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THE NOTCH EFFECT ON THE FATIGUE STRENGTH OF 51CrV4Mo SPRING STEEL

VPLIV ZAREZE NA TRAJNO NIHAJNO TRDNOST VZMETNEGA JEKLA 51CrV4Mo

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Standardized and technological testing of the fatigue strength of spring steels is a complex and time-consuming, and therefore expensive, task. The determination of Woehler's (S-N) curves using a resonant pulsator is relatively fast and simple. In this investigation the test is performed using standard Charpy V-notched specimens with the aim to obtain an appropriate comparison with the results of technological tests on real springs. The steel springs were made of high-quality flat steel with a smooth shot-peened surface, free of notches and with no large microstructure or surface defects. The performed investigation can help with quality control and improvements to the properties of the steel springs. The paper presents a determination of the fatigue strength of 51CrV4Mo spring steel using a resonant pulsator. The notch effect, the influence of the microstructure and the surface quality are also discussed.

Keywords: fatigue strength, S-N curves, notch effect, resonant pulsator, spring steel

Standardizirani postopki določevanja trajne nihajne trdnosti vzmetnih jekel in tehnološko preizkušanje vzmeti so zahtevni, dragi in dolgotrajni. Določevanje Woehlerjevih (S-N) krivulj z resonančnim pulzatorjem je relativno hitro in enostavno. V pričujoči raziskavi smo izdelali S-N-krivulje vzmetnega jekla 51CrVMo4 na standardnih Charpyjevih preizkušancih z V-zarezo zato, da bi ugotovili, ali je možna ustrezna primerjava z rezultati, dobljenimi z dragim in zamudnim dinamičnim preizkušanjem vzmeti. Listnate vzmeti različnih oblik in dimenzij se izdelujejo iz ploščatih profilov visokokvalitetnega vzmetnega jekla, ki imajo po izdelavi gladko peskano površino brez večjih geometrijskih ali mikrostrukturnih napak. Zato, da bi lahko ocenili pravo trajno nihajno trdnost preiskovanega jekla, smo morali upoštevati vpliv koncentracije napetosti, ki nastaja, ker imajo preizkušanci V-zarezo. Uvajanje te preiskovalne metode v redno kontrolo kvalitete bi lahko pripomoglo k izboljšanju kvalitete in razvoju novih vrst vzmetnih jekel.

V članku predstavljamo določevanje trajne nihajne trdnosti vzmetnega jekla 51CrV4Mo z uporabo resonančnega pulzatorja. Predstavljen je način vrednotenja vpliva geometrijske zareze na trajno nihajno trdnost, kakor tudi vpliv mikrostrukture in kvalitete površine jekla.

Ključne besede: trajna nihajna trdnost, S-N krivulje, vpliv zareze, resonančni pulzator, vzmetno jeklo

1 INTRODUCTION

The Štore Steel plant is one of the largest European producers of spring steels for heavy-duty trucks and other automotive applications. Spring manufacturers use different types of spring steels in different strength levels, from 1300 MPa up to 1800 MPa. Parabolic mono-leaf springs are situated at the highest strength, quality and safety level, which is normally interesting for all spring steel producers. For the required high quality level the best spring steel with an appropriate fine-grained microstructure, without segregations and large inclusions, as well as surface defects is necessary. Generally, spring manufacturers produce springs from steel in the as-delivered (flat/round hot-rolled) condition. The springs are then heat treated and tested. It is a typical technological (structural) dynamic (fatigue) test, based on a statistical safety analysis, performed directly with the springs. A typical testing load is (760 ± 440) MPa for parabolic springs and (800 ± 650) MPa for high-quality springs in the frequency range 1–2 Hz. Also, some other additional mechanical investigations are usually performed, i.e., a determination of the Vickers or Rockwell hardness, a Charpy impact test and a standard tensile test.

