In this paper an integrity assessment of a cylinder assembly with a crack was performed. By modeling cracks of different lengths in the cylinder head and considering the values of stress intensity factors and J-integral values at a given crack length on the one hand and determining the critical values of these fracture mechanics parameters on the other hand, the stability of the crack was examined. As part of the research, the dependence of the crack length on the stress intensity factor was established. The methodology proposed in this paper can be adapted to assess the integrity of other similar structural elements.

Keywords: crack, aircraft cylinder head, stress intensity factor, integrity assessment

V članku je opisana raziskava ponavljajočih se poškodb na zračno hlajenih letalskih motorjih zaradi pojava razpok v glavi motorja. Varnosti letalske posadke in potnikov je bil motiv za izvedbo preiskave nastalih razpok. Avtorji opisujejo oceno integritete letalskega motorja s prisotno razpoko na cilindru. Z modeliranjem razpok različnih dolžin na glavi cilindra so določili vrednosti faktorja intenzitete napetosti in *J*-integrala za dano dolžino razpoke. Po drugi strani so na osnovi poznavanja kritičnih vrednosti lomno mehanskih parametrov ocenili stabilnost razpoke oziroma nevarnost za njeno nenadzorovano napredovanje. V raziskavi so določili tudi vpliv dolžine razpoke na faktor intenzitete napetosti. Avtorji v raziskavi ugotavljajo, da se predlagana metodologija lahko prilagojena uporabi za oceno integritete drugih podobnih strojnih oziroma strukturnih elementov.

Ključne besede: razpoka, glava valja v letalskem motorju, faktor intenzitete napetosti, ocena integritete

1 INTRODUCTION

The research in this paper includes an integrity assessment of a Lycoming-IO-360-B1F aircraft air-cooled piston-engine cylinder assembly which failed after 1389 h due to a crack occurrence in the cylinder head[1–4] (**Figure 1**).

Based on the reports from the competent aviation authorities of countries around the world, there have been as many as 47 such failures of conventional air-cooled engines.[5,6] In this paper cracks of different lengths in the cylinder head were modeled. The values of the stress intensity factor and J-integral were obtained and compared with the critical values of the mentioned parameters. Based on this, the crack stability was examined and the integrity of the cylinder assembly was estimated.[7–13] The influence of the crack length in the cylinder head on the value of the stress intensity factor was determined. A cylinder head is made of aluminum casting alloy of grade 242.0. In previous research, necessary mechanical properties of this material were experimentally determined at room and elevated temperature[14] and a structural analysis of the cylinder assembly exposed to a combined thermomechanical load was performed.[15] This research is of great importance, given that the literature is very scarce on the data related to aluminum casting alloy of grade 242.0 and the analysis of its elements. The results obtained can be used for further research in the field of fracture mechanics and fatigue related to the problem of crack occurrence and failure of the structural elements made of the above material, and also of other materials.

2 EXPERIMENTAL PART

This section presents a numerical simulation of a compact-tension (CT) specimen tensile test at elevated temperature using Ansys Workbench. Fracture toughness can be defined as the ability of a structure with a crack to withstand the load to which it is exposed without failure, i.e., fracture toughness is a measure of the resistance of a material to crack propagation.[16] Fracture occurs when the stress intensity factor exceeds the critical value, that is the fracture toughness, K_C. In order to determine the crit-

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Figure 1: Crack in the cylinder head[2]

ical value of the stress intensity factor, the tensile strength of the aluminum casting alloy of grade 242.0 at room and elevated temperature was first defined.[17]

2.1 Tensile test

Determination of the tensile strength of the material was performed on a series of six specimens at room temperature. The dimensions and shape of the specimens were in accordance with standards B 557M[18] and ASTM E646-00.[19] The testing of the mentioned specimens was performed at the Center for Engineering Software and Dynamic Testing of the Faculty of Engineering, University of Kragujevac, on a SHIMADZU servohydraulic pulsator/shredder, type EHF-EV101K3-070-0. The test was performed at room temperature, including the control of displacement increment corresponding to the static load conditions for fracture and in accordance with standards B 557M and ASTM E646-00 (**Figure 2**).

