

# Določevanje parametrov utrujanja jekla z veliko trdnostjo S1100Q

## Determination of the Low-Cycle Fatigue Parameters of S1100Q High-Strength Steel

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*V prispevku je predstavljena preizkusna raziskava za določitev utrujenostnih parametrov jekla z veliko trdnostjo S1100Q, ki se z namenom zmanjšanja skupne teže, pogosto uporablja pri zelo obremenjenih strojnih delih in konstrukcijah (premični žerjavi). Preizkusi so izvedeni v režimu malocikličnega utrujanja po standardu ASTM E 606 z nespremenljivim premerom preizkušanca. Na podlagi izsledkov preizkusa so po predpisani računski metodi po ASTM E 606 določeni ustrezni parametri malocikličnega utrujanja.*

*V drugem delu prispevka je predstavljen računski model za določitev dobe trajanja nosilnega droga protiuteži premičnega žerjava. Računski model temelji na deformacijski metodi ( $\epsilon$ -N), pri čemer so uporabljene poprej določene snovne lastnosti jekla z veliko trdnostjo S1100Q. Na posebej izvedenem hidravlično vodenem utripnem stroju so izvedeni tudi utrujenostni preizkusi nosilnega droga. Primerjava med računskimi in preizkusnimi izsledki kaže dobro ujemanje.*

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**(Ključne besede: utrujanje materialov, doba trajanja, numerični izračuni, deformacijske metode)**

*We designed an experimental investigation to determine the fatigue properties of the high-strength steel S1100Q, which is often used in highly loaded machine components and structures, e.g., mobile cranes, to reduce weight. Fatigue tests were carried out in a low-cycle regime according to the ASTM E 606 standard, where standardized, uniform-gauge test specimens are used. On the basis of the experimental results the appropriate low-cycle fatigue parameters were determined using the calculation procedure described in ASTM E 606.*

*In the second part of the paper, a service-life evaluation of the counterweight of a mobile crane by means of a computational analysis is presented. The computational analysis was performed using the local strain-life approach ( $\epsilon$ -N), where the appropriate material properties for treated high-strength S1100Q steel were used. The experimental fatigue tests on the bars were carried out in a specially constructed hydraulic pulsation test machine. The comparison of the computational and experimental results showed a reasonable agreement.*

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**(Keywords: fatigue, life times, numerical calculations, strain-life approach)**

### 0 UVOD

Pri dimenzioniranju dinamično obremenjenih strojnih delov in konstrukcij postaja vse bolj pomembna napoved njihove dobe trajanja. Pri mnogih konstrukcijah (npr. premični žerjavi) so vedno večje tudi zahteve po zmanjšanju njihove skupne teže. Ena od možnosti za doseg tega cilja je zmanjšanje nosilnih prečnih prevezov z uporabo jekel z veliko trdnostjo, pri čemer je treba uporabiti ustrezne konstrukcijske rešitve, ki zmanjšujejo možnost nastanka utrujenostnih poškodb. Če se le-

### 0 INTRODUCTION

When it comes to the design of cyclically loaded engineering structures and components, the prediction of their service life is of great importance. There is a growing interest in many structures, for example, mobile cranes, in order to reduce the weight of the structure. One way to achieve this goal is to reduce the required cross-sections using high-strength steel. Thus, clear design guidelines are needed to ensure that fatigue failures are avoided in critical cross-sections. Apart from the design of new

te pojavijo, je treba znati oceniti preostalo dobo trajanja konstrukcije.

Izračun dobe trajanja dinamično obremenjenih komponent temelji na poznavanju napetosti oziroma deformacij v kritičnih prečnih prerezi, ki jih običajno določimo numerično po metodi končnih elementov (MKE). Glavne vplivne veličine na dobo trajanja so zunanje obremenitve in trdnostne lastnosti uporabljenega materiala. To pomeni, da je za tovrstne preračune treba poznati trdnostne lastnosti materiala pri utrujevalnih obremenitvah.

Za reševanje problemov utrujanja se dandanes vse več uporablja deformacijska metoda ([1] in [2]), še posebej pri dimenzioniranju dinamično obremenjenih komponent ob navzočnosti raznih zarez. Če je strojni del z zarezo izpostavljen dinamični obremenitvi, je obnašanje materiala mogoče opisati s poznavanjem deformacij ob zarezi. Predvsem v primeru plastifikacije materiala je določitev deformacij preprostejša kakor določitev ustreznih napetosti. Napovedovanje utrujenostnih poškodb z deformacijsko metodo se v takšnih primerih nanaša predvsem na krajevne deformacije ob zarezi in dejansko pomeni določitev števila nihajev obremenitve za nastanek razpoke. Za celotno rešitev problema je mimo lokalnih deformacij ob zarezi treba poznati tudi ustrezne parametre malocikličnega utrujanja uporabljenega materiala.

Slika 1 prikazuje deformacijske krivulje v dvojnem logaritmskem diagramu, kjer je  $N_f$  število nihajev do pojava poškodbe. Skupna amplitudna deformacija  $\varepsilon_a$  na sliki 1 sestoji iz elastične ( $\Delta\varepsilon_e/2$ ) in plastične ( $\Delta\varepsilon_p/2$ ) amplitudne deformacije, ki jih preberemo iz stabilnih histereznih zank. Pri določenem številu nihajev  $N_f$  je skupna deformacija vsota elastične in plastične deformacije ([1] in [2]):

$$\varepsilon_a = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E} \cdot (2 \cdot N_f)^b + \varepsilon_f' \cdot (2 \cdot N_f)^c \quad (1),$$

kjer so  $E$  modul elastičnosti,  $\sigma_f'$  koeficient trdnosti pri utrujanju,  $b$  eksponent trdnosti pri utrujanju,  $\varepsilon_f'$  koeficient žilavosti pri utrujanju in  $c$  eksponent žilavosti pri utrujanju. Utrujenostne parametre  $\sigma_f'$ ,  $b$ ,  $\varepsilon_f'$  in  $c$ , ki jih imenujemo tudi "parametri malocikličnega utrujanja", določimo s preizkusi po standardu ASTM E 606 [3]. Če je pri dejanskem strojnem delu ali konstrukciji poznana skupna amplitudna deformacija  $\varepsilon_a$  (ki jo določimo numerično ali z meritvami), določimo dobo trajanja  $N_f$  z ponavljajočim postopkom po enačbi (1).

