ZNAČAJ ISPITIVANJA ŽILAVOSTI I ZAMORA KOD ALUMINIJSKI 6xxx LEGURA

TOUGHNESS AND FATIGUE ANALYSIS OF AL 6xxx ALLOYS

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REZIME
Mehaničke osobine svakog materijala igraju veliku ulogu u toku izbora vrste materijala za bilo koji mehanički sistem. Jedna od osnovnih mehanička karakteristika koja je krucijalna za izbor materijala je žilavost. Rad prikazuje neke aspekte problema vezano za žilavost i zamor aluminijskih legura. U radu su također opisane standardne procedure prema ASTM i britanskom standardu prema kojima se opisuju procedure kod analize i određivanja osobina žilavosti i zamora materijala za ove vrste legura.

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SUMMARY
Mechanical properties of every material play important role during material selection for any mechanic system. The main mechanics property which is crucial for material selection is Toughness. The paper present some of the aspects in problems of the toughness and fatigue for Aluminum Alloys. The paper also presents the set of the ASTM anf British Standards which describe procedure in analysing and determining toughness and fatige properties for this kind of the alloys.

1. UVOD

Mehaničke osobine predstavljaju osnovni kriterij za odabir nekog materijala u mašinskom sistemu. Pri odabiru jedna od osnovnih mehaničkih osobina prema kojoj se definišu grupe materijala koje ulaze u sastav mehaničkog sistema predstavlja zamor materijala. Zamor predstavlja takvu pojavu u materijalu da nakon određenog broja cikličnih opterećenja material slabi i postaje lomljiv, pri vrijednostima opterećenja koja su ispod dozvoljenih statičkim proračuna [1].

Zamor materijala se manifestira kroz stvaranje inicijalnih prslina, a zatim njihovim postepenim širenjem. Ove prsline se šire postepeno, a nakon izvjesnog vremena postaju osnovni uzrok pucanja i loma struture. Također, u vrijeme konstrukcije mehaničkog sistema od krucijalne je važnosti i spoznaja kritičnih parametara mehanike loma da bi sistema radio bezbjedno.

Legure aluminija u upotrebi su zadnjih 100 godina, a posebno u avionskoj industriji od 30-godina prošlog vijeka.

1. INTRODUCTION

The mechanical properties of the material are the basic criteria for selection of material in the mechanical system. When choosing a material, the basic mechanical characteristic by which to define the group of materials that constitute the mechanical system, is material fatigue. Fatigue is such a phenomenon in the material that after a certain number of cyclic loadings, material becomes weak and brittle in load values that are below the allowable static calculations [1].

Material fatigue manifests itself by creating cracks, and their gradual expansion. These cracks are spreading in a certain proportion, eventually becoming a major cause of cracking and fracture of the structure. Therefore, at the time of construction of the mechanical system, the knowledge of fracture mechanics parameters is crucial, in order for the system to work safely.

Aluminum alloys have been in use for the last 100 years, and especially since the 1930s in the aviation industry.

Avio industrija u širokoj upotrebi koristi aluminijske legure 2xxx[1] i 7xxx. Ostale aluminijske legure također su zatupljene u širokoj upotrebi, ne samo u avionskoj nego i u ostalim industrijskim granama. U autoindustriji sve veći je interes za korištenje legura aluminija (Al) 6xxx, koje predstavljaju legure aliminija sa silicijem i magnezijem. Ove legure u širokoj su upotrebi za izradu karoserije i branika na automobilima. Razlog ovog predstavljaju skoro idealne mehaničke osobine ove grupe legura. 6xxx grupa Al legura u upotrebi je zbog njihovih mehaničkih osobina: lahkoće, dobre žilavosti, oblikovanja, zavarljivosti, otpornosti na koroziju, i niske cijene koštanja.

