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STRUCTURAL INTEGRITY ASSESSMENT OF HIP IMPLANT MADE OF COBALT-CHROMIUM MULTIPHASE ALLOY

PROCENA INTEGRITETA KONSTRUKCIJE IMPLANTA VEŠTAČKOG KUKA IZRAĐENOG OD VIŠEFAZNE Co-Cr LEGURE

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- Co-Cr multiphase alloy
- hip implants

Ključne reči
- parametri mehanike loma
- Co-Cr višefazna legura
- veštački kuk

Abstract

This paper presents an analysis from a fracture mechanical perspective of Co-Cr multiphase alloy materials that are used in total hip replacement implants. Design parameters to be considered for hip implants should be related to fatigue and fracture. This paper addresses the elastic-plastic fracture behaviour of commercially cold-drawn (53%) MP35N (35% Co, 35% Ni, 20% Cr, and 10% Mo). In this course, MP35N fracture behaviour has been investigated both under static loading conditions (J-R curve and J_{Ic} testing according to ASTM E1737) and under impact loading on Charpy instrumented pendulum. An attempt has been made to correlate J_{Ic} values with previously obtained K_{Ic} values. Another important task was to investigate the correlation between KV_{total} and K_{Ic} and between KV_{growth} and J_{Id}. These results indicate good mutual agreement and possible actions toward further increase of toughness.

Izvod

Rad prikazuje analizu parametara mehanike loma višefazne Co-Cr legure, koja se koristi kao materijal za implant kod ugradnje veštačkog kuka. Konstrukcijski parametri koje bi trebalo uzeti u obzir tokom projektovanja implanta kod veštačkog kuka su zamor i lom. Ovaj rad se bavi elastoplastičnom mehanikom loma komercijalnog hladno-vučenog (53%) MP35N (35% Co, 35% Ni, 20% Cr, i 10% Mo). U tom cilju sprovedeno je ispitivanje ponašanja na lom MP35N, pri čemu su urađena i statička ispitivanja (J-R kriva i J_{Ic} ispitivanje u skladu sa ASTM E1737) i ispitivanja udarom metodom po Šarpiju. Napravljen je pokušaj da se povežu vrednosti J_{Ic} sa prethodno dobijenim vrednostima K_{Ic}. Još jedan bitan zadatak bilo je ispitivanje odnosa između KV_{total} i K_{Ic}, kao i između KV_{growth} i J_{Id}. Rezultati ukazuju na dobro međusobno slaganje i na mogućnosti daljeg povećanja žilavosti.

INTRODUCTION

Biomedical implants are generally a short term success because biological and mechanical conflicts often cause the implants to fail. When an implant surgery is performed, there are many potential hazards that can affect the long-term outcome of the operation. This discussion will primarily examine total hip replacement (THR) implants from a mechanical perspective. The fatigue behaviour of biomedical materials is as important as other properties, yet fatigue characteristics are not always considered while selecting a particular material for bio applications.

Total hip replacement (THR), is a surgical procedure in which parts of the hip joint are removed and replaced with artificial parts, known as the prosthesis, Fig. 1. Metallic alloys and composite materials are used for prosthesis. As for the total hip joint, its femoral head prosthesis is often made of cobalt-chromium alloy, while the stem component is made of titanium alloy, Fig. 2.

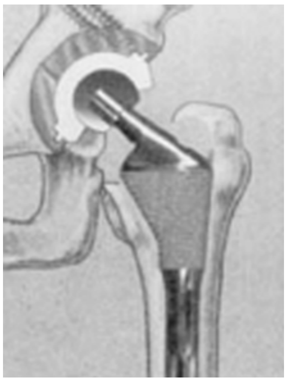

Figure 1. The shape of the artificial hip.
Slika 1. Oblik veštačkog kuka.

Materials to be used in a human body should cause minimal degradation in the body, compatible with the biological environment, and strong enough for the intended purpose, /1/.