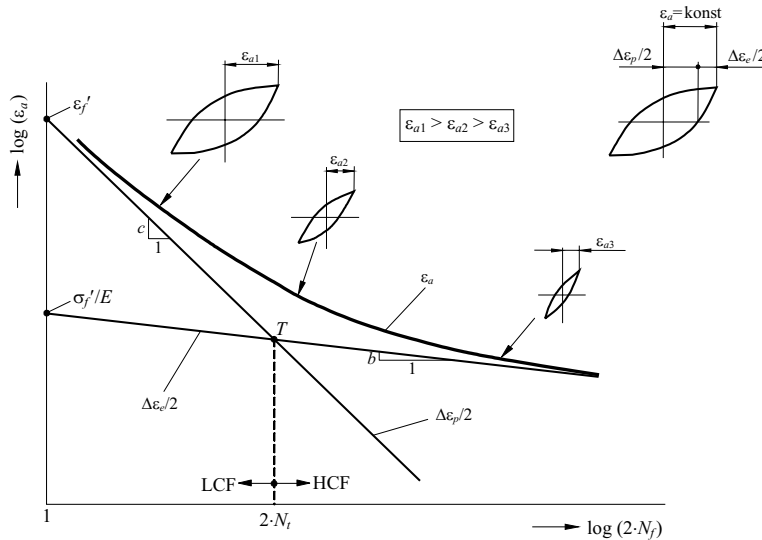
structures, there is also an increasing interest in assessing the remaining fatigue life of existing structures.

The service-life calculation of a cyclically loaded component is based on a knowledge of the stresses or deformations in the critical cross-sections, usually calculated by means of a finite-element analysis (FEA). The main parameters influencing the fatigue life are the external loads and the strength behavior of the material. Therefore, the appropriate fatigue properties of the material should be known for such an analysis.

The strain-based approach to fatigue problems is widely used at present ([1] and [2]). The most common application of the strain-based approach is in the fatigue of notched members. In a notch component subjected to cyclic external loads, the behavior of the material at the root of the notch is best considered in terms of strain. As long as there is an elastic constraint surrounding a local plastic zone at the notch, the strains can be calculated more easily than the stress. Since fatigue damage is assessed directly in terms of local strain, this approach is also called the "local strain approach". A reasonable expected fatigue life, based on the nucleation or formation of small macrocracks, can then be determined if one knows the local strain-time history at a notch in the component and the unnotched strain-life fatigue properties of the material.

Strain-life fatigue curves plotted on log-log scales are shown schematically in Fig. 1, where  $N_f$  is the number of cycles to failure. The total strain amplitude,  $\varepsilon_a$ , shown in Fig. 1 has been resolved into the elastic ( $\Delta\varepsilon_e/2$ ) and the plastic ( $\Delta\varepsilon_p/2$ ) strain components from the steady-state hysteresis loops. At a given life  $N_f$  the total strain is the sum of the elastic and plastic strains, as follows ([1] and [2]):

where  $E$  is the modulus of elasticity,  $\sigma_f'$  is the fatigue-strength coefficient,  $b$  is the fatigue-strength exponent,  $\varepsilon_f'$  is the fatigue-ductility coefficient and  $c$  is the fatigue-ductility exponent. The strain-life fatigue properties  $\sigma_f'$ ,  $b$ ,  $\varepsilon_f'$  and  $c$ , which are often referred to as the "low-cycle fatigue properties", are obtained experimentally according to the ASTM E 606 standard [3]. When the total strain amplitude,  $\varepsilon_a$ , in real machine part or structure is known (it can be measured or determined numerically), the fatigue life  $N_f$  can then be calculated iteratively using Equation (1).



Sl. 1. Deformacijske krivulje s prikazom skupne ( $\epsilon_a$ ), elastične ( $\Delta\epsilon_e/2$ ) in plastične ( $\Delta\epsilon_p/2$ ) amplitudne deformacije

Fig. 1. Strain-life curves showing total ( $\epsilon_a$ ), elastic ( $\Delta\epsilon_e/2$ ) and plastic ( $\Delta\epsilon_p/2$ ) strain amplitude

1 PARAMETRI MALOCIKLIČNEGA  
UTRUJANJA JEKLA Z VELIKO TRDNOSTJO  
S1100Q

1 LOW-CYCLE FATIGUE PROPERTIES  
OF THE HIGH-STRENGTH STEEL  
S1100Q

Določevanje parametrov malocikličnega utrujanja  $\sigma_f'$ ,  $b$ ,  $\epsilon_f'$  in  $c$  je standardizirano po standardu ASTM E 606 [3], ki predpisuje natančna priporočila glede testnih preizkušancev, preizkusnega stroja s pripadajočo opremo, poteka preizkušanja in končnega poročila.

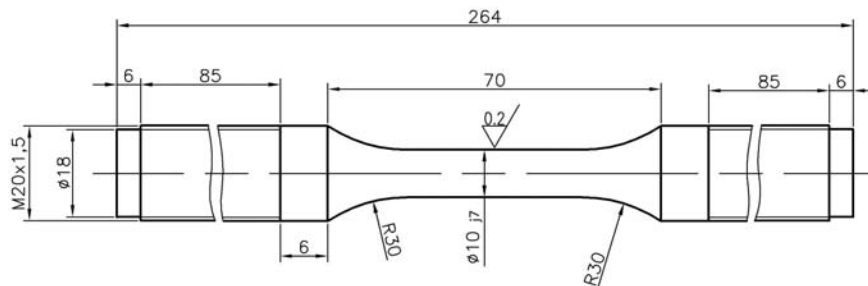
Preizkušani material S1100Q je bil dobavljen v obliki vroče valjanih plošč, iz katerih so bili v smeri valjanja izrezani surovci ustreznih izmer. Iz teh so bili z mehansko obdelavo izdelani končni preizkušanci na sliki 2.