Ispitivanje AL legura na žilavost široko je prisutno, te se nastoji koristiti gdje god to uvjeti dozvoljavaju. Pored osnovnog metala legure, ispitivanje žilavosti zastupljeno je i kod zavarenog spoja, pri čemu je sama tehnologija ispitivanja složenija. Korištenje složenijih ispitivanja nužno je uključiti jer zavareni spoj, zbog svoje heterogenosti, zahtjeva posebna ispitivanja osnovnog metala (OM), zone uticaja toplote, (ZUT) te metala šava (MŠ) [2].

Ispitivanje žilavosti i zamora materijala temelji se na procedurama koje su definisane standardima prvenstveno American Society for Testing and Materials (ASTM) i British Standards Institution (BSI) koji u potpunosti definišu sve procedure ispitivanja kako osnovnog materijala tako i zavarenih spojeva [3]. Modul elastičnosti E, napon tečenja R_p, zatezna čvrstoća R_m te ukupno izduženje, za leguru 6061-T61 dati su u tabeli 1 [4].

Aluminum alloys 2xxx[1] and 7xxx are widely used in the aviation industry. Other aluminum alloys are also represented in wide use, not only in aviation but also in other industries. The automotive industry is showing a growing interest in the use of aluminum alloy 6xxx, which is representing aluminum alloys with Silicon and Magnesium. This alloy is widely used for the bodywork and bumpers of cars. The reason for this is almost ideal mechanical properties of this group of alloys. 6xxx group of Al alloys is widely used because of its mechanical properties: lightness, good toughness, design, weldability, corrosion resistance, and low cost.

Testing of Al alloy toughness is widely present, with the tendency of being used wherever conditions allow. In addition to the base metal alloy, toughness testing is also present in the welded joint, where the testing technology is more complex. Use of complex testing must be enabled as welded joint, because of its heterogeneity, requires special testing of base metal (BM), heat affected zone (HAZ) and weld metal (WM) [2].

Testing of toughness and fatigue is based on the procedures defined by the standards, primarily American Society for Testing and Materials (ASTM) and British Standards Institution (BSI) which fully define all testing procedures of the base material and welded joints [3].

Modulus of elasticity$E$, yield strength σ_p, tensile strength σ_m and total elongation for aluminum alloy 6061-T61 are given in Table 1 [4].

Tabela 1. Mehaničke osobine za leguru 6061-T61[18]
Table 1 Mechanical properties for alloy 6061- T61[18]

Al alloy	$E\ [GPa]$	$R_p\ [MPa]$	$R\_m\ [MPa]$	e [%]
6061-T61 (Tension // to Rolling Direction)	64.8	291.6	317.2	17.0
6061-T61 (Tension ⊥ to Rolling Direction)	67.5	286.1	318.5	16.4

2. STANDARDI ZA ANALIZU I ISPITIVANJE ZAMORA I ŽILAVOSTI AL LEGURA

Sva ispitivanja kako Al legura tako i drugih metala definisana su nacionalnim standardima.

2. STANDARDS FOR THE ANALYSIS AND TESTING OF FATIGUE AND TOUGHNESS OF AL ALLOYS

The testing of Al alloys and other metals is defined by national standards.

[1] *Oznake xxx Al legure predstavljaju prostor za unos osnovni konstutivnih elemenata legure. Npr. 6xxx predstavlja leguru aluminija čiji su osnovni konstituenti Magnezij i Silicij.*

[1]*The xxx Al alloy mark is the space for entering the constituent elements of the alloy. Eg. 6xxx represents aluminum alloy whose basic constituents are Magnesium and Silicon.*

Prve prijedloge standarda za određivanje, pored ostalog, žilavosti loma objavili su Američko društvo za ispitivanje i materijale (American Society for Testing and Materials – ASTM) – ASTM E399-70T, i Britanska institucija za standarde (British Standard Institution – BSI). Standardi su objavljeni po naslovom "Standardni postupak ispitivanja žilavosti loma pri ravnoj deformaciji metalnih materijala" [5], odnosno BS 5447 [6].

