Katarina Čolić[1], Nenad Gubeljak[2], Meri Burzić[1], Aleksandar Sedmak[3], Tamara Mijatovic[4], Aleksa Milovanović[1]

ANALYSIS OF FRACTURE BEHAVIOUR OF THIN S316L STAINLESS STEEL PLATES

ISPITIVANJE PONAŠANJA PRI LOMU TANKIH PLOČA OD NERĐAJUĆEG ČELIKA S316L

Originalni naučni rad / Original scientific paper
UDK /UDC: 669.14.018.8:539.42
620.172.24:669.14.018.8
Rad primljen / Paper received: 17.11.2017

Adresa autora / Author's address:
[1] University of Belgrade, Innovation Centre of the Faculty of Mechanical Engineering, Belgrade, Serbia, email: kbojic@mas.bg.ac.rs
[2] University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia
[3] University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia
[4] University of Belgrade, Faculty of Technology & Metallurgy, Belgrade, Serbia

---

Keywords
- fracture mechanics parameters
- stainless steel
- stress intensity factor (SIF)
- thin plates

Abstract

In this paper are presented experimental analyses of the behaviour of 316L stainless steel in regard to fracture, according to standard methods of investigation on modified tensile C(T) specimens. The S316L alloy is selected for this experimental analysis, often used in many engineering applications. This alloy is not prone to corrosion as other austenitic steels with a higher share of carbon. Results show that material behaviour, in terms of dependence of stress intensity factor (SIF) value relative to thickness of the plate, is necessary to assume with a different model when the specimen thickness is very small. Application of standards in the field of investigation of material resistance to fracture allow simultaneous determination and connection of several fracture mechanics parameters.

Ključne reči
- parametri mehanike loma
- nerđajući čelik
- faktor intenziteta napona
- tanke ploče

Izvod

U okviru prikazanih eksperimentalnih ispitivanja istraženo je ponašanje prema lomu 316L nerđajućeg čelika primenom standardnih metoda ispitivanja na modifikovanim zateznim C(T) epruvetama. Za ovu eksperimentalnu analizu je odabrana legura S316L, jer se ona vrlo često koristi u mnogim inženjerskim primenama, i za nju je karakteristično da nije sklona koroziji kao drugi austenitni čelici sa većim sadržajem ugljenika. Rezultati pokazuju da je ponašanje materijala, u smislu zavisnosti vrednosti faktora intenziteta napona u odnosu na debljinu ploče, potrebno pretpostaviti drugačijim modelom kada su debljine epruveta veoma male, a da je primenom standarda iz oblasti ispitivanja otpornosti materijala na lom, moguće istovremeno odrediti i povezati nekoliko parametara mehanike loma.

INTRODUCTION

Conventional criteria of failure are developed to explain failure of strength on bearing structures, which can be roughly classified as ductile and brittle. This division into brittle and ductile fracture refers to two boundary cases which are of only theoretical importance, because in practice, fractures are preceded by both elastic and plastic deformations. These mixed fractures are characterised by toughness which could be assumed as a measure of capability of the material and structural part to sustain the development of brittle fracture, /1-3/. Origin of brittle fracture is almost certain to be caused by the existence of cracks, notches or stress concentrators. Stresses developed in those areas are the most important factor in determining whether the crack will grow under the influence of acting load.

Theoretical considerations of fracture mechanics allow to define a term of stress intensity factor (SIF) with whom stress intensity in the vicinity of the crack tip can be determined, /1-3/. This value can be utilized for assessing the rate of resistance to fracture, taking into mind that reaching the critical value of this factor allows unstable crack growth.

All materials applied in engineering can be assumed to have inherent defects, such as microcracks. Failure occurs when the crack length reaches critical value, causing catastrophic malfunction, /3-5/. Values of fracture resistance (K_{IC}) can be measured with standard test protocols, such as ASTM E399. In fracture mechanics, crack transmission caused by fatigue in biomaterials is studied: a) for long cracks (> 3 mm) using C(T) specimens; and b) for short cracks (1-250 μm) using microindentation techniques on servo-hydraulic machine.