Preglednica 1 podaja kemijsko sestavo preizkušane gradiva, na sliki 3 pa je prikazana mikrostruktura gradiva. S slike je razvidno, da je

The determination of the low-cycle fatigue properties  $\sigma_f'$ ,  $b$ ,  $\epsilon_f'$  and  $c$  is standardized according to the ASTM E 606 standard [3], which provides detailed recommendations about the test specimens, the testing machine with appropriate equipment, the testing procedure and the final report.

The investigated material S1100Q was supplied as hot-rolled plates. Appropriate sizes of raw material were cut out of the plate in the rolling direction. Further specimens were machined to the final shape shown in Fig. 2.

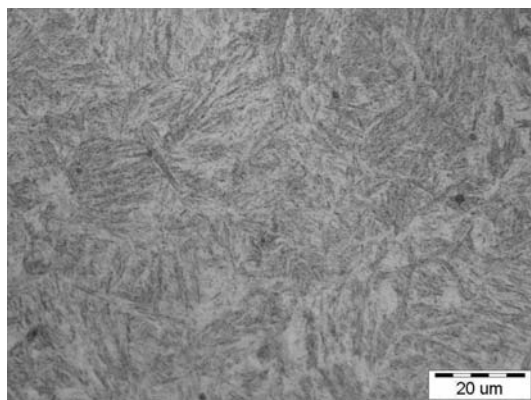
Table 1 shows the chemical composition of the tested material. The material microstructure is shown in Fig. 3. It is evident that the structure



Sl. 2. Testni preizkušane po standardu ASTM E 606  
Fig. 2. Test specimen according to ASTM E 606 standard

Preglednica 1. *Kemijska sestava jekla z veliko trdnostjo S1100Q*Table 1. *Chemical composition of high strength steel S1100Q*

Element	C	Si	Mn	P	S	Cr	Ni	Mo	V	Cu	Al	Nb	N	B
%	0,18	0,2	0,83	0,007	0,003	0,56	1,88	0,564	0,057	0,01	0,61	0,017	0,006	0,002



Sl. 3. *Mikrostruktura materiala*  
Fig. 3. *Microstructure of the material*

struktura gradiva igličasti bainit z zelo drobnimi iglicami. Zaradi različne usmerjenosti rasti posameznih kristalov je moč predpostaviti povprečne mehanske lastnosti v vseh smereh obravnavane sestave.

Pred utrujenostnimi preizkusi je bil izveden statični natezni preizkus z enakim preizkušancem kakor ga prikazuje slika 2. Slika 4a prikazuje tehnični diagram napetost - deformacija, iz katerega so določeni natezna trdnost  $R_m = 1450$  MPa, meja plastičnosti  $R_e = 1148$  MPa in modul elastičnosti gradiva  $E = 194889$  MPa. Iz dejanskega diagrama napetost - deformacija na sliki 4b pa sta ob upoštevanju dejanske napetosti  $\sigma$  in dejanske plastične deformacije  $\varepsilon_p$  iz Hollomonovega razmerja (2) določena trdnostni koeficient  $K = 2272$  MPa in deformacijski eksponent utrjanja  $n = 0,109$ . Pri tem je predpostavljeno, da je razmerje med dejansko napetostjo in plastično deformacijo v dvojnem logaritmskem diagramu linearno, kjer pomenita  $K$  napetost pri  $\varepsilon_p = 1$ ,  $n$  pa strmino premice (sl. 5).

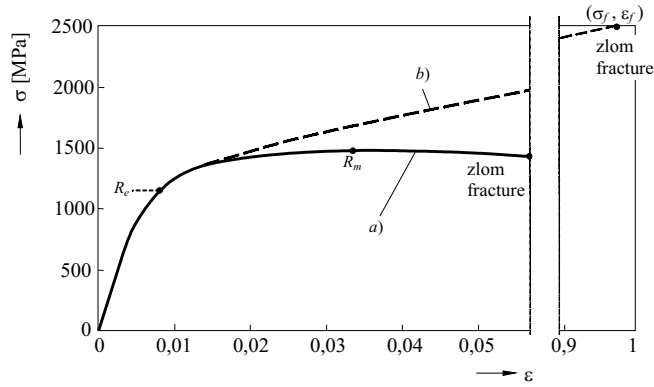
$$\sigma = K \cdot (\varepsilon_p)^n \quad (2).$$

Utrujenostni preizkusi so bili izvedeni z nadzorom deformacije na hidravličnem preizkusnem stroju za utrujanje Instron 1255 (slika 6) z računalniškim vmesnikom in sistemom zbiranja podatkov Instron 8500. Nihaj obremenitve je imel trikotno obliko z obremenitvenim razmerjem  $R = -1$ . Temperatura preizkušanja  $20^\circ\text{C}$  je bila med

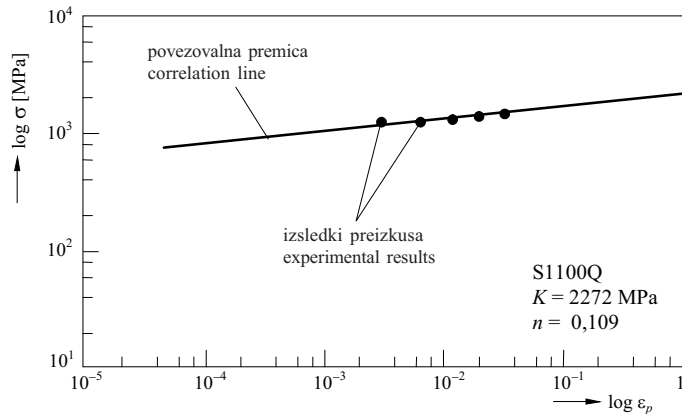
resembles lower needle bainite with extremely fine needles. Because of the different orientations of crystal growth it can be assumed that the average mechanical properties can be used in all loading directions.