Figure 2: Determination of the tensile strength at room temperature

Table 1 shows the experimentally determined values of the tensile strength stress for aluminum casting alloy of grade 242.0 at room temperature.[17]

Table 1: Experimentally determined values of the tensile strength for aluminum casting alloy of grade 242.0 at room temperature

Specimen designation	Tensile strength R_m (MPa)
1	205.7
2	198.4
3	192.5
4	186.7
5	201.3
6	190.8

The testing of static properties at elevated temperature was performed in order to determine the tensile strength of aluminum casting alloy of grade 242.0 at a temperature of 200 °C, corresponding to the operating temperature of the cylinder assembly, i.e., the cylinder head. The mentioned examination was performed at the Kemal Kapetanović Institute in Zenica. The tensile strength of aluminum casting alloy of grade 242.0 was determined on a series of three test specimens. The dimensions and shape of the specimens were designed to be in accordance with standard B 557M.

The testing of the tensile strength was performed on a universal hydraulic machine for static testing, Amsler, type 20 SZBDA (**Figure 3**). First, a test specimen was placed in the heating chamber of the above machine with the temperature set to 200 °C. After reaching the desired chamber temperature the test specimen was, according to

Figure 3: Determination of the tensile strength at elevated temperature

the instructions, heated for another 15 min in order to equalize the temperature field inside the specimen material.

Table 2 shows the experimentally determined values of the tensile strength for aluminum casting alloy of grade 242.0 at elevated temperature.[17]

Table 2: Experimentally determined values of the tensile strength for aluminum casting alloy of grade 242.0 at elevated temperature

Specimen designation	Tensile strength R_m (MPa)
1-E	143
2-E	115
3-E	131

Based on the obtained tensile-strength values for aluminum casting alloy of grade 242.0 at elevated temperature, which were in a range of 115–143 MPa, it can be seen that with the increasing temperature the tensile strength of the material is decreased compared to the values obtained with the test at room temperature.

2.2 Numerical determination of the critical value of the aluminum casting alloy 242.0 stress intensity factor

A CT specimen model was created using Design Modeler in Ansys Workbench. Specimen dimensions were defined by the ASTM E399-12 standard.[20] Based on the 3D model of the CT specimen, a finite-element mesh of the CT specimen, with tetrahedral finite elements having internodes, was created and then the mesh was chopped in the cracked area with the average size of the elements being 0.3 mm (**Figure 4**). The finite-element mesh thus generated consisted of 28293 elements and 47536 nodes.

Using the fracture-tool module in Ansys Workbench, the initial crack was defined. Also, the local coordinate system related to the crack tip was generated. In order to obtain the value of the stress intensity factor at elevated temperature, thermal and structural analyses were combined[17], i.e., the results of the thermal analysis were imported into the structural analysis. During the thermal analysis, a temperature field of 200 °C was applied to the CT specimen, corresponding to the cylinder-head operating temperature.[15]

For the numerical simulation, the back surface of the CT specimen was fixed. The upper and lower surfaces of the specimen were subjected to a load in the vertical direction so that the specimen was tension loaded to such an extent that the safety factor at the crack front had a value of approximately 1 (**Figure 5**). This was the moment when the measure of stress concentration in the vicinity of the crack tip had such a value that it was on the verge of causing its propagation, i.e., the obtained stress