However, the fatigue testing of springs after manufacturing is a time-consuming and expensive task. It is also too late to provide information to the steel producer, who needs timely and appropriate information about the steel's quality in the production from batch to batch. Standard fatigue-strength testing is performed on smooth cylindrical or flat specimens. This can be performed in the tension-compression, bend or torsion modes. It is also expensive and time-consuming work, acceptable as appropriate only for the research and development of new types of steels. Often, steel producers do not have the appropriate mechanical servo-hydraulic fatigue-testing machine. However, they need fast and reliable data about the produced spring steel prior to delivery. Therefore, alternative solutions are required. One of them is a determination of the fatigue bend strength on Charpy V-notched specimens with a high-frequency pulsator [1].

The fatigue strength depends on the loading mode (tension, bend etc.), the variable loading magnitude (amplitude, ratio $\boldsymbol{R} = \boldsymbol{F}_{\mathrm{lower}}/\boldsymbol{F}_{\mathrm{upper}}$ or $\boldsymbol{M}_{\mathrm{min}}/\boldsymbol{M}_{\mathrm{max}}$), the shape of the dynamic cycle, the frequency, the testing conditions (temperature, atmosphere etc.), the surface roughness and the notch effects. The dynamic structural spring tests that simulate the spring's real-load spectrum are the most reliable, but also the most expensive and time consuming task. The aim of this research was to analyze the possibility of assessing a real spring's life and to transfer the results of high-frequency pulsator testing on the spring's real behavior.

The final quality of the manufactured spring does not depend only on the quality of the steel. It also depends significantly on the spring's manufacturing procedure (hot forming, i.e., rolling, bending, punching, eye making), the final heat treatment and the shot peening. Therefore, high-quality steel does not necessarily mean a high-quality spring. The steel's properties can be significantly degraded during the manufacturing of the spring if the spring's manufacturing procedure is not properly carried out. However, the overall spring quality is evaluated on the basis of the final dynamic testing of samples with a definite statistical probability. The steel producer has to guarantee that the delivered spring steel has the appropriate quality. Therefore, it must possess its own well-documented in-process and final independent quality control, including dynamic testing to be able to define the phase in which the steel production is critical regarding the quality in the event of a customer complaint.

In this paper the testing of the fatigue strength of the selected spring steel, 51CrV4Mo, with a resonant pulsator is presented. The notch effect, the influence of the microstructure and the surface quality are also considered. The results are compared with the dynamic testing of real commercial leaf springs made of the same steel quality.

2 DETERMINATION OF S-N CURVES WITH A HIGH-FREQUENCY PULSATOR

The testing was performed with a Cracktronic 70 (Rumul, Switzerland) high-frequency pulsator [1] at the Institute of Metals and Technology, Ljubljana, Slovenia (**Figure 1**). It is based on the accommodated loading frequency for the investigated material (resonance). For this reason it is also called a resonant pulsator. It can serve for the simple fatigue of the specimen until its fracture or for the much more sophisticated monitoring of crack growth. In the latter case the specimen must be equipped with a transducer technology sensor (KRAK-gauges), which can determine the crack initiation and follow the crack growth based on the cracking of a thin foil adhered to the specimen. The sensor provides a DC-voltage output proportional to the crack length. This gauge method is appropriate for ductile structural steels, Al and Ti alloys, when the elastic deformation is followed by plastic yielding, and a steady transition from stable to unstable crack growth is expected. In the case of a hard and brittle material, such as tool, high-speed and spring steels, when the fracture only occurs after elastic deformation, with negligible yielding, crack initiation is connected with fast, sudden unstable crack propagation. In this case only the appropriate bending-moment ratio ($\boldsymbol{R} = \boldsymbol{M}_{\mathrm{min}}/\boldsymbol{M}_{\mathrm{max}}$) should be selected for the applied Charpy V specimen and the number of cycles to its fracture should be recorded. Using this approach the so-called Woehler's or **S-N** curve (stress **S** vs. number of cycles ***N***) can be determined [2]. The resonant pulsator can also serve for the formation of a fatigue crack of definite size (length) to produce precracked specimens for the determination of the fracture-mechanics parameters (plain-strain fracture toughness $\boldsymbol{K}_{\mathrm{Ic}}$, the ***J*** integral or the crack-opening displacement ***COD***).