Before the fatigue tests, the monotonic tensile test was made using the same specimen as shown in Fig. 2. The engineering stress-strain curve is shown in Fig. 4a, from which the ultimate tensile strength  $R_m = 1450$  MPa, the yield stress  $R_e = 1148$  MPa and the modulus of elasticity  $E = 194889$  MPa are recorded. Considering the true stress,  $\sigma$ , and true plastic strain,  $\varepsilon_p$ , from the true stress-strain curve in Fig. 4b, the strength coefficient  $K = 2272$  MPa and the strain-hardening exponent  $n = 0.109$  were determined using the Hollomon relationship (2). Here it is assumed that the plot of true stress versus true plastic strain in log-log coordinates results in a linear curve, where  $K$  is the stress intercept at  $\varepsilon_p = 1$  and  $n$  denotes the slope of the line (see Fig. 5).

The low-cycle fatigue tests were carried out in the strain-controlled regime on an Instron 1255 servo-hydraulic fatigue machine (see Fig. 6) with a computer-aided control unit and an Instron 8500 data-recording system. The loading waveform was triangular with a loading ratio  $R = -1$ . The specimen temperature was  $20^\circ\text{C}$  and this was manually checked



Sl. 4. Tehnična (a) in dejanska (b) krivulja napetost - deformacija  
Fig. 4. The engineering (a) and true (b) stress-strain curve



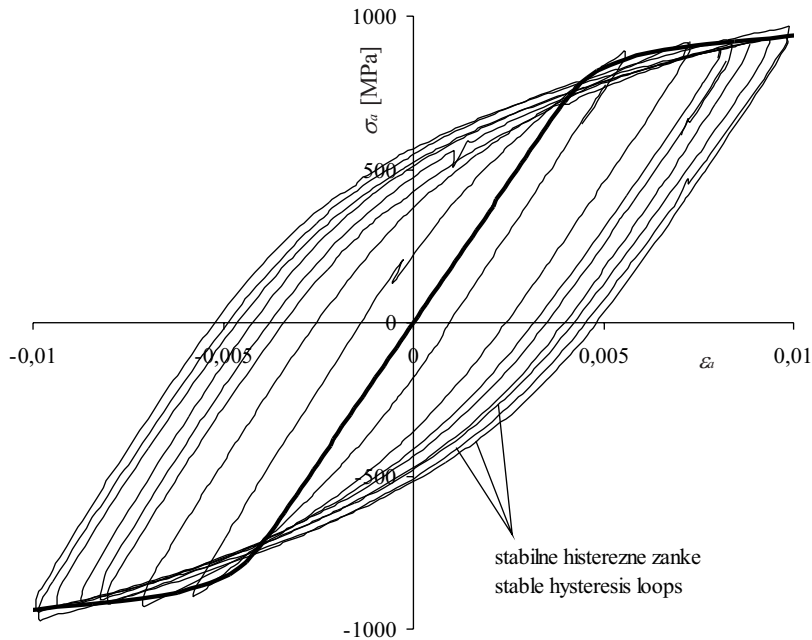
Sl. 5. Razmerje med dejansko napetostjo in dejansko plastično deformacijo  
Fig. 5. True stress versus true plastic strain behaviour



Sl. 6. Preizkusni stroj INSTRON 1255  
Fig. 6. Test machine INSTRON 1255

preizkusom nadzorovana ročno z digitalnim termometrom. Frekvenca obremenjevanja je bila višja pri nižjih amplitudnih deformacijah, saj je nastala energija v tem primeru manjša. Parametri malocikličnega utrujanja so bili določeni na podlagi rezultatov osmih preizkušancev, pri čemer je bil kriterij poškodbe zlom preizkušanca.

during the test procedure using a digital thermometer. The loading frequency was higher for specimens with a lower deformation amplitude, as the energy generated in each cycle is lower. The low-cycle fatigue parameters were determined using the results from 8 specimens, where specimen separation was chosen as the failure criterion.



Sl. 7. Ciklični diagram napetost - deformacija  
 Fig. 7. The cyclic stress-strain curve

Slika 7 prikazuje ciklično krivuljo napetost - deformacija, ki je dobljena na podlagi osmih histereznih zank, ki opisujejo utrujenostno obnašanje preizkušancev na različnih deformacijskih ravneh. Iz diagrama na sliki 7 sta določena ciklični modul elastičnosti  $E' = 183443$  MP in ciklična meja plastičnosti  $R_e' = 875$  MPa.

Podobno kakor pri statičnem je tudi pri utrujenostnem preizkusu odvisnost med dejansko amplitudno napetostjo  $\sigma_a$  in dejansko amplitudno deformacijo  $\Delta\varepsilon_p/2$  v dvojnem logaritemskem diagramu linearna (sl. 8) in jo izrazimo z eksponentno enačbo:

$$\sigma = K' \cdot \left( \frac{\Delta\varepsilon_p}{2} \right)^{n'} \quad (3)$$

kjer sta  $K'$  trdnostni koeficient in  $n'$  deformacijski eksponent utrjanja pri dinamični obremenitvi. S slike 8 se vidi, da je  $K' = 1280$  MPa (pripadajoča napetost pri  $\Delta\varepsilon_p/2 = 1$ ) in  $n' = 0,059$  (strmina premice).