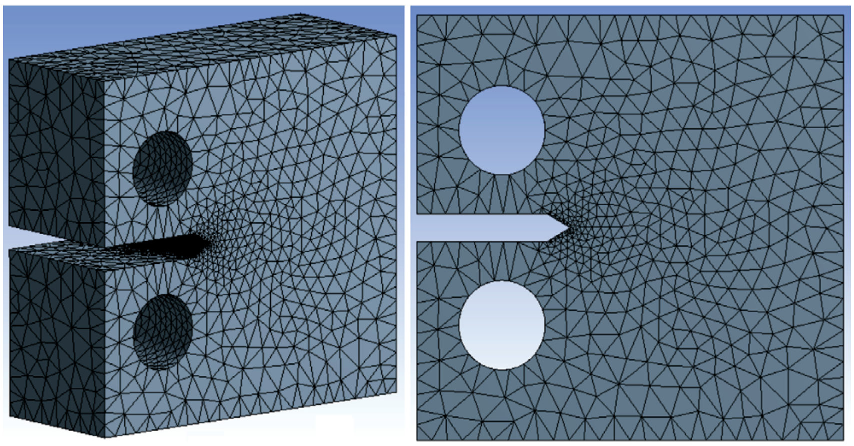

Figure 4: Finite-element mesh of the CT specimen

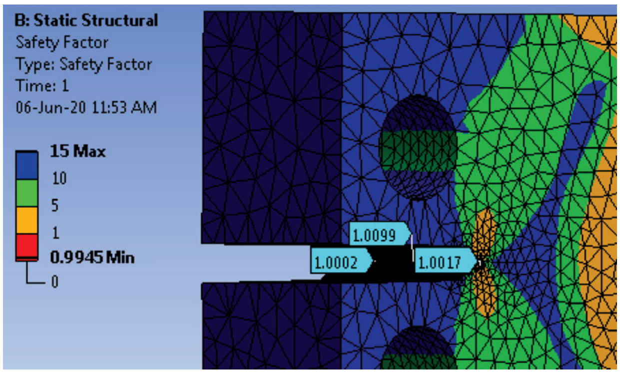

Figure 5: Safety factor at the crack front

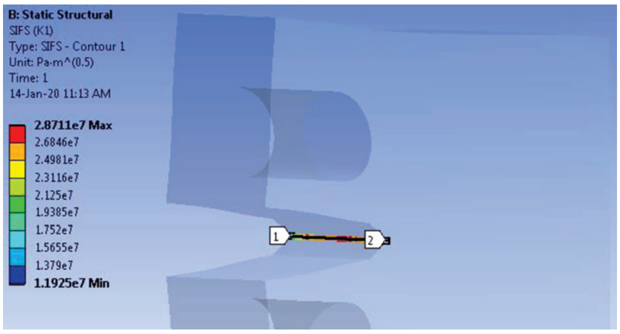

Figure 6: Values of the stress intensity factor for the first integration volume for Mode I of the crack opening

intensity factor in this case represented the critical value of the stress intensity factor.

The volumetric J-integral was used to define the stress intensity factor. This type of J-integral is suitable for application in the analysis of structures in which, in addition to mechanical, a thermal load also occurs and, unlike the contour J-integral, it gives more accurate results.[21] After the numerical simulation, the critical values of the stress intensity factor of the aluminum casting alloy of grade 242.0 for the six volumes of integration were obtained, as well as a value of the J-integral of 12234.7 J/m^2. **Figure 6** shows the results of the stress intensity factor for the first integration volume for Mode I of the crack opening.

Figure 7 shows a diagram of the critical values of the stress intensity factor for the CT specimen for six volumes of J-integral integration for Mode I of the crack opening.

For the analysis of crack stability determination discussed in the following section, the mean value of all integration volumes from **Figure 7** was adopted so that for Mode I of the crack opening, it is 16.25 MPa·m$^{1/2}$ representing the critical value of stress intensity factor of the aluminum casting alloy of grade 242.0.

3 DETERMINING CRACK STABILITY FROM THE ASPECT OF ITS FURTHER PROPAGATION

3D cracks were modeled in the cylinder head at the location where they appeared in practice. The crack lengths varied from 1 mm to 5 mm and, for each case, the stress intensity factor was determined. The obtained values of the stress intensity factor were compared with the critical value of the stress intensity factor, i.e., the stability of cracks was determined from the point of view of their further propagation. A number of papers related to the issue of structural analysis of crack propagation can be found in the literature.[22,23] Within the 3D model of the cylinder assembly, a local plane was formed, in which cracks of different lengths were modeled (**Figure 8**). This plane corresponded to the plane with the crack of the cylinder assembly that failed during flight.

