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EXPERIMENTAL ANALYSIS OF FRACTURE BEHAVIOUR OF STAINLESS STEEL USED FOR BIOMEDICAL APPLICATIONS

EKSPERIMENTALNA ANALIZA PONAŠANJA LOMA NERĐAJUĆEG ČELIKA ZA BIOMEDICINSKU PRIMENU

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Keywords

- fracture behaviour
- stainless steel
- optical stereometric measuring system
- stress intensity factor
- biomedical applications

Abstract

This paper presents an analysis of stainless steel materials that are used as biomaterials in biomedical applications, such as artificial joint implants, from a fracture mechanical perspective. Design parameters that should be considered for artificial implants are fatigue and fracture. Therefore, it is necessary to understand the fatigue crack initiation and propagation characteristics in order to prevent catastrophic failure of the implant. The fracture behaviour of 316L stainless steel is investigated by means of standard fracture mechanics tests performed on modified CT specimens. The GOM optical system and Aramis software are used to perform 3D experimental optical analysis of the specimens. The possibilities of using this method for analysing materials for biomedical applications are discussed. The experimental study consists of evaluation of elastic-plastic fracture behaviour of 316L stainless steel, and determining K_I values. The major strain fields of the stainless steel specimen for crack tip opening and fracture are presented. The results indicate that this new optical stereometric measuring methodology is giving good results in investigations of fracture behaviour of bimetallic materials.

Ključne reči

- ponašanje loma
- nerđajući čelik
- optičko stereometrijski merni sistem
- faktor intenziteta napona
- biomedicinska primena

Izvod

U ovom radu je predstavljena analiza materijala od nerđajućeg čelika, koji se primenjuje kao biomaterijal za biomedicinske svrhe, kao što su veštački implantati zglobova, a sa gledišta mehanike loma. Parametri projektovanja, koje treba razmatrati u veštačkim implantima su zamor i lom. Stoga, neophodno je razumevanje karakteristika inicijacije i rasta zamorne prsline, radi sprečavanja katastrofalnog loma implanta. Istraženo je ponašanje loma nerđajućeg čelika 316L u smislu standardnih ispitivanja mehanike loma izvedenih na modifikovanim CT epruvetama. Optički sistem GOM i Aramis softver se primenjuju za izvođenje 3D eksperimentalne optičke analize epruveta. Diskutovane su mogućnosti primene ove metode za analizu materijala za biomedicinsku primenu. Eksperimentalna studija se sastoji iz procene elasto-plastičnog ponašanja loma nerđajućeg čelika 316L, i u određivanju vrednosti K_I . Predstavljena su polja glavnih deformacija epruvete od nerđajućeg čelika za otvaranje vrha prsline i lom. Rezultati pokazuju da ova nova optičke stereometrijska metodologija daje dobre rezultate u istraživanju ponašanja loma bimetalnih materijala.

INTRODUCTION

There are many stainless steel alloys available for use in biomedical applications, each with individual characteristics that make it a good solution to a certain problem. However, by making one characteristic better, other characteristics may become weaker. Basically, materials which are to be used for biomedical applications should cause minimal degradation in the body; they should be compatible with the biological environment; they should also be strong enough for the intended purpose, /1/. In order to investigate the fracture behaviour of metallic biomaterials, stainless steel materials used in biomedical applications are analysed.

The first stainless steel material utilized for a biomedical application – implant fabrication – was type 302 in modern classification, which was stronger and more corrosion resistant than vanadium steel. Stainless steel 18-8sMo was introduced later, containing a small percentage of molybdenum, added to improve corrosion resistance in chloride solution. During the last several decades, several stainless steel alloys have been developed for biomedical use, but the steel alloy most often used in biomedical applications is grade 316 L. It is suitable for artificial joint implants and for temporary implant devices in biomedical applications, such as fracture plates, screws, and hip nails, and as a material for some medical devices /1, 2/. Any biomedical application making use of stainless steel alloys is susceptible to many damage mechanisms. It is commonly reported in orthopaedic applications, such as knee and hip joint prostheses, that fatigue fracture and wear have been identified as some of the major problems associated with implant loosening, stress-shielding and ultimate implant failure, /3, 4/. Artificial joint prostheses are generally a short-term success, because biological and mechanical conflicts often cause the implants to fail. There are many potential hazards that can affect the long-term outcome of the operation once an implant surgery is performed, /5/. During surgery and general handling of the prosthesis, scratches will inevitably appear on its surface, which will result in an intensification of the stress at those points and provide a location for crack growth propagation. In order to inhibit the catastrophic failure of stainless steel as a mechanical material, it is necessary to understand fatigue crack initiation and fatigue crack propagation characteristics, /6/. Crack propagation characteristics are important in achieving a fail-safe design of structural materials. It is considered that the catastrophic failure of these materials can be avoided by stopping the crack extension during the stable crack propagation stage, even if the crack has already been initiated.