Slika 9 prikazuje krivulje dobe trajanja v dvojnem logaritemskem diagramu, kjer pomeni  $N_f$  število nihajev do zloma preizkušanca. Če primerjamo dobljene veličine na sliki 9 s teoretičnimi veličinami na sliki 1, sledijo parametri malocikličnega utrjanja za jeklo z veliko trdnostjo S1100Q:

- koeficient trdnosti pri utrjanju:  $\sigma_f' = 2076$  MPa
- eksponent trdnosti pri utrjanju:  $b = -0,0997$
- koeficient žilavosti pri utrjanju:  $\varepsilon_f' = 9,93$
- eksponent žilavosti pri utrjanju:  $c = -0,978$

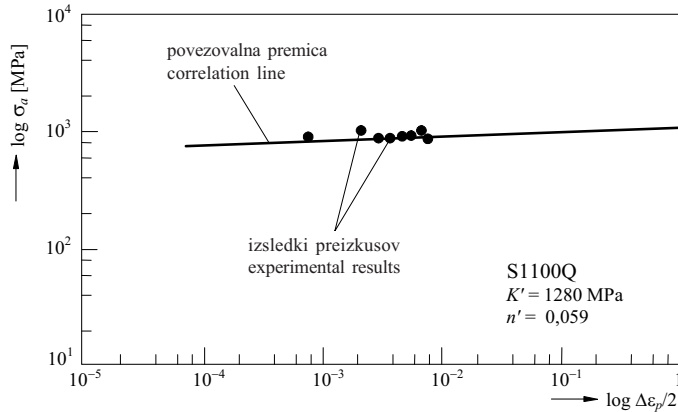
Fig. 7 shows the cyclic stress-strain curve, which is constructed on the basis of 8 stable hysteresis loops describing the fatigue behavior of the specimens loaded on a different strain level. From Fig. 7, the cyclic modulus of elasticity,  $E' = 183443$  MPa, and the cyclic yield stress,  $R_e' = 875$  MPa, are recorded.

Similar to the monotonic deformation in a tension test, a plot of the true stress amplitude,  $\sigma_a$ , versus the true plastic-strain amplitude,  $\Delta\varepsilon_p/2$ , in log-log coordinates results in a linear curve (see Fig. 8) represented by the power function

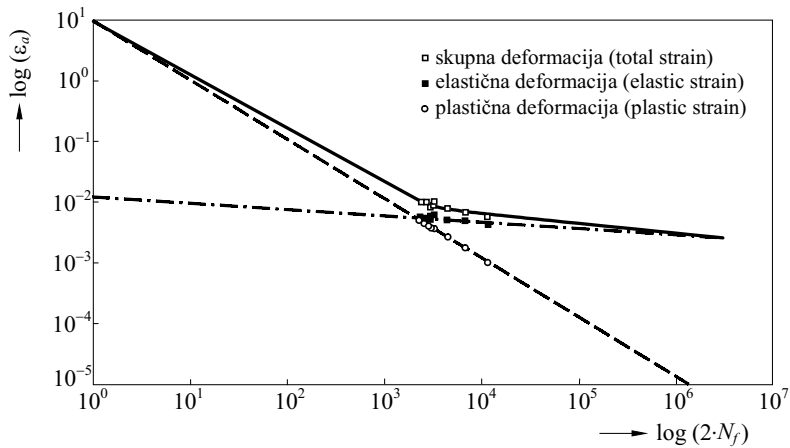
where  $K'$  is the cyclic strength coefficient and  $n'$  is the cyclic strain-hardening exponent. It is evident from Fig. 8 that  $K' = 1280$  MPa (stress intercept at  $\Delta\varepsilon_p/2 = 1$ ) and  $n' = 0.059$  (the slope of the line).

Fig. 9 shows the strain-life fatigue curves plotted on log-log scales, where  $N_f$  is the number of cycles to failure for each tested specimen. If the magnitudes in Fig. 9 are compared with the theoretical ones in Fig. 1, the low-cycle fatigue parameters for the high-strength steel S1100Q result in:

- fatigue-strength coefficient:  $\sigma_f' = 2076$  MPa
- fatigue-strength exponent:  $b = -0,0997$
- fatigue-ductility coefficient:  $\varepsilon_f' = 9,93$
- fatigue-ductility exponent:  $c = -0,978$



Sl. 8. Razmerje med dejansko amplitudno napetostjo in dejansko amplitudno plastično deformacijo  
 Fig. 8. True stress amplitude versus true plastic strain amplitude behaviour



Sl. 9. Deformacijske krivulje jekla z veliko trdnostjo S1100Q  
 Fig. 9. Strain-life curves of high strength steel S1100Q

2 PRAKTIČNI PRIMER

2 PRACTICAL EXAMPLE

Pri goseničnih žerjavih (slika 10) so potrebne protiuteži pogosto obešene na jeklenih verigah. Slednje sestavljajo s sorniki povezani drogovi, običajno izdelani iz jekel z veliko trdnostjo, na primer S1100Q [4]. Na podlagi parametrov malocikličnega utrujanja, določenih v poglavju 1, je v nadaljevanju analizirano obnašanje navedenih drogov pri utrujenostni obremenitvi. Problem je analiziran preizkusno in računsko.

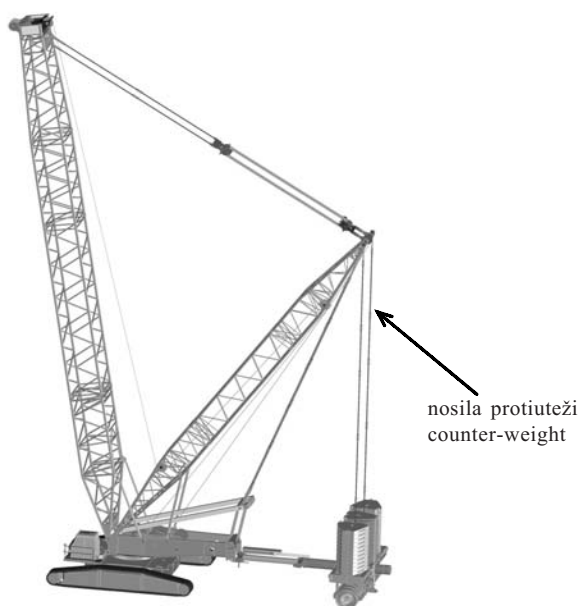
Crawler cranes (Fig. 10) are devices in which a counter weight is usually supported by a steel chain, which consists of a series of highly loaded bars, usually made of high-strength steels like S1100Q [4]. On the basis of the low-cycle fatigue parameters determined in Section 1, the fatigue assessment of such steel bars is analysed using experimental testing and computational analysis, as described in the following sections.