When considering the stability of 3D crack propagation, the nodes along the crack front were observed. In order to avoid an error when calculating the J-integral, several integration volumes around the crack tip were defined.[23]

In the 3D model of the cylinder head, a 1-mm-long crack was modeled. After that, the finite-element mesh was defined. In order to analyze the stress state in the vicinity of the crack tip in more detail, the local coordinate system was set at the crack front and a radius of the sphere of integration of the J-integral of 3 mm was defined. Within this sphere, the finite-element mesh was

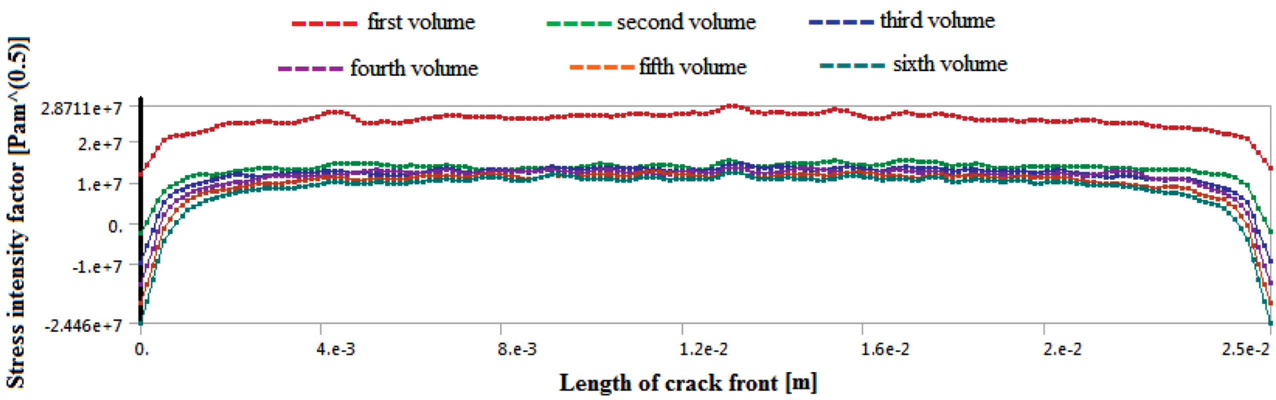

Figure 7: Diagram of critical values of stress intensity factor for Mode I of the crack opening