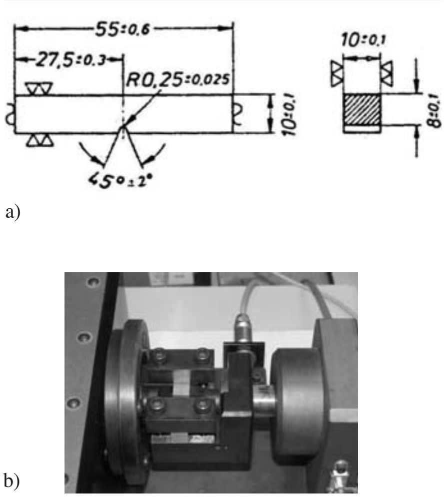
The Cracktronic 70 high-frequency pulsator is designed for the dynamic bending of a standard Charpy V-notched (CVN) specimen (**Figure 2**). The variable bending moment is generated by an electromagnetically driven resonator with a maximum swing angle of 2° (± 1°). The maximum moment is 70 Nm (± 35 Nm) acting in the range of $\boldsymbol{S} = 2\boldsymbol{l} = 40$ mm. The resonant (working) frequency is approximately 180 Hz in the case of steel. The pulsator is connected to a personal computer (PC) and a Fractomat device, which serve for the set up, the data acquisition and the control of the loading conditions (**Figure 1**).

The dimensions of the CVN specimens are: total length $\boldsymbol{l}_{\mathrm{t}} = 55$ mm, width $\boldsymbol{a} = 10$ mm, and height $\boldsymbol{h} = 8$ mm. A standard V-notch with 2-mm depth, opening angle 45° and root radius 0.25 mm was applied (see **Figure 2**). The resistance $\boldsymbol{W}_x$ of a given cross-section is:

$$W_x = \frac{a \cdot h^2}{6} = \frac{10 \cdot 8^2}{6} = 106.67 \text{ mm}^2 \qquad (1)$$

Figure 1: Cracktronik 70 resonant pulsator with the equipment for set up, control, data acquisition, registration and recording of fatigue and crack-growth tests

Slika 1: Resonančni pulzator Cracktronik 70 s pripadajočo opremo za registracijo, prenos in obdelavo podatkov



a)

b)

Figure 2: Standard CVN specimen (a) and its positioning in the Cracktronik pulsator (b)
Slika 2: Standardni Charpyjev preizkušanec z V-zarezo (a) in njegova namestitev v čeljusti resonančnega pulzatorja Cracktronik (b)

The net-bending stress for the applied dynamic moment is then:

$$\sigma_n = \frac{M_{\rm dyn}}{W_x} = \frac{6 \cdot M_{\rm dyn}}{a \cdot h^2} \tag{2}$$

and the static moment is calculated according to:

$$M_{\rm stat} = [M_{\rm dyn} + (R \cdot M_{\rm dyn})]/2 \tag{3}$$

with the loading ratio $\boldsymbol{R} = \boldsymbol{M}_{\rm min}/\boldsymbol{M}_{\rm max} = 0.1$ applied in the performed experiments. The corresponding amplitude is $\boldsymbol{M}_{\rm a}$:

$$M_{\rm a} = M_{\rm dyn} + M_{\rm stat} \tag{4}$$

For example, for the applied $\boldsymbol{M}_{\rm dyn}$= 60 Nm and $\boldsymbol{R}$ = 0.1 the static moment is $\boldsymbol{M}_{\rm stat}$ = 33 Nm and the amplitude $\boldsymbol{M}_{\rm a}$ = 27 Nm, respectively. Conversely, with moments one can express these with the nominal stresses: $\sigma_{\rm dyn}$ = 562.5 MPa, $\sigma_{\rm stat}$ = 309.4 MPa and $\sigma_{\rm a}$ = 253.1 MPa.

