

Full field deformation analysis applied to improved CTOD concept

Damir SEMENSKI¹, Nenad GUBELJAK², Dražan KOZAK³, Petar ČURKOVIĆ¹

¹University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia

²University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia

³University of Josip Juraj Strossmayer in Osijek, Mechanical Engineering Faculty, Slavonski Brod, Croatia

Abstract – Highly precise measuring of 3D displacements in the vicinity of the crack tip by using object grating method enables the visualization of deformation and characterization of the crack propagation process.

Modified CTOD concept based on deformations analysis along the set of lines shifted in direction of the crack propagation is introduced. Through the visualization it provides comprehension of specimen's behavior in conditions of high stress concentration and large displacements.

Object grating method is advantageously used to analyze two specimens with initial crack in a macroscopic heterogeneous welded joint. The crack propagates from the over-match (OM) material towards the under-match (UM) material or vice versa, when the crack propagates in the opposite direction.

The results of the experiments show the potential of object grating method for acquiring deformation field around the crack tip because is enabled to observe the fracture behavior in heterogeneous material structure during the crack propagation.

Keywords: grating method, crack propagation, CTOD.

1. INTRODUCTION

Traditional method for characterization of the crack propagation is limited to one-parameter measurements of CMOD and CTOD; as shown in Fig. 1.

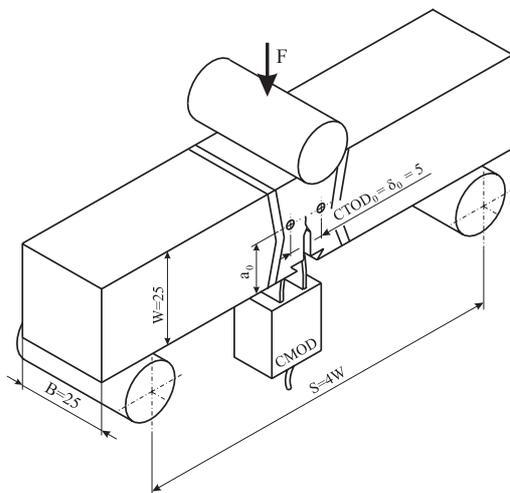


Fig. 1. CTOD fracture toughness specimen

The optical object grating method, on the contrary, provides area based displacement measurement. Results are delivered in the form of local displacements or strain tensor, suitable for further analysis (stress field computation, J -integral calculation) and for the verification of the finite element analysis, due to the full field deformation information. Even though, this method is rarely used in practice because of standard's description for remote clip-gauge measurement, expensive equipment, delicacy of the process and additional computational post-analysis.

In complicated materials structures, such as used today, it is difficult or not possible at all to determine the fracture behavior of heterogeneous materials by the standard procedures. In this paper, the idea is to test the possibilities of the optical object grating method for characterization of crack propagation in heterogeneous structures, in cases where the standard testing procedure is not possible to apply.

The prediction of maximum sustained load of a structure is connected to the appearance of damages in loaded elements when the cracks can be spread out inside the material and cause the fracture. Cracks in different types of structures occur as a consequence of stress concentration caused by holes, misalignments, corrosion or defects in manufacturing process. Therefore all the new constructions have to be designed and produced according to regulations, which led to minimum risk of unpredicted failure. In case when the crack is detected, it can be estimated from the point of view of safety and stability according the principles of fracture mechanics.

2. STRUCTURAL INTEGRITY AND LIFE ASSESSMENT

Many structures today are being operated beyond their intended service life usually in environments more severe than their components were designed. These conditions increased demands on their structural reliability. It is reasonable to apply the structural integrity procedures in early phase of product design, to minimize risk situations for new structures. At the production stage it is necessary to provide the integrity of structure and during the operational phase to assure the fatigue life of the structure. Used properly, these procedures can prevent over-design and provide a balance between safety and costs to be achieved.

Structural life management requires the integration of design and analysis, materials behavior and structural testing. The valuable information gathered by monitoring of

critical structural components should be of help making several important decisions:

- Should the load ratings be changed, either increased or decreased?
- Does the structure need repairs? If detected soon enough, minor repairs can reduce expenditures.
- And most importantly, should the structure be closed immediately to emanate collapse?