The ideal metal for a cemented component would have high fatigue, yield and tensile strength, and corrosion resistance. Also, a high modulus of elasticity may be considered advantageous because it would reduce the strain in the cement around the component and decrease the risk of cement failure, /2/. On the other hand, it would be disadvantageous because the bone may become so unloaded that osteoporosis could develop, resulting in cement failure and subsequent loosening of the component.

Figure 2. Components of the artificial hip implant.
Slika 2. Komponente implanta veštačkog kuka

Three common alloys used in hip replacement implants are stainless steels, titanium alloys and Co-Cr alloys, including cast and forged cobalt chromium molybdenum alloys, wrought cobalt chromium tungsten nickel and cobalt nickel chromium molybdenum alloys, /3/.

Design parameters that should be considered for Co-Cr biomaterials are related to fatigue and fracture, corrosion, and wear. Prosthesis should be able to withstand 3 million cycles per year for an average individual. Fatigue analysis must take into consideration other factors that will prematurely weaken the material, such as corrosion and wear. In addition, combined effects of material failure modes working together should be considered. Numerous other mechanisms such as aseptic loosening, wear, fretting and corrosion may contribute to fatigue and joint failures, /4/.

Case Report, /5/

The patient was an active, 53 year-old man (178 cm, 114 kg) with advanced osteoarthritis of the left hip. The femoral component was a cemented Exactech Opteon stem, size 3, with a 28 mm 110 Co-Cr femoral head (Exactech). Radiographs showed good implant position, Fig. 3a. The patient returned to his usual work and reported no difficulty until 43 postoperative months. Radiographs showed a fractured femoral prosthesis at the neck-shoulder junction Fig. 3b.

It was concluded that pronounced laser etching at the lateral neck shoulder junction caused heat induced changes in the material microstructure and the creation of a local stress riser, /6/. Reduced fatigue resistance in a highly stressed region of the implant, combined with high patient demands, appeared to result in early fatigue failure of the implant, as is presented in Fig. 4a.

COBALT BASED BIOMATERIALS

First Co-Mo alloy used for biomedical applications was called vitallium, and has exhibited better strength at high temperatures as well as better corrosion resistance when compared to other superalloys. By modifying vitallium, other alloys that are used for hip implants have been developed: Co-Cr-W-Ni, Co-Ni-Cr-Mo-W-Fe, and Co-Ni-Cr-Mo, /6/. ASTM standards of Co-Cr alloys for medical and surgical uses are shown in Table 2 (ASTM, Annual Book of ASTM Standards, 2000), /6/.

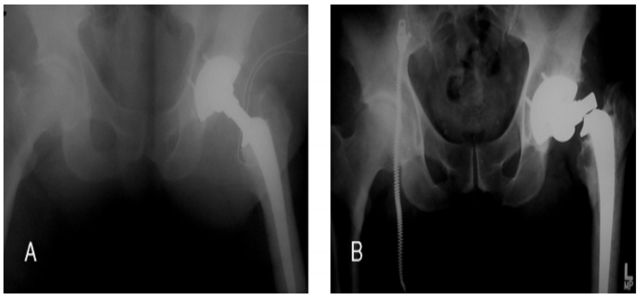

Figure 3. (a) Post-operative radiograph. (b) Follow-up radiograph shows fracture of the well fixed stem at the neck shoulder junction.
Slika 3. (a) Postoperativni radiogram. (b) Prateći radiogram sa vidljivim prelomom dobro učvršćene osnove na ramenom zglobu

