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FRACTURE TOUGHNESS OF THE VACUUM-HEAT-TREATED SPRING STEEL 51CrV4

LOMNA ŽILAVOST VAKUUMSKO TOPLOTNO OBDELANEGA VZMETNEGA JEKLA 51CrV4

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In the work the possibilities of the vacuum heat treatment of spring steel grade 51CrV4 are presented. Charpy-V notch (CVN) impact-test values are widely used in toughness specifications for spring steels, even though the fracturing energy is not directly related to the spring design. The plain-strain stress-intensity factor (K_{Ic}) at the onset of unstable crack growth can be related to the spring design; however, K_{Ic} values are not used in the toughness specifications. This is surprising since to the designer K_{Ic} values are more useful than CVN values, because the design calculations for springs from high-strength steels should also take into account the strength and the toughness of materials to prevent rapid and brittle fracture. An investigation was conducted to determine whether standardized fracture-toughness testing (ASTM E399-90), which is difficult to perform reliably for hard and low ductility materials, could be replaced with a non-standard testing method using circumferentially notched and fatigue-precracked tensile specimens. The results of this investigation have shown that using the proposed method it was possible to draw, for the normally used range of working hardness, combined tempering diagrams (Rockwell-C hardness – Fracture toughness K_{Ic} – Tempering temperature) for the vacuum-heat-treated spring steel grade 51CrV4. Fractographic and metallographic analyses of the K_{Ic}-test specimens used shows in steel the presence of positive and negative segregations. It was found that the width of the segregations bands and the distance between the positive and negative segregations influence significantly the fracture toughness due to the presence of bainite in the negative segregations.

Keywords: spring steels, vacuum heat treatment, hardness, fracture toughness, microstructures

V članku so predstavljene možnosti vakuumske toplotne obdelave vzmetnega jekla 51CrV4. Vrednosti Charpy-V udarne žilavost (CVN) so pogosto navedene v specifikacijah za vzmetna jekla, čeprav energija loma ni neposredno povezana z dimenzioniranjem vzmeti. Ravninsko deformacijski faktor intenzitete napetosti (K_{Ic}) na začetku nestabilne razpoke lahko uporabimo pri dimenzioniranju vzmeti, vendar pa vrednosti K_{Ic} ne najdemo v specifikacijah. To je presenetljivo, saj so za konstruktorje vrednosti K_{Ic} bolj uporabne od vrednosti CVN za visokotrdnostne vzmeti, pri katerih je treba upoštevati poleg trdnosti tudi žilavost materiala, da preprečimo lom. Opravljena je bila preiskava, s katero smo želeli ugotoviti, ali lahko standardizirano preizkušanje lomne žilavosti (ASTM E399-90), ki je težko izvedljivo za trde in krhke materiale z majhno duktilnostjo, nadomestimo z nestandardnim postopkom preizkušanja lomne žilavosti s cilindričnim nateznim preizkušancem z zarezo po obodu in utrujenostjo razpoko v dnu zareze. Rezultati raziskave so pokazali, da s predlagano metodo lahko konstruiramo diagram popuščanja (trdota Rockwell-C – lomna žilavost K_{Ic} – temperatura popuščanja) za vakuumsko toplotno obdelano vzmetno jeklo 51CrV4. S fraktografsko in metalografsko analizo K_{Ic} preizkusnih vzorcev smo ugotovili prisotnost pozitivnih in negativnih izcej v jeklu. Ugotovljeno je bilo, da širina izcej in razdalja med njimi pomembno vplivata na lomno žilavost, in sicer zaradi prisotnosti bainita v negativnih izcejah.

Ključne besede: vzmetno jeklo, vakuumska toplotna obdelava, trdota, lomna žilavost, mikrostruktura

1 INTRODUCTION

A manufacturer of spring steels must provide a technical steel description in their production program. Namely, the durability of the springs is limited by plastic deformation, fatigue and fracturing. From this point of view, the use of spring steel with the following properties is recommended: high ductility and toughness at operating temperatures from –40 °C to +50 °C, good hardenability that provides the required mechanical properties, even at the maximum dimensions.

Steels with a similar chemical composition may behave differently due to various mechanical properties as a consequence of the manufacturing route. The description of the spring steel includes the chemical composition and the basic mechanical and physical as well as technological properties. For the manufacturers of springs, the information relating to the heat treatment of a specific spring steel is important. Assuming that the chemical composition and initial microstructure of the steel correspond to prescribed for steel grade 51CrV4 (DIN 17221 and DIN 17222), then the mechanical properties for a specific application depend mainly on the appropriately selected parameters of the heat treatment.

Hypo-eutectoid steels, such as the spring steel 51CrV4, are usually heat treated conventionally in a furnace with or without a protective atmosphere at a temperature of 30 °C to 50 °C above the A_{c3} point soaked at the austenizing temperature to obtain "homogeneous austenite", and oil cooled to the temperature of the quench oil. The quenching is followed by a tempering at a selected temperature. The conventional tempering diagram for spring steel gives us information about the mechanical properties, i.e., the tensile strength R_m, yield strength $R_{p0.2}$, elongation A_5 and necking Z as a function of the tempering temperature in the range from 350 °C to 700 °C for a specific austenitizing temperature. In the case of spring steels, a minimum impact toughness Charpy-V measured by standard CVN-specimens, must be given. Lately, more and more users also request measured values of the fracture toughness K_{Ic} for the springs after heat treatment, which with the known ultimate tensile strength allows us to calculate the fracture stress σ_f and the critical defect size a_{cr} at the applied stress.