Experimental investigations presented here cover the analysis of metal material behaviour in regard to fracture with application of specimens containing a crack loaded in tension. In the first instance, the goal is to determine the character of this process in the case of a thin plate problem with the use of standard fracture mechanics settings.

Stainless steel S316L and titanium alloy are selected as a suitable material for manufacturing temporary implants, such as bone plates, screws and pins, /6, 7/. Experimental research is performed using modified compact specimens for tension C(T) according to standard, extracted from S316L 2 mm thick plates. Symbol '316' classifies the material as austenitic, 'L' signifies low carbon concentration, since carbon content has to remain low to suppress carbide accumulation (chrome-carbon) on grain boundaries, /8/.

Mechanical properties of stainless steels rely on the applied treating process and it is possible to attain versatile properties. With heat treatment, softer materials are obtained, and with the cold drawing process – a higher strength and hardness are attained. All steels are iron and carbon alloys, and may contain chrome, nickel and molybdenum, /8/. Manganese, phosphorus, sulphur, nitrogen and silicon can be found in traces. Carbon and other elements in the alloy influence mechanical properties of the steel, changing its microstructure.

Stainless steels, i.e. steels resistant to corrosion, are made with an addition of over 12% chrome, which results in the formation of a thin layer of a chemically stable and passive oxide film. This film forms and regenerates in the presence of oxygen. Generally, stainless steel does not corrode. However, in saline and chloride environments, spot corrosion occurs, and when dissolved oxygen reacts with chlorine ions, this type of corrosion accelerates faster.

Nickel is the most important element of the alloy which stabilizes the austenitic form of iron and contributes to the increase of resistance to corrosion. Molybdenum increases resistance to corrosion as well by forming a passive layer. Carbon and nitrogen are soluble in iron and contribute to strength increase. Carbon also has a high affinity to chrome, forming chrome carbides. This leads to the precipitation of carbon in areas around carbides. Because of incorporating into carbides, the chrome concentration decreases, and thereby the resistance to corrosion of steel in the vicinity of carbides. For enhancing the resistance to corrosion, it is necessary to reduce the carbon share.

MATERIALS AND METHODS

Standard fracture mechanics tests are applied on modified C(T) specimens according to ASTM (International Standard Test for Materials) standards E1820-08 and E399-06, /9, 10/. Experiments were performed at the Laboratory for Machine Elements and Structures, the Faculty of Mechanical Engineering, University of Maribor, Slovenia.

In accordance with limited sizes of available samples and the idea to investigate the fracture behaviour of thin plates, the compact specimens for tension are selected, defined by ASTM standard E399-06, i.e. ASTM E1820-08 (Fig. 1). Compared to three-point bending specimens, the C(T) specimen allows significant saving in material as well as application of a lower force.

Test specimens have been extracted from 2 mm thick plates of S316L steel. They are shaped as C(T) samples containing a notch only on one side and a fatigue crack.

Modified specimens with recommended sizes defined by the standard are shown in Fig. 2.

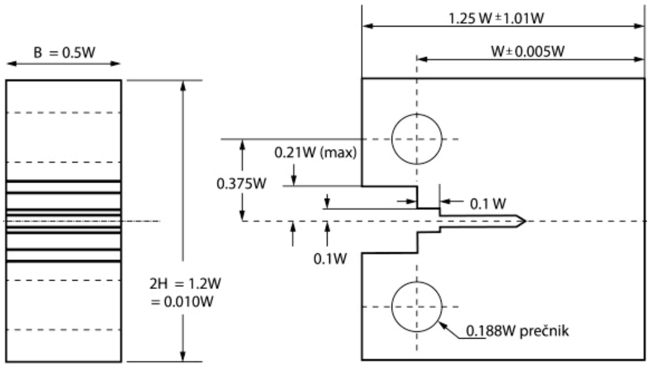

Figure 1. CT specimen, /10/.

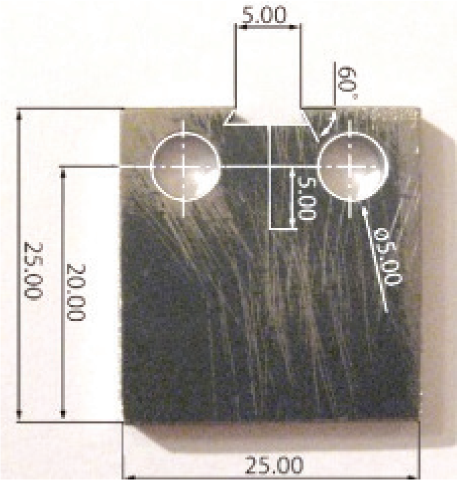

Figure 2. Sizes of the C(T) specimen for fracture mechanics tests.