2.1 Izvedeni preizkusi

2.1 Experimental testing

Preizkusi utrujanja drogov so bili izvedeni na namenski preizkusni napravi, sestavljeni iz dveh togih plošč, povezanih s palično konstrukcijo (sl. 11a). Potrebna sila preizkušanja je dosežena prek hidravličnih valjev na osnovni plošči. Velikost sile je

The fatigue tests were carried out in a specially designed testing machine made of two basic rigid plates, which are connected with a central lattice (Figure 11a). The load is applied using the oil pressure pumped into hydraulic cylinders, which are



Sl. 10. Gosenični žerjav

Fig. 10. Crawler crane

določena posredno prek tlaka olja v hidravličnem sistemu. S spremembo smeri pretoka olja je krmiljena smer delovanja sile. Navedena preizkusna naprava omogoča hkrati simultano preizkušanje štirih preizkušancev z največjo natezno silo 1000 kN za vsak preizkušanec. Dejanske napetosti v preizkušancu so nadzorovane prek tlaka olja in še dodatno z merilnimi lističi. Slaba stran preizkusne naprave so potrebne velike sile za doseg želenih napetosti ter težave pri zagotavljanju želenih frekvenc preizkušanja.

Preizkusni drogovi (sl. 11b) imajo pravokotni prerez (30×50 mm) in so sklenjeni v obliki ušes z izvrtino za sornik. 6 m dolgi drogovci so iz osnovnih plošč izrezani s plamenskim rezanjem, vse površine rezanja pa so pozneje obdelane z brušenjem. Pri preizkusu so drogovci obremenjeni na nateg, pri čemer je zasledovana natezna napetost v kritičnem prerezu droga.

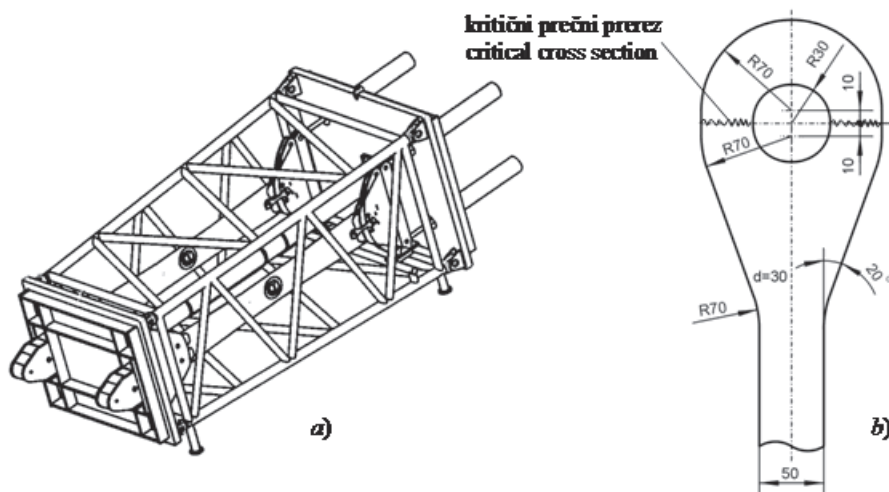
Za zbiranje podatkov je uporabljena ustrežna oprema "National Instruments". Celotni sistem vsebuje kartico zbiranja podatkov AT-MIO-16E-2, vgrajeno v računalnik, modul za analizo signalov SCXI-1520 in programski paket Lab VIEW 6.1. Modul za analiziranje signalov omogoča sprejem do 8 signalov z merilnih lističev pri frekvencah do 300 kHz. Za končno vrednotenje poteka testiranja je treba podati natančno obliko nihaja obremenitve (največja in najmanjša obremenitev znotraj nihaja). Zaradi velike dolžine kablov (približno 12 m) so uporabljeni 350 Ω merilni

mounted on the base plate. The oil pressure provides a simple means of measuring the applied force. Changing the direction of the load is done by reversing the oil flow with electrical control. The machine can test four bars simultaneously, with a 1000-kN maximum tensile force in each bar. The actual stresses were controlled by means of the oil pressure and checked using strain gauges. The loading machine has certain disadvantages, like the need for large forces to achieve the necessary stresses and the difficulty in providing a high testing frequency.

The testing bar (Figure 11b) had a rectangular cross-section (30×50 mm). Each side of the bar contains a head with a hole for a bolt. The fabrication of approximately 6-m-long bars was carried out under normal production procedure, i.e., gas cutting. The grinding was done on gas-cut surfaces. The bars were loaded in tension so that the nominal applied stress was controlled in the critical cross-section.

Equipment produced by National Instruments was used for the data acquisition. The system consists of an AT-MIO-16E-2 multifunction data-acquisition card, running in a PC, with a signal-conditioning module SCXI-1520 and Lab VIEW 6.1 software. This module enables the acquisition of up to 8 signals from strain gauges at a sampling rate of up to 300 kHz. The fatigue analysis and the fatigue testing require an accurate description of the peaks and valleys in the load history. Due to long cables (approximate 12 m), 350 Ω strain gauges and a six-





Sl. 11. Utrujenostna testna naprava (a) in testni preizkušavec (b)  
Fig. 11. Fatigue testing machine (a) and testing bar (b)

lističi s šestimi kablenskimi priključki. Dodana sta še dva dodatna kabla za kalibriranje, tako da je ocenjena napaka meritev manjša od enega odstotka.