The accumulation of creep and fatigue damage over time are two principal degradation mechanisms, which usually lead to crack initiation in critical structure's components. In extreme situations, the growth of these cracks can lead to the structural collapse.

3. SURVEY AND MONITORING

Control of structural elements must be done periodically by the survey rules defined for specific structure. As an example for the offshore gas and oil platforms, there is a request for the survey rules defined for specific platform to ensure the control of selected structural elements. Selection of structural elements of jacket & deck, where it is necessary to perform monitoring, should be done according to the survey plans. Principles of survey procedure, which ensures safety and integrity of the existing structure, are supported by newest experiences of damage and fracture mechanics.

The existing structures are assigned in categories for both life safety and consequence of failure considerations. Inspection strategy is regulated on risk assessment and evaluation of structural elements integrity and shall be based on likelihood of component failure. The criteria are based on loading intensity, stresses, stress concentration of elements and joints and other influences to the assessment of structure fatigue life. Assessment of structural components should be given due to accumulated fatigue degradation effects.

The monitoring procedures and prediction of the rate of accumulation of creep-fatigue damage is therefore essential in developing an effective life assessment strategy to prevent catastrophic failure and to manage the remaining life of these components. Monitoring system should be able to detect structural damage, to provide early warning of structural failure and to check the reliability of the structure from extreme loadings or natural and man-made hazards. Thus the monitoring system provides the information to make decisions with regard to process deactivation under extreme loadings.

Procedure of survey of structural elements and criteria for their selection ensures the safety and integrity of the existing structures. Principles of survey procedure should be supported by newest cognitions of the assessment of the mechanical parts. The application of the experimental procedures helps in the assessment of the integrity of components by using the SINTAP procedure (Structural INTEgrity Assessment) [1].

The collaborative experimental-numerical object grating method using ARAMIS GOM measurement system provides valuable information regarding crack behavior in heterogeneous welded joint. By obtaining strain and stress

field of high accuracy, it is possible to calculate J -integral values, which is of great importance for assuming further crack behavior and predicting the likelihood of unstable crack growth. The robustness and simplicity of ARAMIS system makes it useful for characterization of stress-strain state around the crack tip either under controlled, laboratory conditions or as the actual real time field measurements.

4. CONCEPT

Damage analysis is significant for determination of reliability of mechanical structures' components while the numerical simulations of crack appearances and growing will process the phenomena of structural damages. Advanced experimental methods will provide the verification of behavior of elements with structural damage analysis.

In this paper, an advanced collaborative numerical and experimental approach is introduced, in order to provide the verification of fracture behavior of mechanical elements containing crack and proposes novel testing procedures for cracked element monitoring during the exploitation.

5. MEASUREMENT PRINCIPLES

Photogrammetry is an optical method that gives as a result the 3D coordinates data of analyzed objects' surface points. It is possible to obtain displacement vectors, local strain value as well as contour difference for deformed objects. The points on the surface can be oriented either as deterministic arranged grating or as stochastic pattern applied by surface spraying.

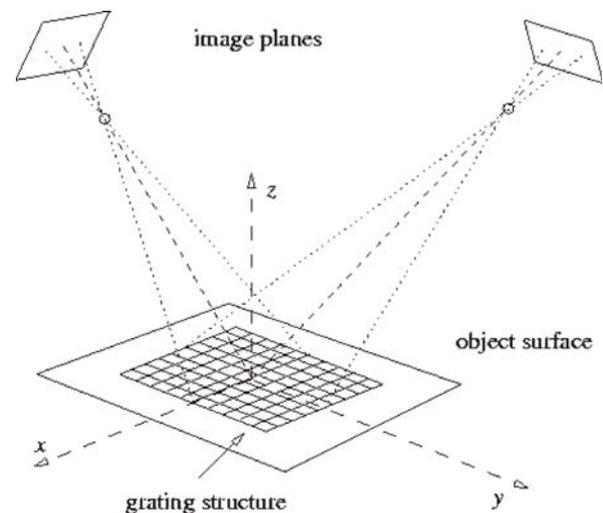


Fig. 2. Image and object planes

The object grating method [2] is advantageously used in order to record the appearance and the propagation of the crack. The applied experimental method is capable of the surface 3D deformation measurements by the optical observation of the attached grating (Fig. 2). Local displacements and deformations in crack vicinity provide valuable information regarding crack propagation and material's crack resistance properties. The measuring

system provides full field high data density, which enables easier understanding of damaged component behavior as well as comparison with finite element simulations.