The fatigue strength $\sigma_{\rm f}$ is the largest stress deviation for the stress amplitude value $\sigma_{\rm a}$ from a mean value $\sigma_{\rm sr}$, for which the material can last for an infinitely long time (mandatory, more than 10^7 cycles) without plastic deformation:

$$\sigma_{\rm f} = \sigma_{\rm sr} \pm \sigma_{\rm a} \tag{5}$$

Fatigue strength is dramatically reduced if the material contains a geometrical stress concentrator, such as a notch, a hole or a large reduction of the area. CVN specimens applied for testing the fracture toughness using the Cracktronic 70 have a sharp V notch. Therefore, it must be taken into consideration whether one can assess the real fracture toughness of the spring steel and the lifetime of the manufactured springs. However, it also necessary to consider the influence of metallurgical (inclusions, pores, decarburisation layer, residual stresses, segregations etc.) and mechanical factors (in-rolled scale, residuals of casting powder, surface roughness, hard white layer etc.), which can also act as stress concentrators and crack initiators, resulting in a drastic reduction of the fatigue strength. The ratio between the maximum $\sigma_{\rm max}$ and nominal stress $\sigma_{\rm n}$ applied to the real structure is called the theoretical elastic stress concentration $k_{\rm t}$. It is also called the geometrical or shape factor:

$$k_{\rm t} = \frac{\sigma_{\rm max}}{\sigma_{\rm n}} \tag{6}$$

The theoretical calculations of $k_{\rm t}$ are very complex, possible only for simple geometries, and can be found in the appropriate literature [7]. Therefore, nowadays $k_{\rm t}$ is calculated exclusively by the FEM for more complex geometries and loading configurations. The reduction of fracture toughness due to the notch is experimentally evaluated by a determination of the S-N curves of notched and un-notched specimens. The fracture-toughness reduction factor $k_{\rm f}$ is then given by the ratio between the fracture toughness of un-notched $\sigma_{\rm f}$ and the notched specimens $\sigma_{\rm fn}$:

$$k_{\rm f} = \frac{\sigma_{\rm f}}{\sigma_{\rm fn}} \tag{7}$$

It depends on the shape and the size of the notch, the material and the load configuration. Neuber [2] improved the calculation of the notch sensitivity by taking into consideration these factors with the following equation:

$$k_{\rm f} = \frac{\sigma_{\rm f}}{\sigma_{\rm fn}} = 1 + \frac{k_{\rm t} - 1}{1 + \sqrt{\rho'/r}} \tag{8}$$

where ρ' is a material constant that depends on the material's tensile strength and r is the radius of the notch tip. The material's notch sensitivity during fatigue can then be finally expressed by the so-called notch-sensitivity factor q:

$$q = \frac{k_{\rm f} - 1}{k_{\rm t} - 1} \tag{9}$$

3 PREPARATION OF THE CVN SPECIMENS

Standard CVN specimens (10 × 10 × 55) mm were cut out and machined from flat (90 × 32) mm spring steel, 51CrV4 type, in the as-delivered (hot-rolled) condition, with Rockwell hardness $HRc \approx 30$ and tensile strength $R_{\rm m} \approx 900$ MPa. The fatigue of the V-notched strength with the Cracktronic 70 was determined in the as-delivered, and also in the as-heat-treated condition with the specimens machined in two ways: by rough milling only and with an additional fine grinding. A heat treatment corresponding to the material's highest strength level of 1800 MPa was selected: austenitization 860 °C for 20 min, oil quenching and tempering at 350 °C for 60 min. The average values of the tensile properties were as follows: tensile strength $R_{\rm m}$ = 1810 MPa, yield strength $R_{\rm p0.2}$ = 1714 MPa, elongation A = 8 % and reduction of area Z = 43 %. The Rockwell hardness was $HRc \approx 50$ and the Charpy impact energy 8 J to 9 J.