In accordance with standard procedure, at first the preparation of specimens is acquired, namely fatigue cracks are created on compact tension specimens. The fatigue crack is required to create a plane strain condition. In the vicinity of the fatigue crack tip the desired stress field can be acquired in a reproductive way, but under the conditions provided by the appropriate fatigue crack. In the crack initiation tests, the specimens are exposed to a certain number of straining cycles in order to initiate the fatigue crack. Crack growth is monitored to the size enough for failure. Specimens are produced by electrical discharge machining (EDM), and the fatigue crack (cca. 5 mm) is created by cyclic loading from the servo-hydraulic machine.

Assessment of the nominal limit force P_f, i.e. maximal force for fatigue initiation is determined according to:

$$P_f = \frac{0.4 B b_0^2 R_T}{2W + a_0}$$

where: B –specimen width (mm); b_0 –ligament length (mm); R_T –effective yield strength (MPa), according to:

$$R_T = \frac{R_{p0.2} + R_m}{2}$$

where: $R_{p0.2}$ –yield strength (MPa); and R_m –ultimate tensile strength (MPa). Fatigue crack generation is performed on an 'Instron' servo-hydraulic machine.

The standard specimen with a crack is loaded in a precisely determined fashion, according to ASTM. In the course of the experiment, the loads and relative displacement of two points are recorded, symmetrically located at opposite ends of the crack plane. Tests on specimens with a fatigue crack are performed with a tensile testing machine, and the load is plotted in a form of force.

Crack opening serves as a deformation rate, i.e. the characteristic rate of crack opening displacement measured with a special extensometer. During the test, loads and displacements are recorded using a data acquisition program of the tensile testing machine. In accordance with specimen dimensions, the maximal loads in this experiment have been adopted to be 4.5 kN.

Analysis is performed on the electromechanical tensile testing machine ‘Instron’. Specimen setup is displayed in Fig. 4. The specimen is placed on a tensile testing tool, and since thin specimens are used, they are clamped so to prevent buckling of the specimens. All experimental research in this paper is performed at room temperature (20°C).

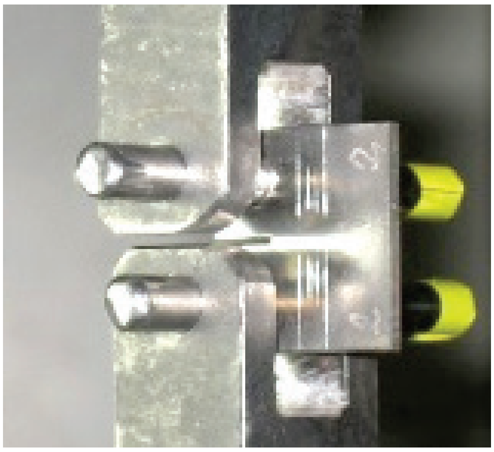

Figure 4. C(T) specimen setup on the ‘Instron’ machine.

RESULTS

Chemical composition of the specimens used in this experimental analysis are determined by gravimetric procedure and shown in Table 1. Tests for determining tensile characteristics are conducted at room temperature according to relevant ISO specification. Mechanical properties of S316L steel are shown in Table 2.

After the completion of fracture mechanics tests, results obtained are determined according to calculations defined by ASTM E399-06. Due to the limited space, further results are shown for calculations performed on two specimens. Based on data gathered from the software and from the tensile testing machine, diagrams of force F–crack tip opening δ (Crack Mouth Opening Displacement, CMOD) are plotted. Force–CMOD diagrams after result processing are shown in Fig. 5.

Table 1. Chemical composition of tested S316L steel.

Chemical composition, mass. %							
C	Mn	P	S	Si	Ni	Cr	Mo
0.03	1.95	0.25	0.03	0.70	12.5	17.5	3.0

Table 2. Tensile properties of S316L steel alloy.