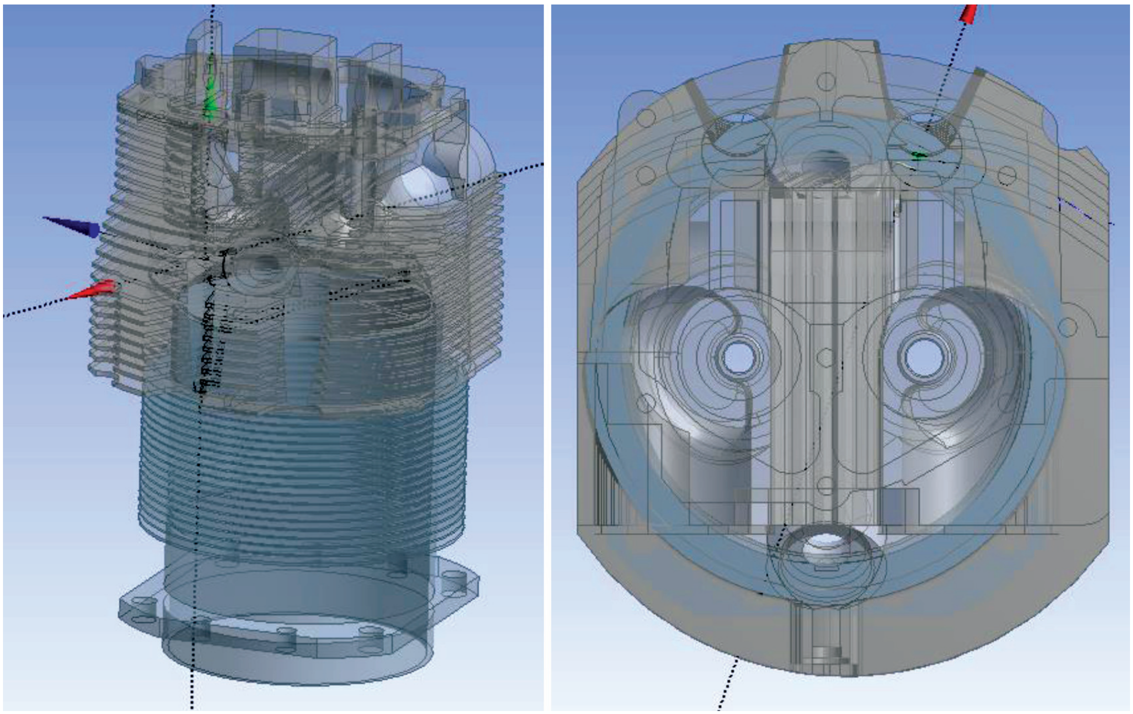

Figure 8: Local plane of the 3D crack on the cylinder assembly

chopped so that the average size of the tetrahedral finite elements with internodes was 0.1 mm (**Figure 9**).

The testing of the stability of the defined crack was performed under a thermomechanical load and boundary conditions defined in previous research.[15] **Figure 10** shows the lifetime of the cylinder head with a 1-mm-long crack.

It is clear that the minimum number of cycles to failure applies to the vicinity of the crack tip. The lifetime of the rest of the cylinder head ranges from 2.80×10^8 to 2.98×10^8 cycles, which corresponds to the lifetime of the cylinder head estimated at 3600 h[24], i.e., the number of cycles of 2.92×10^8 taking into account that one cycle implies one operating stroke of the engine, that is two full crankshaft revolutions which, based on the given nominal number of revolutions, last for 0.044 s.[17] Based on the analysis of the material fracture by the fracture tool module in Ansys Workbench, the stress intensity factor was determined, representing the measure of stress concentration in the vicinity of the crack tip. The stress intensity factor was obtained for the crack opening mode, i.e., Mode I of the crack opening. **Figure 11** shows the values of the stress intensity factor for the