4 RESULTS AND DISCUSSION

Figure 3 shows the S-N curve of the investigated steel in the as-delivered condition. The surface of the specimens was only rough honed and not fine grinded. The crack initiation and the fracture of the specimens were clearly distinguished during the testing by the gradual drop of the working frequency. The notch fatigue strength is approximately 235 MPa. The obtained value is very low and almost four times lower than the tensile strength of steel in the as-delivered condition (approximately 900 MPa). Usually, the fatigue strength has to be 50–60 % of the tensile strength, and in this case it was only 26 %. This difference can be mainly attributed to the effect of the stress concentration caused by the V-notch.

The next series of ten specimens was heat treated in the above-mentioned conditions. The heat treatment was performed before machining. However, the specimens were only rough honed and not fine grinded. They were then fatigued with the Cracktronic 70 and the S-N curve was determined. The obtained notched fatigue strength is extremely low (approximately 95 MPa), almost 20-times lower than the tensile strength of the heat-treated steel (approximately 1800 MPa). This is proof that, in addition to the notch effect, the surface quality (roughness) contributes significantly to the decrease of the fatigue strength. It is especially important if the samples are in the heat-treated condition, when a high strength level of the spring steel is obtained. The detrimental influence of the surface roughness on the fatigue strength is well known [2-5], but such a large influence was not expected. The SEM investigations revealed the formation of an oxidation/decarburisation layer during the heat treatment (**Figure 4**), indicating that the very low fatigue strength cannot be attributed only to the notch effect and the surface roughness, but also to this layer. In order to clarify the effect of this layer, the next ten specimens were machined with a supplement of 0.2 mm, which was removed by fine flat

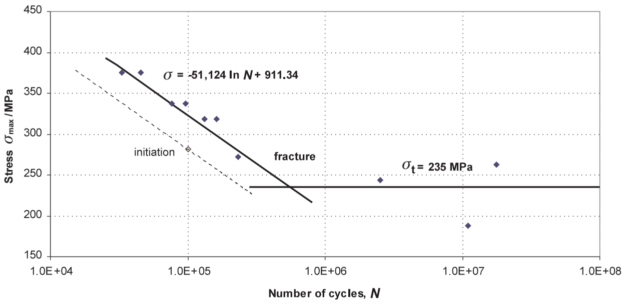


Figure 3: Woehler's curve of the investigated spring steel, 51CrV4, in the as-delivered condition.

Slika 3: Woehlerjeva krivulja preiskovanega jekla 51CrV4 v izhodnem (vroče valjanem) stanju.

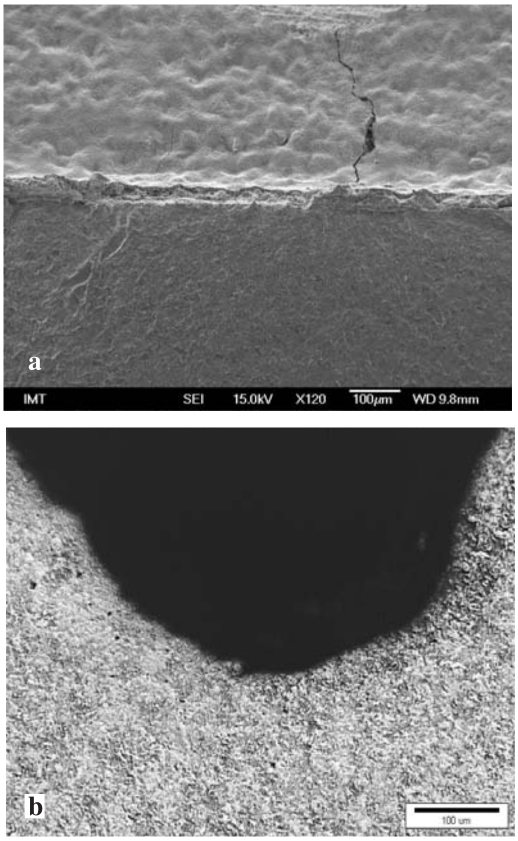


Figure 4: Micrographs of a heat-treated CVN specimen: a) SEM fracture surface in the root of the V-notch and the surface of the notched region, magnification 120 times, b) root of V-notch, visible in the cross-section under a light microscope, magnification 100 times

Slika 4: Mikroskopska posnetka toplotno obdelanega CVN-preizkušanca: a) SEM-preloma v korenu V-zareze in površina področja v zarezi; povečava 120-krat, b) koren V-zareze v prerezu, viden pod optičnim mikroskopom: povečava 100-krat

(surface roughness approximately $R_a \approx 0.3$–0.5 µm and profile (V-notch) grinding after the heat treatment. In this way, the oxidation-decarburisation layer that was eventually formed during the heat treatment was removed.