The measuring system consists of a loading device with the specimen and two CCD cameras (resolution 1024x768 pixels and 256 gray levels). For known positions of the two cameras and two homologous image points, $p_1(x_1, y_1)$ and $p_2(x_2, y_2)$, it is possible to determine the corresponding image point $P(X, Y, Z)$ through well known space intersection procedure (Fig. 3):

$$\begin{bmatrix} x - x_0 - d_x \\ y - y_0 - d_y \\ c \end{bmatrix} = s \times \mathbf{R} \times \begin{bmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{bmatrix} \quad (1)$$

where x, y are image coordinates, x_0, y_0 are principal points, d_x, d_y are lens distortions, c and s are camera constants, \mathbf{R} is rotation matrix, X_0, Y_0, Z_0 are coordinates of the projection centre and X, Y, Z are coordinates of object points.

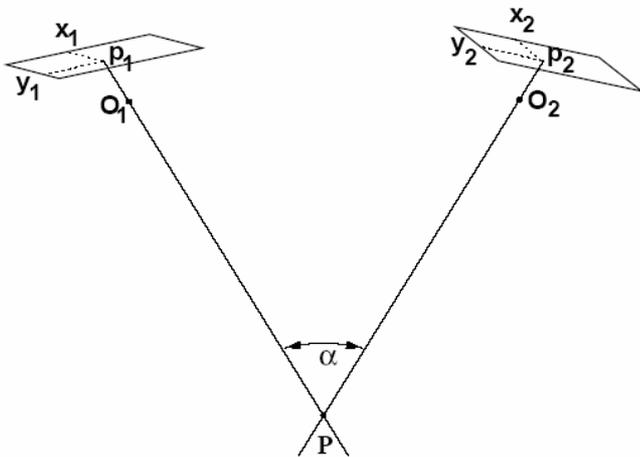


Fig. 3. Projection of the point P

The parameters of the projection centre and parameters of the rotation matrix are known as exterior orientation, and constants of the camera are known as interior orientation. These two constants are calculated through calibration procedure. The calibration object must be recognized from several views with the two cameras.

In order to determine 3D displacement, the calculation of the object coordinates for present deformation state for each point P must be performed. The relation between an object point in undeformed $P_0(X_0, Y_0, Z_0)$ and deformed state $P(X, Y, Z)$ is given by equation (1). It is important that each point in un-deformed state could be found in deformed state with its new coordinates. Otherwise it is not possible to define displacement and strain for this point. Displacement vector $P(U, V, W)$ is calculated as displacement difference for each coordinate by the equation (2):

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix}_P = \begin{bmatrix} X_d \\ Y_d \\ Z_d \end{bmatrix}_{P_d} - \begin{bmatrix} X_u \\ Y_u \\ Z_u \end{bmatrix}_{P_u} \quad (2)$$

For standard CTOD measurement only one component of the deformation vector ($V=Y_d-Y_u$) is considered; the advantage of full 3D approach is obvious.

As the displacement field is determined for each load stage, the strain distribution can be numerically calculated through the triangulation procedure.

One way to calculate the surface strain is through the transformation of 3D displacement distribution into a 2D displacement distribution. Strains can be calculated for each point; since these homologous points represent the same object point in two loaded states, 3D coordinates can be calculated by back projection.

Once 3D coordinates of each point are determined, strain determination becomes a matter of computation from the displacement field. The algorithm is as follows: For each of the object point P_u and P_d a tangential plane is calculated; the object points in neighborhood are included in calculation. The rectangular surrounding area is represented as the object's facet. The points surrounded by the facet's border are projected onto the tangential plane in direction of the tangential plane normal vector, which leads to a 2D problem.

In order to get higher accuracy of calculation, the facet's size should be optimized [3]. Facet's minimization is limited by contrast and size of average applied stochastic pattern as well as with software's limitations.

6. EXPERIMENTS

The fracture behavior of specimen with crack in middle of heterogeneous weld metal is analyzed (Fig. 4).