Nešto kasnije je BSI objavio prijedlog standarda za određivanje otvaranja prsline DD 19 (Standard Test Method for Crack Opening Displacement), usvojen kao BS 5762 [7]. Poslije usvajanja ovih standarda, predložen je veliki broj standarda za ispitivanje epruveta sa prslinama. Među njima su najviše korišteni:

- ASTM E 813 – 89: (Standardni postupak ispitivanja J_{Ic})[8].
- ASTM E 1152 – 87: (Standardni postupak ispitivanja za određivanje J-R krive)[9].
- ASTM E 1737 – 96: (Standardni postupak ispitivanja za određivanje žilavosti loma pomoću J integrala). Ovaj standard je objedinio dva standarda (E 813 i E 1152), koji su u najvećem dijelu podudarni, a na osnovu iskustva iz njihove primjene u prošireno područje primjene J integrala u karakterizaciji materijala [10].
- ASTM E 1820 – 99a: (Standardni postupak ispitivanja za mjerenje žilavosti loma). Ovaj standard je objedinio standarde E 399, E 1290 i E 1737 [11].

Sličan pristup je usvojen i u Britanskim standardima, pa je u BS 7448 "Fracture mechanics toughness tests" [12] definisano ispitivanje žilavosti loma, odnosno u njegovom prvom dijelu "Methods for determination of K_{Ic}, critical CTOD and critical J values of metallic materials" objedinjeni su postupci za određivanje K_{Ic}, kritičnog CTOD i kritične J vrijed-nosti metalnih materijala. U drugom dijelu BS 7448 "Methods for determination of KIc, critical CTOD and critical J values of welds in metallic materials" [13], koji je objavljen 1997. godine, propisuje se postupak ispitivanja pomoću parametara mehanike loma, zavarenih spojeva. U razradi su treći dio za određivanje dinamičke žilavosti loma i četvrti dio za određivanje krivih otpornosti.

The first proposals of standards for determining fracture toughness were published by the American Society for Testing and Materials (ASTM) – ASTM E399-70T, and the British Standards Institution (BSI). The given proposals were accepted under the title ''Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials as ASTM E 399-86 [5], or BS 5447 [6].

Somewhat later, the BSI published a draft standard for determining crack opening DD 19 (Standard Test Method for Crack Opening Displacement), adopted as BS 5762 [7]. After the adoption of these standards, a number of standards were proposed for testing specimens with cracks. Among them, the most common are:

- ASTM E 813 – 89: Standard Test Method for J_{Ic}, a Measure of Fracture Toughness[8].
- ASTM E 1152 – 87: Standard Test Method for Determining J-R Curve [9].
- ASTM E 1737 – 96: Standard Test Method for J Integral Characterization of Fracture Toughness. This standard has integrated two standards (E 813 and E 1152), which are matching for the most part, based on the experience of their application in the extended application area of *J* integral in the characterization of materials [10]
- ASTM E 1820 – 99a: Standard Test Method for Measurement of Fracture Toughness. This standard integrated standards E 399, E 1290 and E 1737 [11].

Similar approach was adopted in the British standards, so BS 7448 ''Fracture mechanics toughness tests'' [12] defines testing of fracture toughness. Its first part ''Methods for determination of K_{Ic}, critical CTOD and critical J values of metallic materials'' integrates procedures for the determination of K_{Ic}, the critical CTOD and critical J-value of metallic materials. The second part of BS 7448 ''Methods for determination of K_{Ic}, critical CTOD and critical J values of welds in metallic materials'' [13], published in 1997, determines the procedure for testing the fracture mechanics of welded joints. The third part for the determination of dynamic fracture toughness and the fourth part for the determination of resistance curves are being developed.

3. ISPITIVANJA ALUMINIJSKIH 6XXX LEGURA

Često je u primjeni legiranje osnovnog materijala da bi se dobile one mehaničke osobine koje su potebne da se poveća napon tečenja materijala, žilavost materijala, električne i toplotne osobine, povećana otpornost od korozije i dr. Legiranje materijala, s druge strane, zahtjeva posebna ispitivanja dinamičkih osobina poput razvoja prsline i određivanja dinamičke čvrstoće materijala.