Sample	Yield strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation A (%)
SAMPLE A			
A-1	267	614	69
A-2	267	614	69
A-3	275	586	63
	270	605	67
SAMPLE B			
B-1	273	587	70
B-2	276	592	67
B-3	273	587	70
B-4	276	592	67
	275	590	69

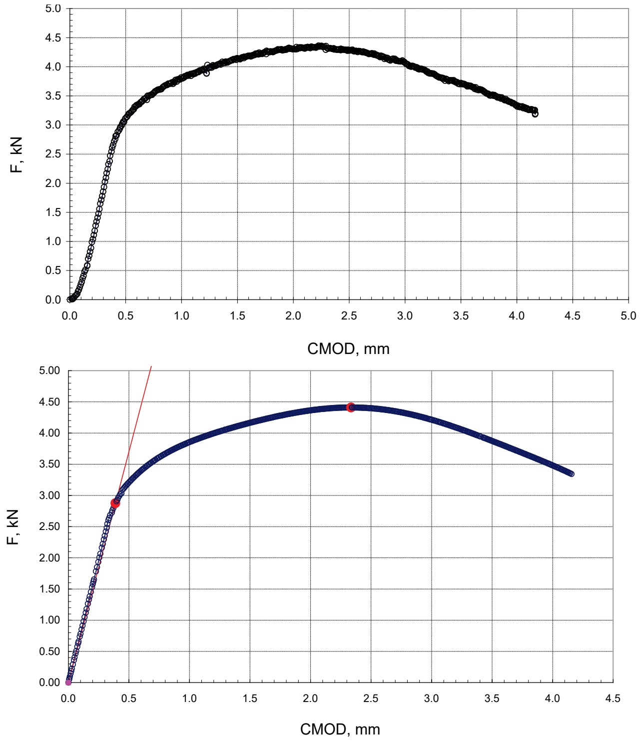

Figure 5. Force F-CMOD for specimens S316L/1 (top), and S316L/2 (bottom).

Parameters according to standard defined procedures are shown in tabular form for each specimen. Results for specimen 1 are shown in Table 3, and for specimen 2 in Table 4. Final results of the determined stress intensity factor are shown in Table 5 for specimen 1, and in Table 6 for specimen 2.

Table 3. Calculation parameters determined for specimen S316L/1.

F_{max} (N)	F_Q (N)	F_{max}/F_Q	a/W	$f(a/W)$	B (mm)	B_N (mm)	W (mm)
4.362	2.881	1.514	0.250	4.925	2	2	20

Table 4. Calculation parameters determined for specimen S316L/2.

F_{max} (N)	F_Q (N)	F_{max}/F_Q	a/W	$f(a/W)$	B (mm)	B_N (mm)	W (mm)
4.410	2.875	1.534	0.250	4.925	2	2	20

Table 5. Stress intensity factor, K_I (MPa√m), specimen S316L/1.

K_{Ic} (MPa·m$^{0.5}$)	R_T (MPa)	E (MPa)	$2.5\cdot(K_Q/R_{p0.2})^2$ (mm)
51.376	432.5	210 000	34.315
K_Q			does not satisfy dimension criterion

Table 6. Stress intensity factor, K_I (MPa√m), specimen S316L/2.

K_{Ic} (MPa·m$^{0.5}$)	R_T (MPa)	E (MPa)	$2.5\cdot(K_Q/R_{p0.2})^2$ (mm)
51.269	432.5	210 000	34.173
K_Q			does not satisfy dimension criterion

Considering that the dimension criterion in determining the critical stress intensity factor is not satisfied, it is noted that the experimentally obtained stress intensity factor values correspond to the K_Q parameter. Calculations of other fracture mechanics parameters are determined by application of the BS 7448-3/2005 and ASTM E1820-08 standards, /11, 12/.