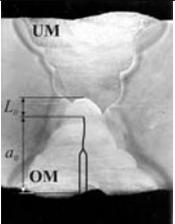


Fig. 4. Loaded and deformed specimen

A specimen according to the standard BS 7448 is used. The tests were performed under the room temperature of 24°C and displacement control (1mm/min). High strength low-alloyed HSLA steel in a quenched and tempered condition, corresponding to the HT 50 grade was used as base metal (BM).

The measured mechanical properties of the base metal and all-weld metals for the selected specimens are given in Table I. Picture within the table shows the cross section of the heterogeneous welded joint. Mis-matched factors M , eg. weld metal vs. base metal yield stress, is 0,86 for the under-match (UM) and 1,19 for the over-match (OM) material.

TABLE I. Mechanical properties of materials

	$R_{p0.2}$	R_m	M
	MPa	MPa	$\frac{R_{p0.2,WM}}{R_{p0.2,BM}}$
Over-match (OM)	648	744	1,19
Base metal (BM)	545	648	-
Under-match (UM)	469	590	0,86

Two specimens were tested (Fig. 5): Anotch 11 where the crack propagates from OM to UM weld part and Anotch 06 where the crack propagates in opposite direction. The initial notch length was 11 mm for Antoch 11 and 6 mm for Anotch 06.



Fig. 6. Experimental setup

The applied load F and the crack mouth opening displacement-CMOD were recorded during the tests. Diagram (Fig. 6) shows experimentally obtained CMOD vs. load plot where the unstable behavior is exhibited after stable crack propagation when achieved maximum sustained load.

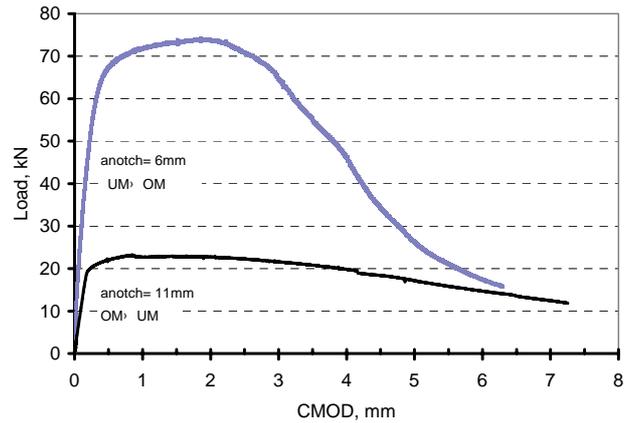


Fig. 5. Experimentally obtained CMOD vs. load

Measuring of crack tip opening displacements (CTOD) is performed along three lines that are shifted up and down towards the direction of crack propagation (Fig. 7) because one can expect discontinuity caused by heterogeneous material structure. The distance between the parallel lines of the measurement is approximately 1,5 mm in direction of the crack propagation, and approximately 5 mm at the distance in direction perpendicular to the crack propagation.

Line AB matches the measurement direction of the standard CTOD measurement. However, by using object grating method, displacements are gained all around the crack-tip region.

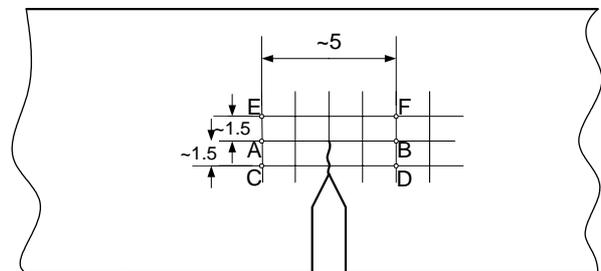


Fig. 7. Characteristic grid key-points for observing local CTOD

Stochastic pattern is applied to the surface by spraying graphite spray that allows high local resolution (Fig. 8). The tolerance is defined by the stochastic domains applied to the surface and corresponding facets applied in later computational phase of calculation. The goal is to achieve stochastic domains as little as possible for higher accuracy. The computation time significantly depends on the size of facets, on the amount of the recorded pictures and on the surface of analyzed area. In this experiment the facet dimension was 11x11 pixels; the observed surface was approximately 100 mm².