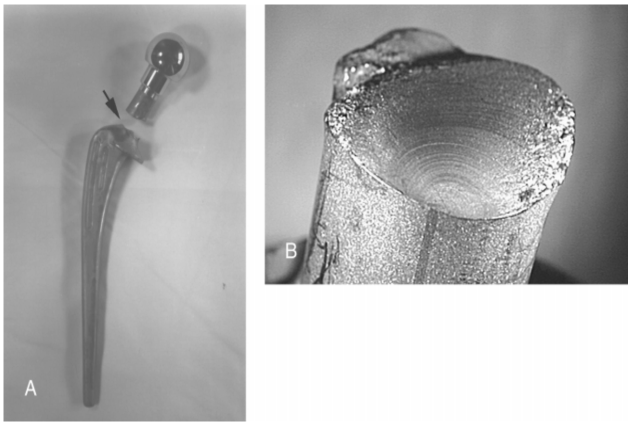

Figure 4. (a) Fractured implant from case. (b) Magnified view of the implant fracture surface.
Slika 4. (a) Slomljeni implant. (b) Uvećani prikaz prelomne površine implanta.

Table 1. ASTM standards of Co-Cr alloys.
Tabela 1. ASTM standardi za legure Co-Cr

Specification	*Nominal contents*
F75-98	Co–28Cr–6Mo casting alloy and cast products
F90-97	Wrought Co–20Cr–15W–10Ni alloy
F562-95	Wrought Co–35Ni–20Cr–10Mo alloy
F563-95	Wrought Co–Ni–Cr–Mo–W–Fe alloy
F799-99	Co–28Cr–6Mo alloy forgings
F961-96	Co–35Ni–20Cr–10Mo alloy forgings
F1058-97	Wrought Co–Cr–Ni–Mo–Fe alloys
F1537-94	Wrought Co–28Cr–6Mo alloy

The multiphase Co-Cr alloy MP35N (35% Ni, 35% Co, 10% Mo, 20% Cr) is a biomaterial used for hip implants, because it exhibits a superior combination of strength, toughness, and corrosion resistance. The MP35N alloy can be cast or forged. Mechanical properties of both alloys are better of those of the cast Co-Cr-Mo alloy considering wear resistance and corrosion resistance, /7/.

While strengthening mechanisms in MP35N are now reasonably well understood, as well as the influence of cold-work and aging on strength and ductility, there is very little information in literature on the fracture toughness of this alloy. Several attempts were made in literature to determine plane strain fracture toughness of MP35N, using either 3-point bend specimens (L/T direction, according to ASTM specification), or Short Rod specimens with chevron slot (T/L direction), /8/.

Most of the previous studies have failed to obtain a valid and consistent measurement according to ASTM E399 standard because of insufficiently thick sections, as shown in Fig. 5 and explained in more detail in /8, 9/. This is mainly because MP35N multiphase alloy exhibits an impressive combination of high strength and toughness even after extensive plastic strain (e.g. 53% of cold-work) and subsequent aging at about 600°C for 4 hours, positioning it second only to TRIP steels at the suitably plotted diagram, Fig. 6, /10/. Anyhow, previous studies of MP35N properties, including fracture toughness tests, /8, 9/, have indicated further possibility for toughness and strength enhancement, once the fracture behaviour of this alloy is better understood. Toward this end, MP35N fracture behaviour has been investigated both under static loading conditions (J-R curve and J_{Ic} testing according to ASTM E1737) and under impact loading on Charpy instrumented pendulum.

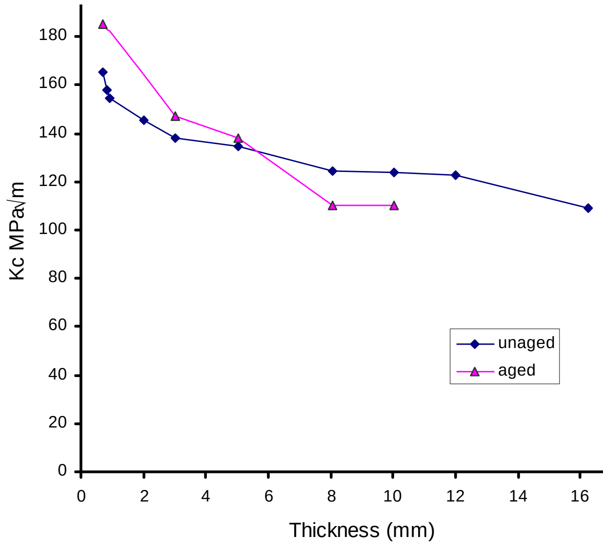

Figure 5. Influence of sample thickness on the fracture toughness of commercially drawn MP35N alloy, /9/.
Slika 5. Uticaj debljine uzorka na žilavost loma komercijalnog izvučene legure MP35N, /9/