Santana i dr. ispitivali su dinamičku otpornost na lom aluminijskih legura 6061-T6 sa prslinama i AlSi 4140T čeličnih epruveta pod visoko frekventnim i nisko frekventnim zamorimim opterećenjima. U radu su pokazali da se plastičnost aluminijske legure povećava kada se povećava nivo zamornog oštećenja [14].

Ding i drugi ispitivali zamorno ponašanje legure AA6061 kao kompozitnog materijala [15].

4. DINAMIČKA ČVRSTOĆA ALUMINIJSKIH LEGURA

Zamorna prslina i lom način su definisanja zamora metala. Kako se u ovom slučaju radi o legurama aluminija, vrlo je važno da se ista analizira na ispitivanja visokocikličnog zamora. Dinamička čvrstoća legure pri promjenjivom opterećenju igra značajnu ulogu u ocjeni stabilnosti konstrukcije. Iskustva su pokazala da se prsline i oštećenja javljaju pri velikom broju promjena opterećenja, dok su naponska opterećenja niža od napona tečenja. Od posebne važnosti za svaku konstrukciju jeste da se materijal prethodno podvrgne ispitivanjima na visokociklični zamor. Za opterećenja niža od napona tečenja, koji je karakteristika za visokociklični zamor, najčešće se ispitivanje izvodi u krutom režimu, pri zadanoj amplitudi opterećenja R_{a}[MPa]. Prakticira se, da ciklus opterećenja simulira uvjete rada konstrukcije sa uproštenim oblicima ciklusa opterećenja. Ciklični zamor predstavlja se u formi krive $\sigma -$ N, pri čemu σ predstavlja naprezanje a N broj ciklusa.

Kriva $\sigma - N$ prikazuje rezultate ispitivanja pri čemu se na testnoj mašini na ordinati nanosio normalni sinusoidalni napon, dok se na apcisi nanosio odgovarajući broj ciklusa.

Dijagram pokazuje da u koliko se materijal optereti naponom ispod graničnog napona, za odgovarajući broj ciklusa, neće doći do oštećenja, bez obzira koliko puta on bio podrvgnut ovom opterećenju.

3. PRECEDING TESTING OF ALUMINUM 6XXX ALLOYS

Alloying of the base material is frequently applied in order to obtain those mechanical properties which are required for the increased yield strength of materials, toughness, electrical and thermal properties, increased corrosion resistance, etc. On the other hand, material alloying require special testing of dynamic properties such as crack growth and dynamic toughness.

Santana et al examined the dynamic resistance of aluminum alloy 6061-T6 with cracks and AlSi 4140T steel tubes under high frequency and low frequency fatigue loads. Analysis showed that the plasticity of aluminum alloy is increased when increasing the damage level [14].

Ding et al examined the fatigue behavior of alloy AA6061 as a composite material[15].