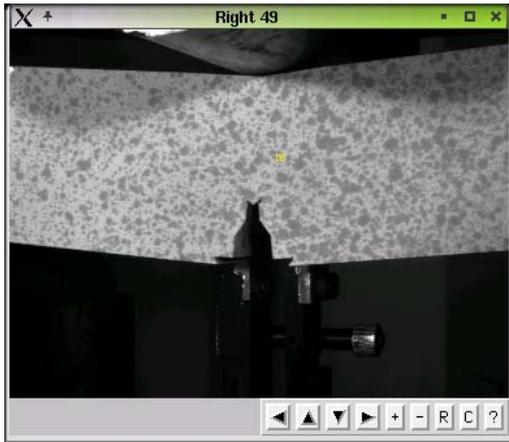


Fig. 8. Stochastic pattern applied to the surface

The displacement of random grating attached to the specimen surface is recorded. Image of undeformed and one deformed stage in the form of von Mises strain distribution around the crack tip are shown in Figures 9 and 10. The rectangular pattern represents the facets attached to the surface. Fig. 9 shows the unloaded specimen's surface, while Fig. 10 represents the one loaded stage. This makes possible to visualize large out-of-plane displacements as well as to extract the intensity of deformation and displacement. By following each point at the corresponding loaded stage one can easily understand the deformation process.

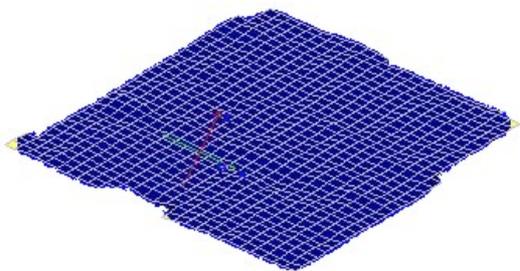


Fig. 9. Digitalized surface of un-deformed state

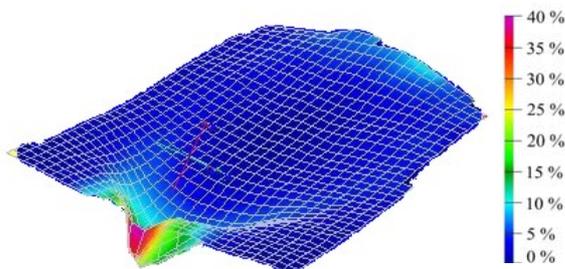


Fig. 10. Recorded von Mises strain distribution (Anotch 06)

The invented C(T)OD concept shows the differences in displacements measured at different shifted lines.

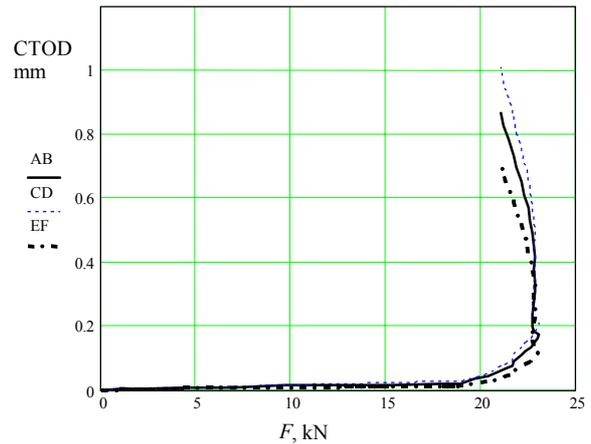


Fig. 11. Local C(T)OD vs. load in OM weld metal (Anotch 06)

Diagram (Fig. 11) shows uniform deformation distribution for all three lines up to the point of approximately 0,4 mm CTOD value. It is obvious that the uniformity of CTOD value distribution is consequences of positioning the crack tip in over-match material. After while CTOD distribution starts to diverge according to the distance of corresponding measured line from neutral, so called point of rotation (Fig. 12). CTOD value is increased faster for the line CD, which is away from the point of rotation. The line nearest to the point of rotation, line EF had the smallest increment of the CTOD value. Maximum CTOD values lead to 0,70mm, 0,83mm and 1,00mm.