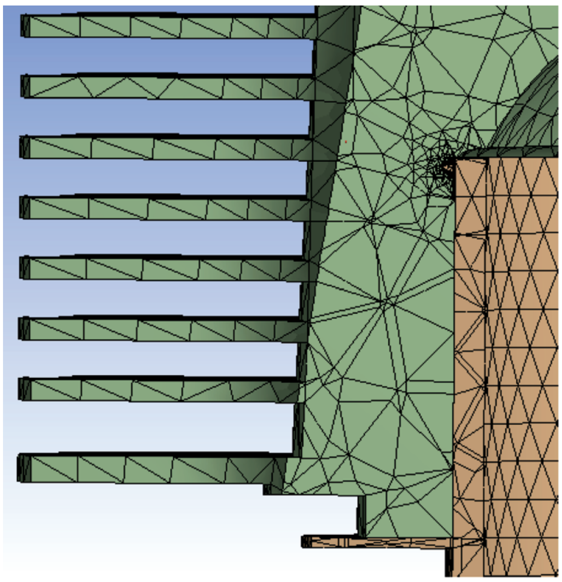

Figure 9: Finite-element mesh in the vicinity of a 1-mm-long crack

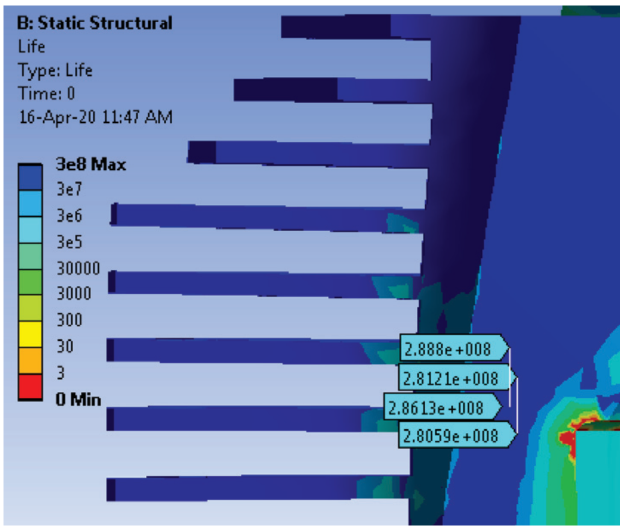

Figure 10: Lifetime of the cylinder head with a 1-mm-long crack

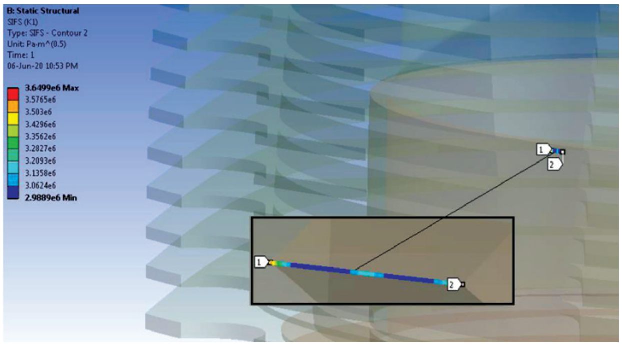

Figure 11: Stress intensity factor values for a 1-mm-long crack

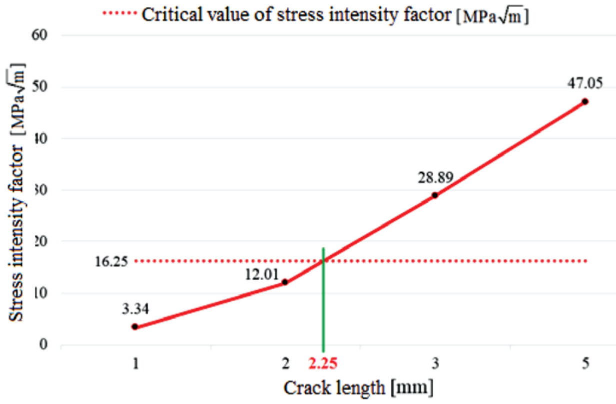

Figure 13: Dependence of the stress intensity factor on the crack length

1-mm-long crack for the second of the six integration volumes.

Figure 12 shows a diagram of the values of the stress intensity factor for six analyzed volumes of integration. For further crack stability analysis, a mean value of all integration volumes of 3.34 MPa·m$^{1/2}$ was adopted.

Using the fracture tool module, the values of the J-integral in the case of a 1-mm-long crack were obtained. All six volumes of integration were analyzed. A mean value of the J-integral of 94.76 J/m^2 was adopted for further analysis of the considered crack stability. The same procedure was performed for (2, 3 and 5) mm-long cracks.

In order to test the resistance to breakage of the cylinder head, the values of stress intensity factors for cracks of different lengths were investigated. The dependence of the stress intensity factor on the crack length is shown in **Figure 13**.

From the above diagram, it can be seen that with the crack growth from 2 mm onwards the value of the stress intensity factor increases. The values of the stress intensity factor in the presence of 1-mm and 2-mm-long crack in the cylinder head are 3.34 MPa·m$^{1/2}$ and 12.01 MPa·m$^{1/2}$, respectively. Taking into account that the critical value of the stress intensity factor is 16.25 MPa·m$^{1/2}$ it is concluded that a crack length of 2.25 mm is considered the critical crack length so that the cylinder head is a stable structure in terms of further crack propagation during operation in the presence of a crack length below 2.25 mm.

4 RESULTS AND DISCUSSION

The numerically obtained value of the stress intensity factor for the 1-mm-long crack is 3.34 MPa·m$^{1/2}$, while the value of the J-integral is 94.76 J/m^2. Taking into account the critical value of the stress intensity factor of 16.25 MPa·m$^{1/2}$, and the critical value of the J-integral of 12234.7 J/m^2, it is concluded that a 1-mm-long crack in the cylinder head can be considered stable with regard to further propagation. Based on the numerical analysis of the cylinder assembly with a crack in the cylinder head, it was found that the value of the stress intensity factor for a 2-mm-long crack is 12.01 MPa·m$^{1/2}$, while the value of the J-integral is 1200.5 J/m^2. If we take into account the critical value of the stress intensity factor of 16.25 MPa·m$^{1/2}$, and the critical value of J-integral of 12234.7 J/m^2, it can be concluded that in the case of a crack length of 2 mm the values of stress intensity factor and J-integral are below the critical values so that the crack of the stated length in the considered construction can still be considered stable.