MATERIALS AND EXPERIMENT

S316L is the alloy chosen for this experimental analysis, considering its widespread use in many biomedical applications, for it does not corrode easily like other stainless steel alloys with higher carbon content. Under certain circumstances, however, even 316L stainless steels may corrode inside the body, e.g. in highly stressed and oxygen-depleted regions, such as contact points under the screws of the bone fracture plate. Methods for surface modification, such as glow-discharge nitrogen implantation, anodization and pas-

sivation are often used to improve corrosion and wear resistance, and fatigue strength of 316L stainless steel. 316L is the modified molybdenum-bearing grade steel, the low-carbon version of 316, with maximum carbon content of 0.03%. This leads to better corrosion resistance in chloride solution, and minimization of sensitization. Chemical composition of the specimens used in this experimental analysis is determined by gravimetric analysis, and is presented in Table 1.

Table 1. Chemical composition of 316 L steel (wt. %).
Tabela 1. Hemijski sastav čelika 316 L (mas. %)

C	Mg	P	S	Si	Ni	Cr	Mo
0.03	1.95	0.25	0.03	0.70	12.5	17.5	3.0

To impart corrosion resistance in stainless steels, minimum effective concentration of chromium is 11%. The amount of 3% molybdenum gives the 316L alloy better overall corrosion resistance than other austenitic stainless steels, and particularly, higher resistance to pitting and crevice corrosion in chloride environments. 316L stainless steel cannot be hardened by thermal treatment, but its hardness and strength can be substantially increased by cold working, with subsequent reduction in ductility, /7/.

Experimental analysis of stainless steel alloys for biomedical applications presented in this paper is based on an optical methodology measuring system, /8/. The 3D measurement system consists of Aramis software and a special set of stereo cameras and lenses. This method is suitable for analysis of irregular object geometries made of various materials, as is often the case in biomedical applications, /9, 10/. This 3D measurement system is used in this experimental analysis to analyse structural integrity and determine material properties.

The experimental testing arrangement is presented in Fig. 1. The system uses two digital cameras that provide a synchronized stereo view of the specimen. It also includes the stand that provides the stability of the sensors, an image recording and power control unit, and the data processing system, /11/.

The experiment is performed to evaluate fracture behaviour and crack propagation in two S316L alloy specimens. In crack initiation testing, specimens are subjected to a number of stress cycles required for initiation of the fatigue crack, and its subsequent growth to a size large enough to produce failure. In this experiment, the S316L alloy fracture behaviour is analysed at room temperature (20°C).

The fracture behaviour of 316L stainless steel is investigated by means of standard fracture mechanics tests performed on modified CT specimens, /12/. The S316L notched CT specimens are machined to the sizes given in Fig. 2.

System calibration using calibration plates is performed prior to the start of the experiment. The chosen volume is based on the specimen dimensions, and in accordance to the tables in the instructions manual, /11/. As a first step in the preparation of the object to be measured, it is necessary to place referral points – markers. When using the Aramis system, the referral points are placed with a white spray, so as to create the best possible contrast. This enables the software to track changes that occur in the object as it is subjected to loading.



Figure 1. Testing arrangement.
Slika 1. Postavljanje ispitivanja

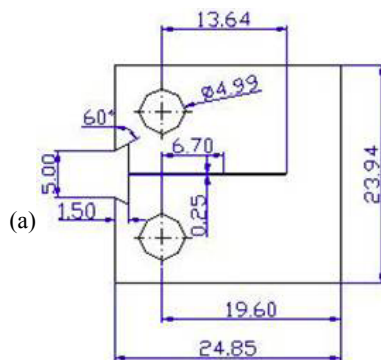


Figure 2. Modified CT specimen (a) and S316L specimens (b).
Slika 2. Modifikovana CT epruveta (a) i S316L epruvete (b)

After the calibration of the system and specimen, the experimental measurement procedure is successfully performed. The procedure included creating a new project, setting the recording speed and lighting around the object.

After the measuring project is created in the software, the images are recorded during various loading stages of the object. It was then necessary to define the evaluation area and a starting point, so that the measuring project could be computed.

RESULTS AND DISCUSSION

Tensile tests are carried out at room temperature according to relevant ISO specifications. Mechanical properties of S316L alloy are presented in Table 2.