The next step was the determination of the S-N curve with the Cracktronic 70. **Figure 5** shows the S-N curve of the investigated steel in the heat-treated condition, indicating the fatigue strength of about 310 MPa. The obtained value is still approximately six times lower than the tensile strength of the steel in the heat-treated condition, but at the expected level if the notch effect is considered.

To better understand the effect of stress concentration caused by the notch on the fatigue strength a finite element method (FEM) was applied in this investigation to simulate three-point bending in the elastic loading regime. However, this is only a rough approximation to the real conditions of the experiment. The FEM simulation, performed by CASTEM [6], has shown that the net-stress concentration factor k_t is between 3.8 and 3.9, depending on the number of nodes applied at the notch

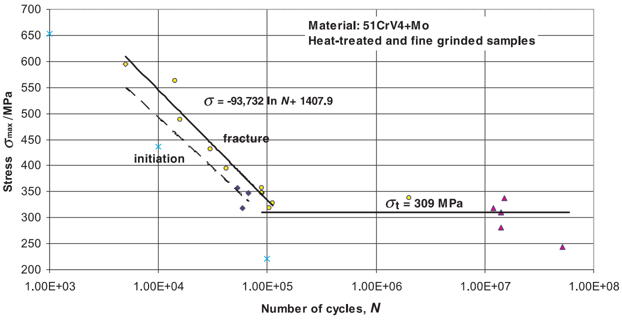


Figure 5: Woehler's curve of the investigated spring steel, 51CrV4, in the as-heat-treated condition; fine grinded specimens

Slika 5: Woehlerjeva krivulja preiskovanega vzmetnega jekla 51CrV4 v poboljšanem stanju; fino brušeni preizkušanci

root. It means that the maximum stress at the notch root is approximately 3.85-times larger than the mean value. This value of the stress-concentration factor is similar to an experimentally verified value for standard CVN specimens [7,8]. If the experimentally obtained notch fatigue strength is multiplied by this factor one can predict the fatigue strength of a smooth (un-notched) specimen of spring steel:

$$\sigma_f = k_f \cdot \sigma_{fn} \approx k_t \cdot \sigma_{fn} = 3.85 \cdot 310 = 1193.5 \text{ MPa} \qquad (10)$$

The performed dynamic testing of the manufactured springs at (760 ± 440) MPa and (800 ± 650) MPa (σ_f = 1200 MPa and 1450 MPa) and a frequency of 1 Hz showed that the springs last from $7.9 \cdot 10^4$ to $1.2 \cdot 10^5$ cycles and $4.0 \cdot 10^4$ to $6.8 \cdot 10^4$ cycles, respectively. Most frequently it was the second leaf of the springs near eyes or holes that was broken by fatigue. One can calculate from **Figure 5** that the selected spring steel will fracture for this number of cycles if the notched material is exposed to a dynamic load from 312 MPa to 351 MPa. Taking into account the notch effect, this corresponds effectively from 1250 MPa to 1350 MPa, which agrees very well with the performed dynamic testing of the manufactured springs. For high-quality springs the required fatigue fracture limit is from $2.25 \cdot 10^5$ to $5.5 \cdot 10^5$ cycles at a higher loading level (σ_t = 1450 MPa). This means that the steel quality has to be improved by approximately 20 %, to σ_{fn} = 375 MPa (see **Figure 5**).