The value of the stress intensity factor in the case of a 3-mm-long crack is 28.89 MPa·m$^{1/2}$ where the value of the J-integral is 3142.1 J/m^2. Comparing the obtained

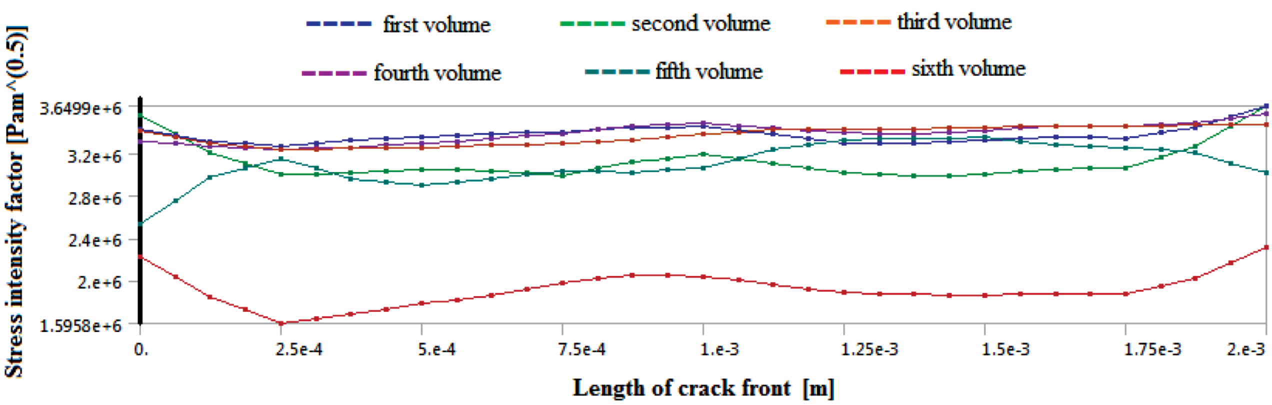

Figure 12: Diagram of values of the stress intensity factor for a 1-mm-long crack

values with the critical values of the stress intensity factor of 16.25 MPa·m$^{1/2}$ and the J-integral of 12234.7 J/m^2, it is concluded that in the case of a 3-mm-long crack the value of the stress intensity factor is higher than the critical value. Based on the above, a 3-mm-long crack in the considered construction cannot be considered stable.

The numerical analysis of the cylinder assembly with a 5-mm-long crack in the cylinder head showed a value of the stress intensity factor of 47.05 MPa·m$^{1/2}$ and a value of the J-integral of 17284.3 J/m^2. Compared with the critical values of the stress intensity factor of 16.25 MPa·m$^{1/2}$ and the J-integral of 12234.7 J/m^2, it is concluded that in the case of a 5-mm-long crack the values of the stress intensity factor and J-integral are much higher than the critical values, indicating an uncontrolled crack growth.

5 CONCLUSIONS

The research reported in this paper refers to determination of the critical value of the stress intensity factor for aluminum casting alloy of grade 242.0 as the constituent material of the cylinder head of an aircraft piston engine that failed due to a crack in the cylinder head. For cracks of different lengths, values of the stress intensity factor were obtained and compared with the critical value; the crack stability, i.e., the integrity of the cylinder assembly was assessed. Within the simulation, the stress intensity factor for Mode I of the crack opening (the opening mode) was considered. This crack mode is characterized by a force that separates the crack surface by acting perpendicularly to the crack plane. The research in the paper shows that the critical crack length is 2.25 mm and that the analyzed cylinder assembly can be considered a stable structure in the presence of a crack length less than 2.25 mm. The obtained results are of great importance for further research in the field of fracture and fatigue mechanics related to the problem of cracking and failure of structural elements made of aluminum casting alloy of grade 242.0, and also of other materials. As the issues discussed in this paper are very complex with respect to the nature of the load where mechanical and thermal loads are present, it is important to emphasize that this methodology is comprehensive and adaptable when assessing the integrity of any structural element.

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