Table 2. Mechanical properties of S316L alloy.
Tabela 2. Mehaničke osobine legure S316L

Tensile strength (MPa)	0.2% Yield strength (MPa)	Elongation (%)
860	690	12

During the test, forces and the displacement are recorded, and the results for two specimens are presented by diagrams shown in Fig. 3. According to the literature, the intensity of forces for biomedical implants could be high, so maximal loads that are applied in this experiment are 45 kN.

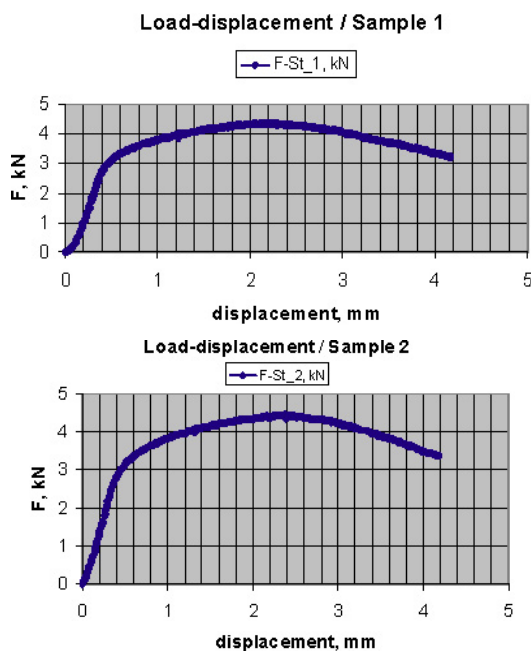


Figure 3. Load-displacement for samples 1 and 2 of S316L.
Slika 3. Opterećenje-pomeranje za epruvete 1 i 2 od S316L

During the computation process, Aramis observes the deformation of the object across the images by means of square or rectangular image details (facets). Aramis recognizes the structure of the measuring object surface captured in the digital camera images, and allocates coordinates to the image pixels. The first image in the measuring project therefore represents the initial, undeformed state of the measuring object.

After the computations, the results are processed and prepared for the final report. Figure 4 shows Aramis report for sample 1 at stage 183, which is just before the occurrence of final cracking of sample 1.

Stress intensity factor K_I at the notch tip is determined following the standard procedure and using the equation

$$K_q = \frac{P_q}{B\sqrt{W}} f\left(\frac{a}{W}\right)$$

where B is the specimen thickness, /12/. Considering that specimen thickness is 2 mm, K_I for the two specimens S316L is determined. Results are presented in Table 3.

Table 3. Results for stress intensity factor of S316L specimens.
Tabela 3. Rezultati faktora intenziteta napona za S316L epruvete

Specimen S316 L	Sample 1	Sample 2
Stress intensity factor K_I (MPa√m)	116	120

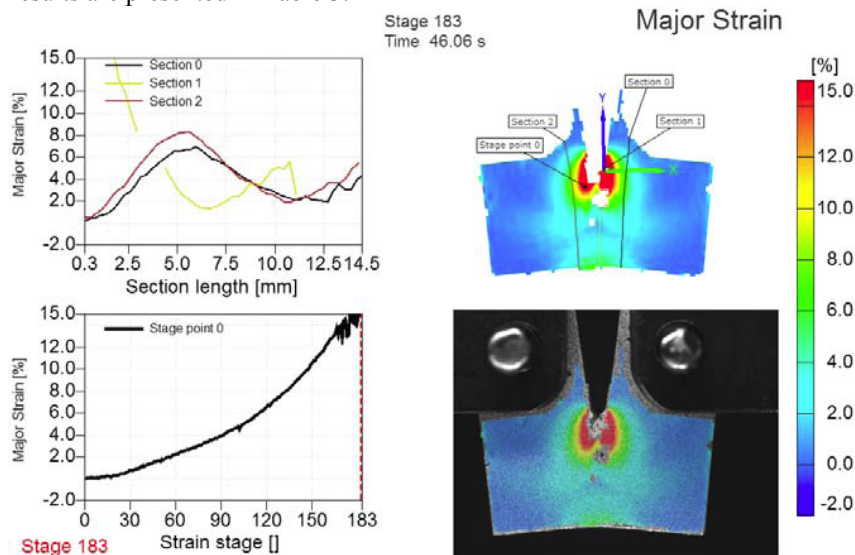


Figure 4. S/N curves for notched specimens of both segregation orientations.
Slika 4. S/N krive epruveta sa zarezom za obe orijentacije segregacija

The results of this study show the major strain field with the compressive load acting upon the specimen during crack tip opening, crack propagation and failure. Crack tip opening displacement (CTOD) is monitored by Aramis and

the major strain field of the S316L alloy specimen 1 is shown in Fig. 5. The major strain field of the S316L alloy specimen 2, just before final cracking, is shown in Fig. 6.