A relatively good agreement of the above calculations with the results of the structural testing of the real springs was obtained. This simple calculation did not take into consideration the influence of the material's strength, the residual stresses, the size of the inclusions and other effects. Therefore, a better and more detailed analysis based on the FEM local-stress concept and extreme value statistics [9,10] will be performed in the future.

5 MICROSTRUCTURE INVESTIGATION AND FRACTOGRAPHY

Microstructure investigations under light (LM) and scanning electron (SEM) microscopes were also performed. Standard metallographic specimens were made and the microstructures were observed at different magnifications in the rolling and perpendicular directions. **Figures 6a** and **6b** show a typical ferrite-pearlite microstructure of the spring steel in the as-delivered condition. However, the steel has a fine structure of tempered martensite with clearly visible segregations of the main alloying elements (Cr and Mo) after the heat treatment (**Figures 7a** and **7b**). Some sulphide (MnS), alumo-silicate and other hard inclusions were also found (**Figure 7b**). All these defects can significantly contribute to lower fatigue strength of the steel.

Due to the significantly higher depth resolution the SEM is much more appropriate for observing the fractured surfaces than the LM. **Figures 8a** and **8b** show SEM micrographs of typical fractured surfaces of the CVN specimens after fatigue testing with the Cracktronic 70 device. The final fracture is quasi-ductile. The fractured surfaces are striated due to the fatiguing of the material. The cracks also spread perpendicularly to the notch tip and are initiated on the larger hard particles (**Figure 8b**).

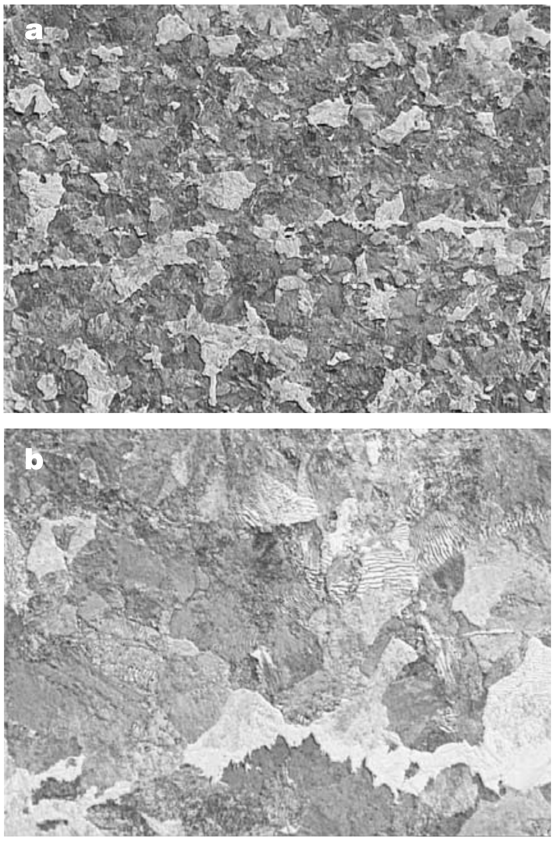


Figure 6: Microstructure of investigated spring steel, 51CrV4, in as-delivered condition: a) magnification 100 times and b) magnification 200 times; LM, etched in nital

Slika 6: Mikrostruktura preiskovanega vzmetnega jekla 51CrV4 v vroče valjanem stanju: a) povečava 100-krat in b) povečava 200-krat; optični mikroskop, jedkano v nitalu