4. FATIGUE STRENGTH OF ALUMINUM ALLOYS

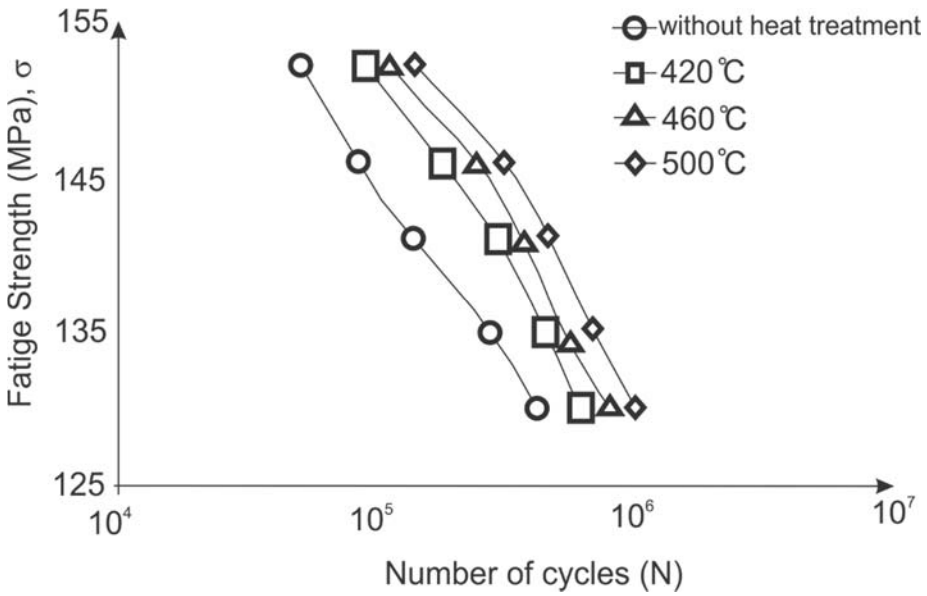
Fatigue crack and fracture are the ways of defining the metal fatigue. As, in this case, it is an aluminum alloy, it is very important for it to be analyzed at high cyclic fatigue tests. Fatigue strength of the alloy at variable load represents an important role in assessing the stability of the structure. Experience has shown that the cracks and defects occur in a large number of load changes, whereas the tensile stress is lower than the yield stress. Of particular importance for each structure is that materials undergo primary testing on the high-cycle fatigue. For loads lower than the yield stress, which is characteristic for high-cyclic fatigue, the most common test is performed in rigid mode, at a given stress amplitudeσ_a [MPa]. It is common that load cycle simulates the working conditions of construction with simplified forms of load cycles. Cyclic fatigue is represented asσ – Ncurve, wherein σ represents stress and N number of cycles.

Curve $\sigma – N$ shows the results of testing in which the normal sinusoidal load was applied on the testing machine where an appropriate number of cycles was applied on the x-axis.

The diagram shows that, if the material is loaded below the limit for the appropriate number of cycles, there will be no defect, regardless of how many times it was submitted to this load.

Vijek zamora predstavlja broj naponskih ciklusa određenog oblika, koje epuveta može prihvati, a da ne dođe do loma, odnosno broj ciklusa opterećenja koje material može da izdrži, a da ne dođe do njegovog loma. Dinamička čvrstoća sa brojem ciklusa za aluminijske legure 6xxx prikazana je na slici 1. Sa slike se može uočiti da na smanjenje dinamičke čvrstoće uzrokuje povećanje broja ciklusa [1].
Na slici se također može uočiti da uspoređivanje dinamičke čvrstoće aluminijske legure sa različitima brojem ciklusa sa ili bez toplotne obrade. Toplotna obrada urađena je na temparaturama 420, 460, 500 ^{o}C i držanje na tim temperaturama 1 sat. Može se uočiti da se broj ciklusa povećava za legure koje su termički obrađene i to za 44%, 55% i 64% u odnosu na neobrađenu leguru respektivno[16].

Fatigue life represents the number of load cycles of a certain shape that tube can accept without cracking, or the number of cycles that the material can accept to avoid its fracture. Fatigue strength with the number of cycles for aluminum alloy is shown in Figure 1. The Figure 1 indicates that the reduction in fatigue strength causes an increase in the number of cycles [1].
Figure 1 also depicts the comparison of fatigue strength of aluminum alloy with a different number of cycles with and without heat treatment. Heat treatment was conducted at temperatures of 420, 460, and 500 □C for 1 hour of toughening. We can see that the number of cycles increase for the alloys that were heat treated to 44%, 55% and 64% compared to non-treated alloys, respectively [16].