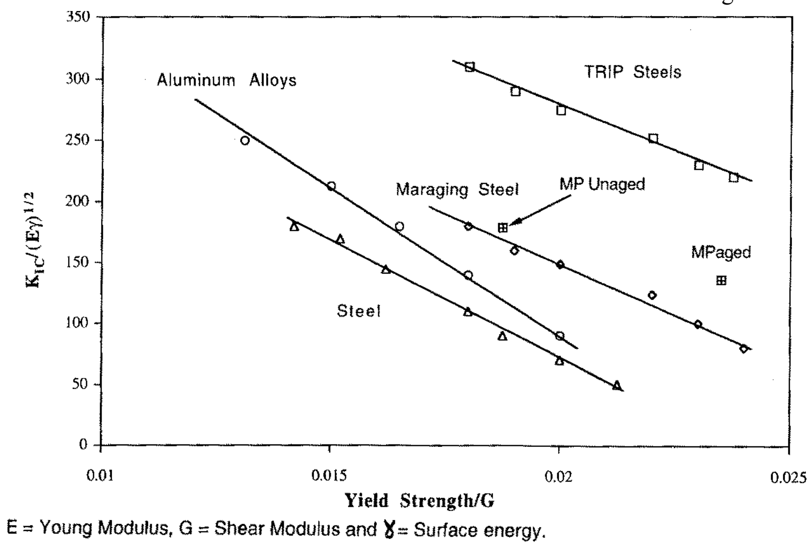

Figure 6. Normalized strength-toughness curves of MP35N vs. other materials, /9/.
Slika 6. Normirane krive čvrstoća-žilavost MP35N i drugih materijala, /9/

EXPERIMENTAL INVESTIGATION AND RESULTS

The standard static fracture mechanics test was performed in order to evaluate the resistance of aged and unaged MP35N alloy to stable (e.g. the blunting effect) and unstable crack growth and to investigate the influence of crack orientation. Three point bend and Pacman specimens were used oriented differently (T-T, L-T, and T-L) to account for possible anisotropy effects, indicated in /9/. One of the main tasks was to compare J_{Ic} values obtained from J-R curves, with previously obtained K_{Ic} values.

The main purpose of impact testing was to evaluate the effects of dynamic loading to MP35N fracture behaviour. Impact toughness evaluation on instrumented Charpy pendulum should enable better understanding of crack initiation and growth processes due to its possibility to separate corresponding energies, /10/. Another important task was to investigate the correlation between KV_{total} and K_{Ic} and between KV_{growth} and J_{Id}. Finally, the Charpy instrumented pendulum was used for impact testing of pre-cracked specimens, in order to evaluate J_{Id} values and investigate further effects of orientation and aging on MP35N fracture behaviour under impact load.

Results for standard Charpy tests are shown in Table 2, together with separated energies and crack initiation and growth, and the values for corresponding K_{Ic} obtained using the empirical relation: $K_{Ic} = 32.4\sqrt{CV}$. As one can see, there is reasonable agreement between values shown in Fig. 5 and those obtained here for the crack growth energy.

Table 2. Charpy instrumented test.
Tabela 2. Ispitivanje instrumentiranim Šarpi klatnom

specimen	total energy (J)/ K_{Ic}	crack initiation energy / K_{Ic}	crack growth energy / K_{Ic}
1	52.9 / 236	38.2 / 200	14.7 / 124
2	51.9 / 233	37.5 / 198	14.4 / 123

Elastic-plastic fracture mechanics parameters were tested in three point bending (standard Charpy specimen, pre-cracked: $a_0/W = 0.545$; L = 4W = 40 mm, B = W = 10 mm). Results are given as J-Δa static curve, both in graphical form, Fig. 7, and in Table 3. The J_{Ic} = 130 N/mm and corresponding K_{Ic} = 165 MPa√m (for E = 210 GPa).