Analysis of the diagram of F-CMOD defines relevant maximal values, $F_{\max}$ and CMOD$_{\max}$. Using the curve fitting procedure values of compliance coefficient C_1 are calculated, according to:

$$C_1 = \frac{d\,\text{CMOD}}{dF}.$$

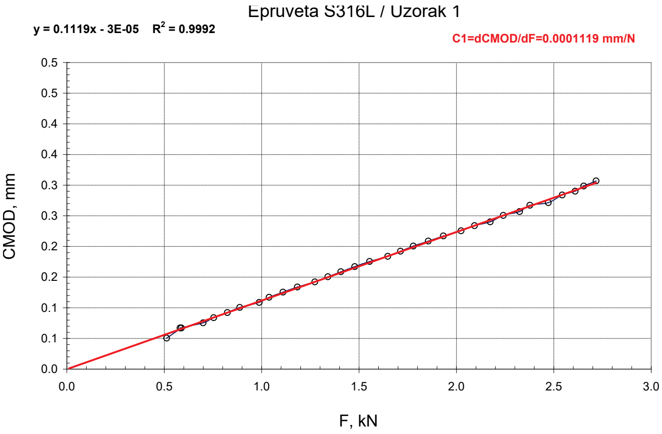

Figure 7. Determination of compliance coefficient C_1.

The procedure for determining this value for one specimen is displayed in Fig. 7 according to:

$$\delta_{(BS)} = \frac{K^2(1-\nu^2)}{2ER_{p0.2}} + \frac{r_p(W-a_0)V_p}{r_p(W-a_0)+a_0+z},$$

where the required value is determined as

$$V_p = \text{CMOD}_{\max} - C_1F.$$

Values of elastic and plastic surface are determined by ASTM E1820-08 standard procedure. Figure 8 shows these values for one of the specimens. Calculated parameters are shown in Table 7.

By determining the necessary parameters according to ASTM, the procedure for CMOD assessment is implemented according to

$$\text{CTOD}_{(\text{ASTM})} = \text{CTOD}_{\text{el}} + \text{CTOD}_{\text{pl}}.$$

Using the defined procedures, the following fracture parameters are obtained, shown in Table 8. Typical fractured surfaces of broken specimens are shown in Fig. 9.

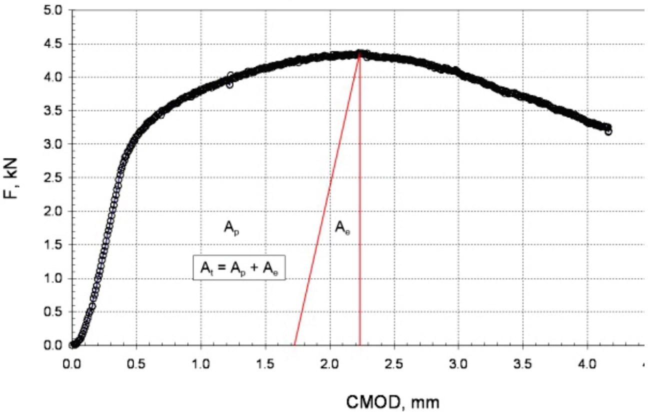

Figure 8. F-CMOD elastic and plastic region for one of the specimens.

Table 7. Obtained results of the elastic and plastic surfaces.

Specimen S316 L	$F_{\max}$ (N)	CMOD$_{\max}$ (mm)	C_1 (mm/N)	A_t (Nmm)	A_e (Nmm)	A_p (Nmm)
Sample 1	4.362	2.226	1.11900E-04	7.586	1.065	6.522
Sample 2	4.410	2.341	1.27800E-04	8.397	1.243	7.154

Table 8. Obtained fracture mechanics parameters.

Specimen S316 L	BS				ASTM				
	V_p (mm)	CTOD$_{\text{el}}$ (mm)	CTOD$_{\text{pl}}$ (mm)	CTOD$_{\text{t}}$ (mm)	J_{el} (N/mm)	CTOD$_{\text{el}}$ (mm)	J_{pl} (N/mm)	CTOD$_{\text{pl}}$ (mm)	CTOD$_{\text{t}}$ (mm)
Sample 1	1.738	0.045	0.948	0.993	24.995	0.023	31.012	0.029	0.052
Sample 2	1.777	0.046	0.969	1.016	25.548	0.024	34.020	0.032	0.056

Figure 9. S316L specimen after fracture (left); fractured surface (right).