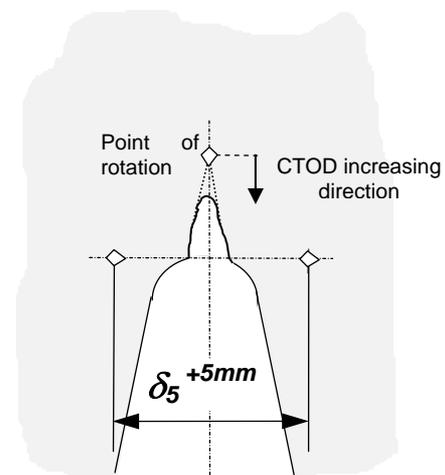


Fig. 12. Definition of neutral point (point of rotation)

On contrary, diagram in Fig. 13 shows divergence distribution of CTOD values immediately when the loading is applied. This difference of measured CTOD values is almost fully linear up to the value of 0,2 mm CTOD. During the increasing of the applied load, CTOD difference diverge more and more up to the maximum measured CTOD values of 0,43mm, 0,78mm and 0,98mm.

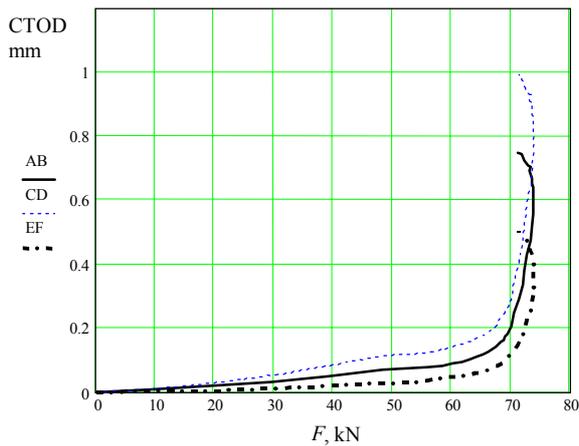


Fig. 13. Local C(T)OD vs. load in UM weld metal (Anotch 11)

Significant load difference for the corresponding CTOD values for these two experiments is caused by the difference in the length of initial crack. Maximum load for the specimen Anotch 06, is approximately 23 kN and for the specimen Anotch 11 it is about 72 kN.

7. CONCLUSIONS

The approach to innovative analysis of crack propagation in heterogeneous welded joint is presented.

The measurement procedure is based on tracing of corresponding points through different load stages and simultaneously obtaining local displacement field. In comparison to the standard CTOD test, two additional reference lines are shifted; one ahead and one ahead behind the crack tip. The method enables better understanding and visualization of crack opening geometry for different load stages, as well as its ability to analyze the crack propagation in heterogeneous material structures.

Results of two experiments performed on specimens with the tip of initial crack once in over-match, once in under-match material show that crack propagation

significantly depends on the material in the vicinity of crack tip. The strain field analysis shows that use of different combination of materials makes possible the significant intervention to the behavior of the introduced crack for the same loading conditions.

High accuracy and simplicity of the measurement procedure, relatively short time from the measurement to final results makes the object grating method suitable and powerful tool in fracture mechanics problems analysis. The measured results can be easily exported and visualized, which makes them suitable for further analysis and comparison to the results of numerical analysis.

REFERENCES

- [1] N. Gubelj, M. Kocak, U. Zerbst, "Use of SINTAP procedure for the assessment of strength mis-matched HSLA steel welds", *Welding in the world*, Vol. 45, spec. issue, pp 177-185, July 2001.
- [2] R. Ritter, K. Andersen, B. Kamp, "Three-dimensional surface deformation measurement by a grating method applied to crack tips", *Optical Engineering*, Vol. 31(7), pp. 1499-1504, 1992.
- [3] M. Gomerčić, "The compensation of out-of-plane displacements in deformation measurement by grating method", *Österreichische Ingenieur-und Architekten-Zeitschrift (ÖIAZ)*, Vol. 144 (5), pp. 223-227, 1999.

AUTHORS: Damir Semenski, Assoc. Prof., University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, pp 102, HR-10002 Zagreb, CROATIA, damir.semenski@fsb.hr
Nenad Gubelj, Assoc. Prof., University of Maribor, Faculty of Mechanical Engineering, Smetanova ulica 17, SI-2000 Maribor, SLOVENIA, nenad.gubelj@uni-mb.si
Drazen Kozak, Ass. Prof., University of Josip Juraj Strossmayer in Osijek, Mechanical Engineering Faculty, Trg I. Brlic-Mazuranic 18, HR-35000 Slavonski Brod, CROATIA, drazen.kozak@sfsb.hr
Petar Ćurković, B.Sc., University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, pp 102, HR-10002 Zagreb, CROATIA, petar.curkovic@fsb.hr