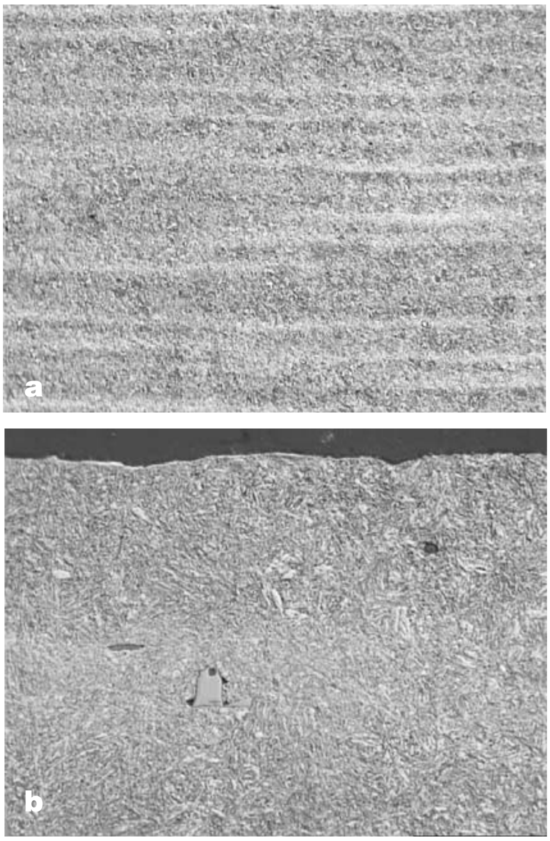


Figure 7: Microstructure of investigated spring steel, 51CrV4, in heat-treated condition: **a)** magnification 100 times and **b)** magnification 200 times; LM, etched in nital

Slika 7: Mikrostruktura preiskovanega vzmetnega jekla 51CrV4 v poboljšanem stanju: a) povečava 100-krat in b) povečava 200-krat; optični mikroskop, jedkano v nitalu

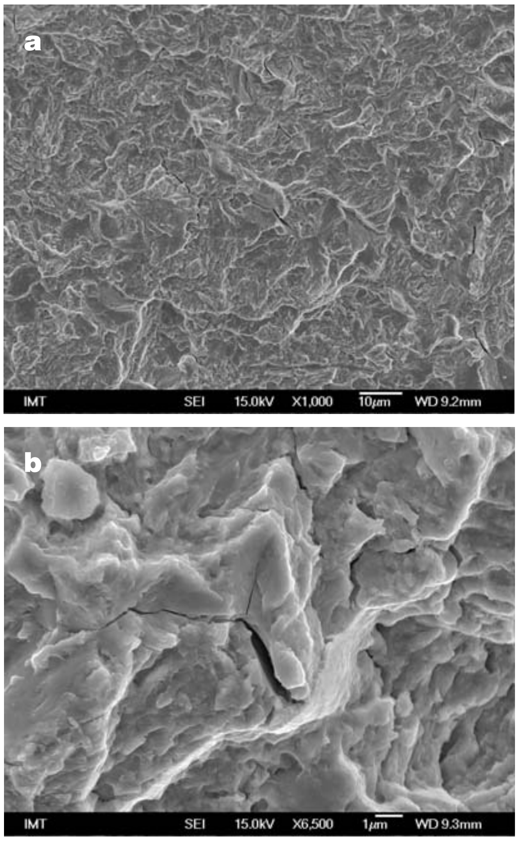


Figure 8: SEM micrograph of fractured surface of investigated spring steel in the as-heat-treated condition: a) magnification 100 times and b) magnification 6500 times

Slika 8: SEM-posnetek prelomne površine po utrujanju CVN-preizkušanca iz preiskovanega vzmetnega jekla 51CrV4 v poboljšanem stanju: a) povečava 100-krat in b) povečava 6500-krat

6 CONCLUSIONS

The results of the performed investigations showed that it is possible to determine the fatigue strength of spring steels with a resonant pulsator using Charpy V test specimens. They must be properly prepared with a fine flat and profile grinding after the heat treatment. From the obtained S-N curves and the determined notched fatigue strength one can simply predict the real fatigue strength of the spring steel by the application of the corresponding stress-concentration factor.

The significance of the notch and the surface roughness for the results is clearly demonstrated by the performed investigations. However, other defects, such as an oxidation/decarburisation layer, segregations and inclusions can also significantly decrease the fatigue strength of the steel and the manufactured spring. The influence of the segregations and the inclusions in this type of steel, as well as the influence of residual stresses caused by the machining and shot-peening of the springs will be analyzed and evaluated in the near future.

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