## 2.2 Računska analiza

Računska analiza je potekala v dveh korakih. V prvem je s programskim paketom Abaqus 6.4 [5] numerično po MKE določeno napetostno in deformacijsko polje v kritičnem prečnem prerezu droga. Pri numerični analizi sta bila uporabljena numerični model na sliki 12a in vzorec obremenitve na sliki 12b. Vzorec obremenitve na sliki 12b je enak kakor pri poprej opisanih testnih preizkusih.

V naslednjem koraku je izvedena analiza utrujanja s programskim paketom FE-Safe [6]. Analiza utrujanja je zasnovana na deformacijski metodi ( $\epsilon-N$ ), pri čemer je za določitev števila nihajev obremenitve  $N_f$  do pojava utrujenostne poškodbe v kritičnem prečnem prerezu droga uporabljena Coffin-Mansonova enačba z Morrow popravo vpliva srednje napetosti [7]:

$$\frac{\Delta \epsilon}{2} = \frac{(\sigma_f' - \sigma_m)}{E} (2N_f)^b + \epsilon_f' (2N_f)^c \quad (4)$$

kjer so  $\Delta \epsilon$  dejanska amplitudna deformacija,  $\sigma_m$  srednja napetost ter  $E$ ,  $\sigma_f'$ ,  $\epsilon_f'$ ,  $b$  in  $c$  materialni parametri, opisani v poglavju 1.

## 2.3 Preizkusni in računski rezultati

Slika 13a prikazuje utrujenostni prelom preizkusnega droga. S slike 13b je razvidna začetna

wire connection were used. An additional two wires were used for the shunt calibration. It is estimated that the measurement error was less than 1%.

## 2.2 Computational analysis

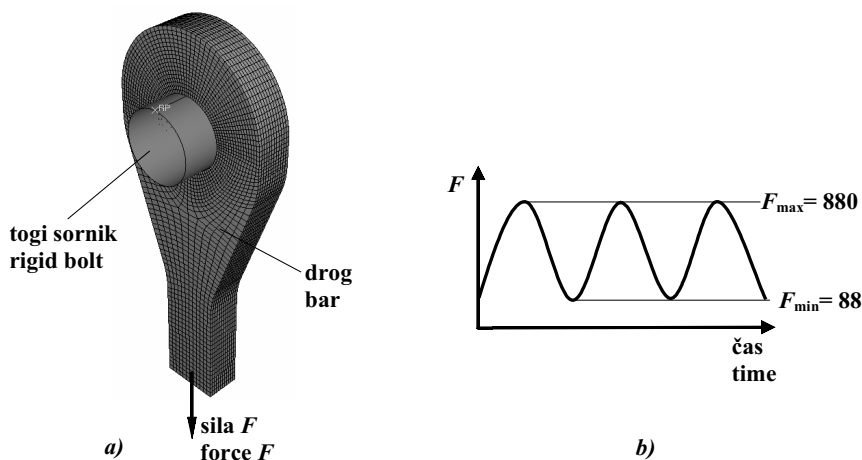
The computational analysis was made in two steps. First, a stress and deformation field in the critical cross-section of the bar was determined numerically using the FEM program code Abaqus 6.4 [5]. The FE model shown in Fig. 12a and the loading pattern shown in Fig. 12b were used in the computational analysis. Here, the loading pattern in Fig. 12b is the same as that used in the experimental testing, described previously.

In the next step, the fatigue analysis was performed using the FE-Safe program code [6]. The fatigue analysis was based on the strain-life method ( $\epsilon-N$ ), where the Coffin-Manson relationship with a Morrow mean stress correction was used to determine the number of stress cycles,  $N_f$ , required for the fatigue failure in a critical cross-section of the treated bar connection [7]:

where  $\Delta \epsilon$  is the true strain range,  $\sigma_m$  is the mean stress and  $E$ ,  $\sigma_f'$ ,  $\epsilon_f'$ ,  $b$  and  $c$  are material parameters described in Section 1.

## 2.3 Experimental and computational results

Figure 13a shows the fatigue breakage of the tested bar. The fatigue crack was initiated at the edge



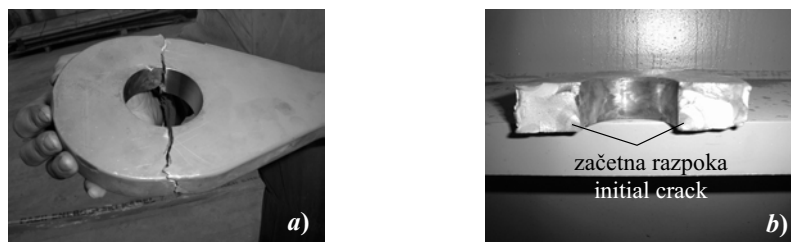
Sl. 12. Numerični model (a) in vzorec obremenitve (b)  
 Fig. 12. Numerical model (a) and loading pattern (b)

razpoka na robu izvrtine, ki se je z nadaljnjim utrujanjem širila do končnega zloma v kritičnem prerezu preizkusnega droga. Število nihajev obremenitve  $N_f$  do končnega zloma je razvidno iz preglednice 2.