DISCUSSION

Assessment of the resistance to crack development essentially depends on whether the plane stress or the plane strain state is established in the observed area of the structural element. In the area of elastic load, cracks cause stress concentration with local stress increase above yield strength, i.e. to fracture. To a certain limit, fracture toughness highly depends on the material thickness. The fracture process in thin plates is governed by plane stress state, since the plate is too thin for stress to spread over that dimension. With thick plates, the plane strain state is dominant ($\sigma_z \neq 0$) when K_{IC} becomes a material property.

The minimal size criterion that needs to be satisfied for accomplishing the plane strain condition is not easy to attain considering that it is assumed on the basis of experience. Likewise, there is a limit in the material size required to produce specimens. Comparing the experimental results with the K_{IC} data from reference standard literature, and on the basis of previous research, /11, 12/, we can consider that the K_C varies with thickness of tested sample, B, and that the dependence of K_C in regard to plate thickness can be presented with a reference diagram. It can be concluded that within a selection of very thin specimens, the values of stress intensity factor are less than critical for the specified material. Therefore, it is possible to assume that with further reduction of thickness, a further reduction of stress intensity factor occurs, i.e. the behaviour of the material in the area of small plate thickness has to be presumed with a different model.

Slant fracture occurs at plane stress state (traces of shear at angle of about 45°) as an indication of partially ductile fracture, while in plane strain condition the square fracture surface appears as an indication of brittle fracture. Any combination of these types of fracture leads to a surface of combined fracture, which has occurred on specimens during testing.

Since the requirements for conditions of plane strain state

$$B \geq 2.5\left(\frac{K_{\mathrm{Ic}}}{R_{p0.2}}\right)^2$$

are not satisfied, after defining experimental values of K_Q, the determination of CTOD_C or J_C parameters are acquired. They can be set by standard tests according to ASTM E1820.

Although the CTOD parameter is experience based, it is gladly accepted because even in complicated problems it is easily determined and gives good results. In the area of small scale yielding (SSY) it is possible to connect it with K_I:

$$\delta = \frac{K_{\mathrm{I}}^2}{mE\sigma_T} = \frac{G}{m\sigma_T}$$

In order to determine critical CTOD using BS standard it is necessary to fortify the beginning of crack growth, i.e. to determine the relevant value of δ_t by using the definitions recommended according to standard. The used value is δ_m, i.e. the value δ_t when reaching the highest load in the plasticity zone. It is necessary to bear in mind that in mentioned standards there are differences not only in the interpretation of the beginning of crack growth and crack-jump, but in other details as well, for example in defining limit values of parameters.

In terms of problems that lack the physical basis in the introduction of parameter CTOD, it is understandable to introduce yet another parameter of elastic-plastic fracture mechanics, i.e. the J integral. It should be emphasized that this parameter is theoretically based, and its calculation is highly justified. Using ASTM procedure, the values of elastic and plastic share are determined. In Table 9, the comparative calculated values are presented. The total J parameter is obtained by summation of these two shares.

Table 9. Final values of estimated J integral.

Specimen	J_{el} (N/mm)	J_{pl} (N/mm)	J (N/mm)
S316 L sample 1	24.995	31.012	56.007
S316 L sample 2	25.548	34.020	59.568

It is possible to compare results acquired by demonstrated experimental research with the research results of fracture mechanics parameters on similar specimens of the same material which had excluded the utilization of three-dimensional optical measurement system, /7/. Estimation of the required parameters and the assessment of crack tip opening values by standard methods, and also the application of stereometrics monitoring of crack growth in the material, shown in /7/, indicate different values for CTOD. Using the ASTM standard procedure, significantly smaller values of this parameter are determined in comparison to values defined by the BS procedure, or by using optical measurements. For steel specimens with higher δ_t parameter, values are obtained using the BS procedure in regard to the optical camera application. Certain values using stereometrics procedure for measuring CTOD$_{F\max}$ are 0.134 and 0.237 mm for steel specimens, /7/. The application of stereometrics monitoring of the crack tip opening values during crack growth are acquired. Measured values of the initial size at the moment before specimen fracture for steel are 1.088 and 2.600 mm, /7/.

Except from the complexity of fracture toughness testing procedure, the final result depends on several other factors which can produce substantial total error, although K_{IC} is measured directly by definition. Errors can be up to 3% in the test (inaccuracy of the measuring instruments and incorrect positioning of specimens); 5% in reading of the force F_Q, and 3% when measuring crack length, which in total can generate an error above 10%.