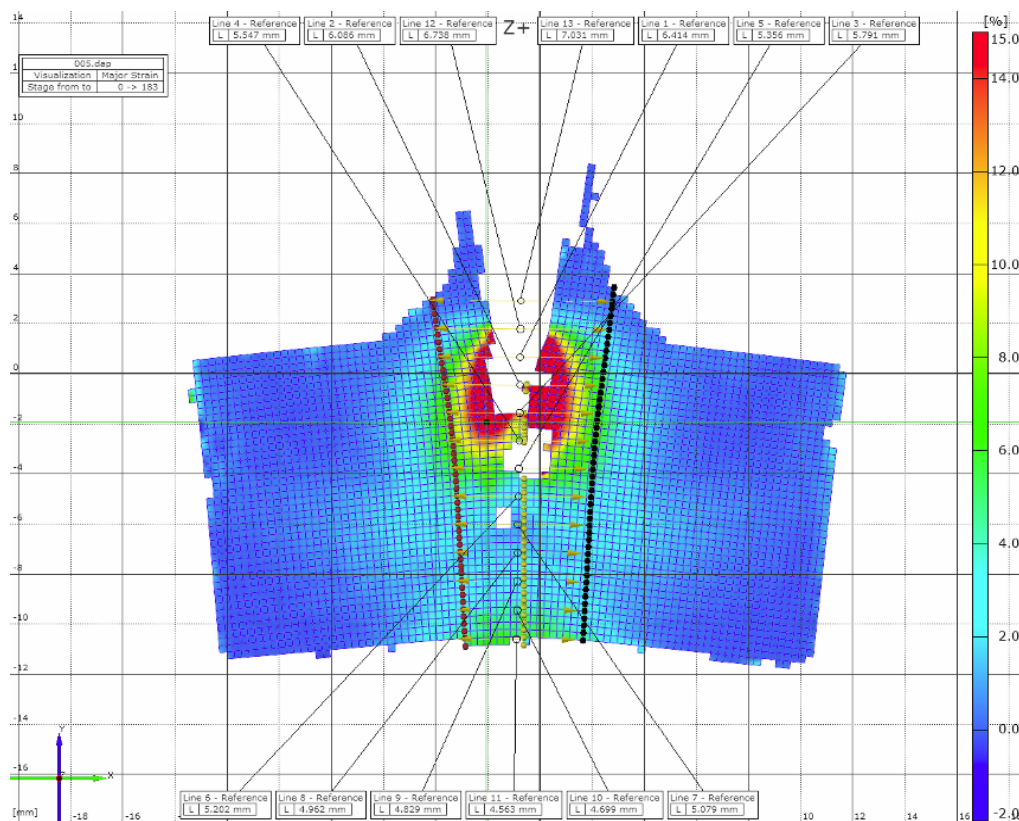


Figure 5. Major strain field of the S316L specimen 1.
Slika 5. Polje glavnih deformacija epruvete S316L 1