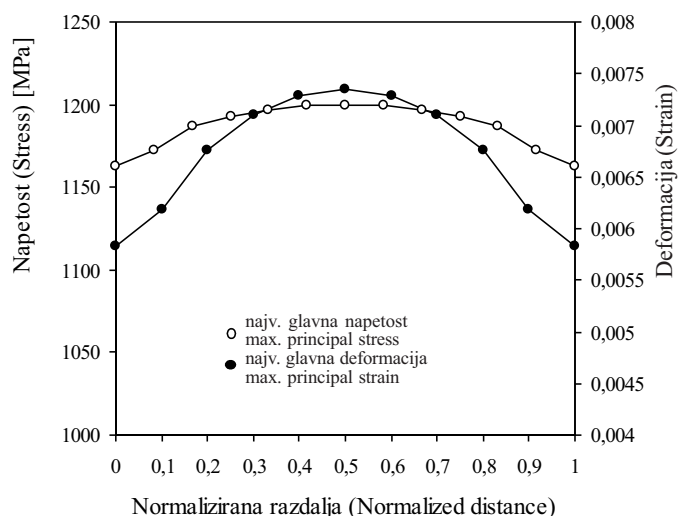
Slika 14 prikazuje porazdelitev napetosti in deformacij vzdolž kritičnega prereza droga, ki so bile upoštevane pri analizi utrujanja s programskim paketom FE-Safe. S slike je razvidno, da se pojavljajo največje napetosti in deformacije v sredini droga, kar je v nasprotju z rezultati preizkusov, pri katerih so se začetne razpoke pojavile na površini preizkušancev. Domnevno so začetne površinske razpoke posledica plamenskega rezanja pri izdelavi testnih preizkušancev. Čeprav so bili preizkušanci po plamenskem rezanju še dodatno obdelani z brušenjem, le-to ni v zadostni meri odpravilo površinskih nepravilnosti (površinska hrapavost, mikrorazpoke, vključki itn.), na katera so jekla z veliko trdnostjo še posebej občutljiva. Računsko število nihajev obremenitve  $N_f$  do končnega zloma navaja preglednica 2.

of the hole, which can be seen from Figure 13b. The initial crack then propagates until the final fracture in the critical cross-section. The number of stress cycles,  $N_f$ , required for the final fracture is shown in Table 2.

Figure 14 shows the stress and strain distribution along the critical cross-section of the bar, which was used for the fatigue analysis with the FE-Safe program code. It is clear that the maximum stresses and deformations appear in the middle of bar thickness, which is opposite to the experimental testing, where the crack is initiated at the edge of the hole. It can be explained by the fact that the test bar specimens were produced with a thermal cutting process, which results in initial surface damage. Although additional surface grinding was applied, this was apparently not sufficient to alleviate the sensitivity of high-strength steel to notches and other material imperfections (surface roughness, micro-cracks, inclusions etc.). The computational number of stress cycles,  $N_f$ , required for final fracture is shown in Table 2.



Sl. 13. Utrujenostni prelom testnega droga (a) in primer prelomne površine (b)  
 Fig. 13. Fatigue breakage of testing bar (a) and example of fracture surface (b)



Sl. 14. Porazdelitev napetosti in deformacije v kritičnem prečnem prerezu droga  
Fig. 14. Stress and strain distribution in the critical cross section of bar

Preglednica 2. Število obremenitvenih ciklov  $N_f$  do končne poškodbe  
Table 2. Number of stress cycles  $N_f$  required for final failure

Preizkusni izsledki Experimental results				Računski izsledki Computational results
Preizkus 1 Test 1	Preizkus 2 Test 2	Preizkus 3 Test 3	Preizkus 4 Test 4	28705
38029	26727	24795	29036	

### 3 SKLEPI

V podanem prispevku je predstavljena preizkusna določitev parametrov malocikličnega utrujanja jekla z veliko trdnostjo S1100Q. Na temelju utrujenostnih prelomov preizkušancev (prelomna površina poteka poševno pri vseh preizkušancih) lahko povzamemo, da ima preizkušano gradivo dobro utrujenostno trdnost. V primerjavi s statičnim preizkusom je modul elastičnosti pri cikličnem preizkusu manjši za približno 7,5 %. Zaradi razmeroma nizkega eksponenta utrujanja se bo pri utrujenostnih obremenitvah praviloma pojavilo ciklično mehčanje gradiva.

V drugem delu prispevka je predstavljen preizkusni in računski postopek določitve dobe trajanja nosilnega droga protiuteži pri žerjavu. Oba postopka potrjujeta, da je izvrtina za sornik v ušesu droga kritično mesto za nastanek utrujenostne razpoke in pojav končne poškodbe. V preglednici 2 predstavljeni izsledki pomenijo koristne informacije inženirjem pri oceni utrujenostne trdnosti nosilnega droga protiuteži kot pomembnega člana v žerjavnih konstrukcijah.

### 3 CONCLUSION

We carried out an experimental determination of the mechanical properties and the low-cycle fatigue parameters of the high-strength steel S1100Q. On the basis of the fracture behavior during the fatigue tests (the fracture surface was not in-plane for all the tested specimens) it can be concluded that the investigated material shows good fatigue strength. The modulus of elasticity is, based on fatigue tests, approximately 7.5% lower compared to the monotonic test. Because of the low strain-hardening exponent the cyclic softening of the material is expected as a result of fatigue loading.

In the second part of the paper, the experimental and computational procedure to determine the service life of a counterweight-bar bolted connection is presented. Both procedures show that the connection hole in the bar end is the most critical location for crack initiation and final failure. The results presented in Table 2 are useful information for the designer about a fatigue assessment of a counterweight bar, as an important supporting part for crane structures.

4 LITERATURA

4 LITERATURE

- [1] Stephens R.I., Fatemi A., Stephens R.R., Fuchs H.O (2001) Metal fatigue in engineering, *John Wiley & Sons Inc*, New York.
- [2] Zahavi E., Torbilo V. (1996) Fatigue design, *CRC Press*, New York.
- [3] ASTM E 606 (1998) Standard practice for strain-controlled fatigue testing, *ASTM standard*.
- [4] Kramberger J., Potrč I., Bombek G. and Flašker J (2003) Fatigue assessment of high strength steel beam for crawler track cranes, *Gep*, Vol. 10-11, 87-90.
- [5] *Abaqus*, Version 6.4, Online documentation, 2003.
- [6] *FE-Safe*, Version 5, User's manual, 2003.
- [7] Suresh S. (1998) Fatigue of materials, *Cambridge University Press*, Cambridge.

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