Slika 1. *Zamorna čvrstoća sa brojem cikličnih opterećenja za grupu termički obrađenih aluminijskih 6xxx legura [16]*
Figure 1*. Fatigue strength with number of cyclic loads for the group of thermally treated Aluminum 6xxx alloys [16]*

5. RAST ZAMORNE PRSLINE KOD ALUMINIJSKIH LEGURA

Teorijskim analizama nije moguće u potpunosti objasniti fenomen ponašanja materijala kod promjenjivog opterećenja, pa se kombinacijom eksperimentalnog i teorijskog pristupa o ovom fenomenu mogu izvući određeni zaključci i dobiti kvalitetni rezultati [17]. Pogodnom analizom i ispitivanjem moguće je jasno odrediti prelaznu fazu zamorne prsline, u kojoj ona nastaje, i u kojoj zamorna prslina raste do kritične veličine, odnosno do loma materijala.

5. FATIGUE CRACK GROWTH IN ALUMINUM ALLOYS

Theoretical analysis cannot fully explain the phenomenon of behavior of materials with variable loads, whereas the combination of experimental and theoretical approach of this phenomenon can help make some conclusions and obtain quality results [17]. Suitable analysis and testing can clearly define transitional phase of fatigue crack, in which it occurs, and the second phase in which the crack grows to a critical size, or to material fracture.

Pri svakom lomu nedvosmisleno se može izračunati broj ciklusa potrebnih da zamorna prslina nastane N_i i broj u kojima se ona razvija do kritične veličine N_p. Shodno tome, ukupan broj ciklusa može se predstaviti sljedećim izrazom:

$$N_U = N_I + N_p. \qquad (1)$$

Parisova jednačina u stanju je da odredi razliku između nastajanja i rasta zamorne prsline što je od velikog značaja.

Standard ASTM E647 [18] definiše na koji način se može izmjeriti rast zamorne prsline, koja je prije toga prošla fazu nastajanja. Važna činjenica se ovdje može primijetiti, a to je da bez obzira što je u konstrukciji nastala faza stvaranja prsline, konstrukcija se još uvijek može eksploatirati sve dok veličina prsline ne pređe kritičnu veličinu. Ukoliko se poznaje brzina rasta zamorne prsline, konstrukciju je moguće eksploatirati potpuno bezbjedno sve do perioda u kojem se očekuje da veličina zamorne prsline prelazi kritičnu vrijednost.

Otpornost materijala i stabilnost rasta prsline pri cikličkom opterećenju općenito je data kroz krive $\sigma - N$, odnosno $a - N$, pri čemu σ – predstavlja ciklično nprezanje, N- broj ciklusa, a dužina prsline. Pored ovih dijagrama vrlo važan dijagram predstavlja i brzina rasta zamorne prsline da/dN u odnosu na veličinu otvaranja prsline CTOD, K_{Ic} koeficijent intenziteta napona.

Općeniti dijagram između rasta zamorne prsline i ΔK za većinu aluminijskih legura 6xxx prikazuje slika 2. Na slici 2 su prikazani dijagrami za aluminijsku leguru 6061-T61 za različite vrste procesa obrade i zamorne prsline.

Na slici 2 brzina rasta zamorne prsline računata je uz prisustvo niske vrijednosti zaostalih naprezanja R=0.1.

6. ZAKLJUČAK

U rada su prikazani neki od osnovnih značajki aluminijskih legura oznake 6xxx, koje široku upotrebu imaju u auto industriji. U radu su prezentiranih i osnovni standardi za ispitivanje parametara mehanike loma, dinamičke čvrstoće i drugim važnih osobina legura. Poseban aspekt stavljen je na britanske i američke standarde ispitivanja koji su se prvi pojavili i definisali ovu problematiku.

During each fracture, the number of cycles required for fatigue crack to occur N_i and number in which it develops to a critical size N_p can clearly be calculated. Consequently, the total number of cycles can be represented by the following equation.

$$N_U = N_I + N_p. \qquad (1)$$

Paris equation is able to determine the difference between initiation and crack growth rate which is of great importance.

Standard ASTM E647 [18] defines how one can measure the fatigue crack growth, which has previously passed the initiation phase. An important fact to be noted here is that regardless of the fact that crack initiation phase has occurred in the construction, the construction can still be exploited until the crack size does not exceed the critical size. If the fatigue crack growth is known, the construction can be exploited completely safe until the period in which it is expected that the size of the fatigue crack will exceed the critical value.