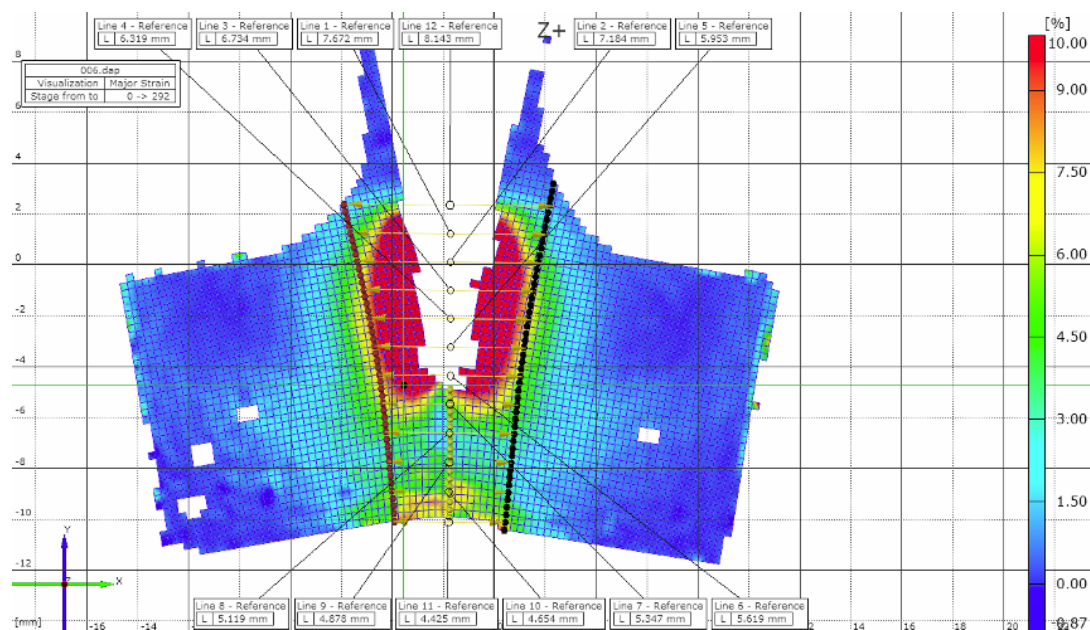


Figure 6. Major strain field of the S316L specimen 2.
Slika 6. Polje glavnih deformacija epruvete S316L 2

CONCLUSION

The results of this study show that mechanical issues are very important in the design and selection of 316L stainless steel materials. Fatigue fracture and wear have been identified as some of the major problems associated with implant failure of biomedical devices. The actual *in vivo* mechanisms are complex and involve the hostile body environment. Materials used in biomedical implants are subjected to high stresses and high cycle loading. This very demanding condition, coupled with the aggressive body environment, leads to fatigue failure of metallic implants.

In this paper a 3D experimental optical analysis of S316L used for biomedical applications is performed, using GOM optical system and Aramis software. The stress intensity factor on modified CT stainless steel specimens is obtained. The possibilities of using this method for analysing materials for biomedical application are discussed.

Aramis delivers complete 3D surface and strain results, which would require a large number of traditional measuring devices (strain gauges, LVDT extensometers) to otherwise capture. Aramis is a non-contact, material-independent measuring system, which provides accurate 3D surface coordinates displacements and velocities, values of surface strain (major, minor and thickness reduction) and strain rates for statically and dynamically loaded objects. Aramis helps to better understand material and component behaviour, and as it is well-suited to monitor experiments with high temporal and graphical resolution, it is suitable for determining biomaterial properties.

While it is not possible to avoid failure, recent work has focused on predictive tools to enable more accurate prediction so as to avoid catastrophic failure *in vivo*. The measuring system based on multiple sensors with Aramis software has been proven to be beneficial in biomedical applications, and it can be used for synchronous capture of the complete object or multiple areas of the object, especially with meas-

urements involving nonhomogeneous materials, or capturing complex loading situations, which is the case in biomedical applications.

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REFERENCES

1. Park, J.B., Lakes, R.S., *Biomaterials - An Introduction*, Plenum Press, New York, 1992.
2. Milne, I., Ritchie, R.O., Karihaloo, B., *Comprehensive Structural Integrity*, Vol. 9: Bioengineering. Elsevier Ltd, Oxford, 2003.
3. Buford, A., Goswami, T., *Review of wear mechanisms in hip implants: Paper I - General*, *Materials and Design*, 25 : 385-393, 2004.
4. Teoh, S.H., *Fatigue of biomaterials: a review*, *International Journal of Fatigue*, 22 : 825-837, 2000.
5. The, B., Hosman, A., et al., *Association between contact hip stress and RSA-measured wear rates in total hip arthroplasties of 31 patients*, *Journal of Biomechanics*, 41 : 100-105, 2008.
6. Niinomi, M., *Fatigue characteristics of metallic biomaterials*, *International Journal of Fatigue*, 29 : 992-1000, 2007.
7. *Metal Handbook*, Tenth Ed. - Vol 1 & Vol 2, Properties and Selection: Iron, Steel, and High- Perf. Alloys, ASMI, Materials Park, Ohio, 2005.
8. Cloud, G., *Optical Methods of Engineering Analysis*, Cambridge University Press, Cambridge, 1995.
9. Zhang, D., Arola, D., *Applications of digital image correlation to biological tissues*, *Journal of Biomedical Optics*, 9(4) : 691-699, 2004.
10. Sztetek, P., et al., *Using digital image correlation to determine bone surface strains during loading and after adaption of the mouse tibia*, *Journal of Biomechanics*, 43 : 599-605, 2010.
11. ARAMIS User Information - Hardware, aramis_hw_en_rev-c, Braunschweig, Germany, 2007.
12. Anderson, T.L., *Fracture Mechanics: Fundamentals and Applications*, 3rd ed, CRC Press, London, 2005.