Finally, dynamic fracture mechanics parameter, J_{Id}, was evaluated using standard Charpy specimens, pre-cracked: a_0/W = 0.441 and 0.503; tested in the same way as impact toughness; L = 4W = 40 mm, B = W = 10 mm. Results are given in Table 5. Results for dynamic fracture mechanics parameter, J_{Id}, indicate good agreement with results for corresponding static parameter, namely J_{Ic}, obtained both by standard technique and by using the instrumented Charpy.

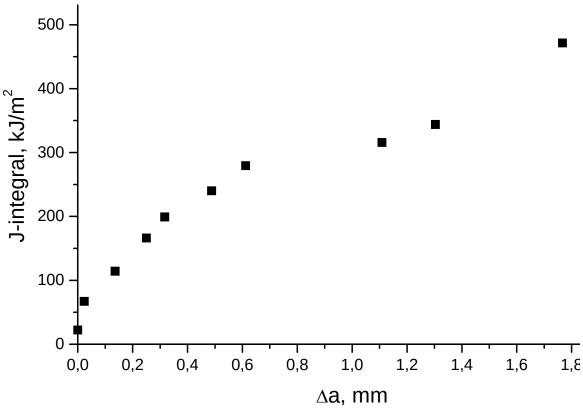

Figure 7. J-R curve for MP35N alloy.
Slika 7. J-R kriva za leguru MP35N

Table 3. Data for J-R curve evaluation – Tabela 3. Podaci za izračunavanje J-R krive

unloading	Force		Load line displacement		Slope at unloading	Crack elongation	Crack elongation	Crack length ratio	Area	J
	F_{max} (N)	F_{min} (N)	max (mm)	min (mm)	tgα	(per step) Δa (mm)	(total) Δa (mm)	a/W	A (Nm)	(KJ/m)
1	8850	6250	0.365	0.320	57778	0	0.000	0.545	0.808	22.07
2	13050	9600	0.46	0.4	57500	0.024	0.024	0.547	1.040	66.91
3	15450	13200	0.535	0.495	56250	0.111	0.136	0.559	1.069	114.07
4	14850	12100	0.610	0.560	55000	0.115	0.250	0.570	1.136	166.10
5	11600	9700	0.665	0.630	54286	0.067	0.317	0.577	0.727	199.08
6	8550	6450	0.75	0.71	52500	0.171	0.488	0.594	0.856	239.96
7	6250	4200	0.87	0.83	51250	0.124	0.612	0.606	0.888	279.37
8	4750	3350	0.99	0.96	46667	0.497	1.109	0.656	0.660	315.56
9	2900	1550	1.13	1.1	45000	0.194	1.304	0.675	0.536	343.85
10	2300	650	1.32	1.28	41250	0.463	1.767	0.722	0.494	471.43

Table 5. Dynamic fracture toughness test.
Tabela 5. Ispitivanje dinamičke žilavosti loma

specimen	J_{Id} (N/mm)	K_{Id} (MPa√m)	a_0/W
1	58.1	120.5	0.441
2	57.6	120.0	0.503

CONCLUSIONS

Information provided in this paper shows that mechanical and material issues are very important in the design and selection of materials for artificial hip implants. Reviews of early fractures of femoral component made of Co-Cr alloy have identified several factors that contribute to implant failure.

An attempt was made to correlate J_{Ic} values with previously obtained K_{Ic} values. Another important task was to investigate the correlation between KV_{total} and K_{Ic} and between KV_{growth} and J_{Id}. These results indicate good mutual agreement and possible actions toward further increase of toughness.

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