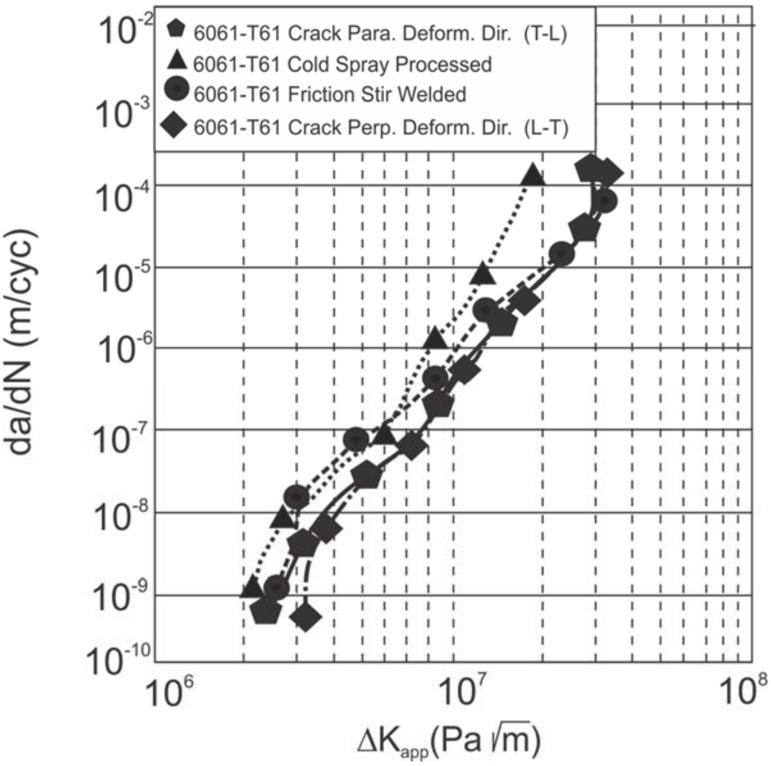
Strength of material and stability of crack growth under cyclic loading is generally given through the curve $\sigma - N$ or $a - N$, where σ – represents a cyclic load, N – number of cycles, a – crack length. In addition to these diagrams, one very important diagram presents the fatigue crack growth rate da/dN in relation to the size of the crack opening displacement CTOD, KIc stress intensity factor.

The general diagram of fatigue crack growth and ΔK for most aluminum alloys 6xxx is shown in Figure 2. Figure 2 shows diagrams of aluminum alloy 6061-T61 for different machining process and values of the initial fatigue crack.

In Figure 2, fatigue crack growth rate is calculated with the presence of low levels of residual stresses R = 0.1.

6. CONCLUSION

The paper presents some of the basic properties of aluminium 6xxx alloys, which are widely used in the automotive industry. The basic standards for testing the parameters of fracture mechanics, dynamic strength and other important properties of alloys are presented in this paper. A special aspect was put on the British and US standards of testing which are first appeared and defined this area.



Slika 2. *Rast zamorne prsline za AL6061-T61 pri različitim procesima obrade uz zaostalo naprezanje[17]*
Figure 2. *Fatigue crack growth for alloy AL6061-T61 for various machining process [17]*

Za aluminijsku leguru 6061 prikazane su osnovne mehaničke osobine koje predstavljaju ulazne parametre za ispitivanje dinamičke čvrstoće, vijeka trajanja legure u odnosu na dinamička ciklična naprezanja, te rast zamore prisilne. Ispitivanja aluminijskih legura pokazuju da se plastičnost povećava sa povećanjem veličine zamornog oštećenja.

For aluminium alloy 6061 basic mechanical properties are presented. Those values were input parameters for testing the dynamic strength, the life of the alloy in relation to dynamic cyclic stresses, and the fatigue crack growth. Aluminium alloy tests show that plasticity increases with increasing damage level.

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