CONCLUSIONS

There are many common features in the experimental determination of fracture mechanics parameters especially when measuring their critical values, i.e. material properties. The latest standard in this field, ASTM E1820-08, serves as a confirmation of this statement. The mentioned standard unifies the fracture toughness measurement as a critical value of any of the three fundamental fracture mechanics parameters - K_{IC}, CTOD$_{IC}$ or J_{IC}. K_{IC} is determined directly by definition, and standard measurement procedures for CTOD and J integral are based on indirect, i.e. approximate relations - in the first case on a relation of CTOD with CMOD, and in the other case on a relation of J integral with the surface beneath the F-δ curve.

The obtained fracture mechanics parameters of metallic biomaterials confirm that by applying contemporary standards from the field of analysis of material resistance to fracture, it is possible to simultaneously determine and link few fracture mechanics parameters. Using the same specimens and test procedures it is possible to determine values of the stress intensity factor, crack tip opening displacement, and J integral for each of the examined biomaterials. Due to different definitions of CTOD and utilization of different standards, various values of this parameter can be attained.

Application of non-contact measurement methods for deformation fields and fracture parameters provides good results in investigating the behaviour of materials used for complicated geometries in the presence of cracks in terms of CTOD parameter determination. This parameter has no defined theoretical background, but it is necessary, by using modern standards in this field, to calculate the characteristic parameters of fracture mechanics.

Analysing the experimental results, it is concluded that the behaviour of the material, in terms of dependence of stress intensity factor value relative to plate thickness must be assumed with a different model when specimen thickness is very small.

Analysis of fracture mechanics parameters and the fracture behaviour of stainless steel for thin plate manufacture and its engineering use is of substantial importance for the integrity and structural life assessment, but mechanisms that lead to crack appearance are related to various influential factors.

ACKNOWLEDGEMENT

This work is a result of the research financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, project no. TR35040.

REFERENCES

1. Anderson, T.L., Fracture Mechanics: Fundamentals and Applications, 3rd ed., CRC Press, London, 2005.
2. Sedmak, A., Primena mehanike loma na integritet konstrukcija (in Serbian: *Fracture Mechanics Application to Structural Integrity*), University of Belgrade, Faculty of Mech. Engng., Belgrade, 2003.
3. Pluvinage, G., Fracture and Fatigue Emanating from Stress Concentrators, Springer, Dordrecht, 2004.
4. Niinomi, M. (2007), *Fatigue characteristics of metallic biomaterials*, International Journal of Fatigue, 29(6): 992-1000. doi:10.1016/j.ijfatigue.2006.09.021
5. Sedmak, A., Čolić, K., Burzić, Z., Tadić, S. (2010), *Structural integrity assessment of hip implant made of cobalt-chromium multiphase alloy*. Struc. Integ. & Life, 10(2):161-164.
6. Milne, I., Ritchie, R.O., Karihaloo, B. (eds.): Comprehensive Structural Integrity, Vol.9: Bioengineering. Elsevier Ltd, Oxford, 2003.
7. Čolić, K., Sedmak, A., N. Gubeljak, et al. (2012), *Experimental analysis of fracture behaviour of stainless steel used for biomedical applications*, Struc. Integ. & Life, 12(1):59-63.
8. Metal Handbook, Tenth Ed. – Vol.1 & Vol.2, Properties and Selection: Iron, Steel, and High- Perf. Alloys, ASMI, Materials Park, Ohio, 2005.
9. ASTM E1820-08, Standard Test Method for Measurement of Fracture Toughness.
10. ASTM E399-06, Standard Test Method for Linear-Elastic Plane Strain Fracture Toughness of Metallic Materials.
11. Schwalbe, K.H., Basic engineering methods of fracture mechanics and fatigue, GKSS - Research Center, Geesthacht, 2001.
12. Čolić, K., Analiza otpornosti na lom biomaterijala za veštački kuk (in Serbian: *Fracture resistance analysis of artificial hip biomaterial*), doctoral thesis, University of Belgrade, Faculty of Mechanical Engineering, 2013.