The trend of the heat treatment of machine parts, including springs, is in the direction of vacuum heat treatment. Namely, cooling rates that can be achieved in modern vacuum furnaces with cooling in a stream of N_2 or in a mixture of He and N_2 under a pressure up to 25 bar, already reach cooling speeds close to the cooling rates in oil. One can expect that the obtained microstructure and mechanical properties of the springs after vacuum quenching and tempering will be comparable to those achieved with a conventional heat treatment. In vacuum heat treatment, there is no risk of decarburization, no formation of the oxide layer and no residues of quench oil on the surface. It offers then a significant advantage when compared to conventional heat treatment. The objective of our work was to create a specific tempering diagram for the investigated steel 51CrV4 from which the relations between the Rockwell-C hardness, the fracture toughness K_{Ic}, the austenizing and the tempering temperature could be determined.

2 THEORETICAL PART

2.1 Hardness, ductility and toughness

Factors contributing to the isotropic mechanical properties of steel are a high cleanliness, a low level of residual elements, of non-metallic inclusions (NMI) and primary carbides without segregations. This can be achieved with an appropriate process route of the continuous cast spring steel through the Clean Steel Concept[1] using the Continuous Soft Reduction (CSR)[2] process.

The properties used to evaluate the heat treatment of spring steel are the Rockwell-C or Brinell hardness. In the hardened state the hardness may be an indication of the austenitizing temperature, from which the spring steel has been quenched. In the tempered state, the hardness is important for users, although based on the hardness, it is not possible to distinguish between the springs that were quenched and tempered in various ways. For example, the same hardness can be achieved by varying the austenitizing and tempering temperature, but the toughness can be different. From this point of view, it has sense to introduce into the tempering diagram an additional criterion such as toughness. Unfortunately, for the determination of toughness there are no generally accepted test methods. Consequently, the literature often refers to the data determined by different test methods. The comparison of these data may sometimes lead to confusing discussions.

The Charpy-V notch (CVN) impact test is widely used in toughness specifications for spring steels, even though the fracturing energy is not directly related to the spring design. The user requirements for springs are in the direction of the operation of springs at a higher tensile strength (1800 MPa and more), which allows the use of only a single parabolic leaf spring, resulting in a lower weight of the vehicle. However, with such a high strength, the toughness is low, and therefore it is necessary to measure the toughness of such springs with a more sensitive method than the Charpy-V impact toughness. The plain-strain stress-intensity factor (K_{Ic}) at the onset of unstable crack growth can be related to the spring design; however, the test values are not used in the toughness specifications.

Introducing a linear elastic fracture mechanic (LEFM) for the evaluation of the heat treatment of springs makes it necessary to draw a distinction between the ductility and the toughness. In this context, the ability of a material to resist the initiation and spread of fracture at gross plastic deformation is ductility and the correct meaning of the toughness is the ability to resist the growth of an existing crack at a tensile load [3,4]. The ductility and toughness are, consequently, two different material properties, even though both, unfortunately, are denominated as toughness. The opposite of both properties is, however, the same, i.e., brittleness.

The most reliable measure of toughness is the plain-strain fracture toughness (K_{Ic})[5]. The minimum size of the specimens depends on the yield stress and the fracture toughness of the material, both of which are required for the plain-strain deformation. A fatigue crack of defined length is propagated from a mechanical notch in the specimens, ensuring that the notch effect is at a maximum and equal for all tests. The same value of fracture toughness should be found for tests on specimens of the same material with different geometries and with a critical combination of crack size and shape and fracture stress. Within certain limits, this is indeed the case, and information about the fracture toughness obtained under standard conditions can be used to predict the failure for different combinations of stress and crack size, and for different geometries[6].

To determine the fracture toughness K_{Ic}, of spring steels, standard CT (Compact Tension) and SENB (Single Edge Notch Bend) specimens and non-standard circumferentially notched and fatigue-precracked tensile-test specimens (K_{Ic}-test specimen) can be used[7].

2.2 Relationship between ultimate fracture stress and defect size

In metal materials there are always defects present, with their importance increasing with increasing strength and reducing ductility and toughness. In springs the two-dimensional defects are critical. The fracture strength of brittle materials depends on the size and the orientation of the defect. It usually decreases rapidly with the increasing defect size. If LEFM can be applied to calculate the material behaviour, the fracture strength can be calculated with the following equation[8–10](1):

$$\sigma_f = \frac{K_{IC}}{Y \cdot \sqrt{\pi - a}} \quad \text{for: } \sigma_f < \sigma_{Ys} \tag{1}$$

K_{Ic} fracture toughness
a defect size
σ_f fracture stress (tensile strength)
σ_{ys} yield stress
Y correction factor (depending on the geometry: Y = 1.11 for surface cracks)

Equation (1) can be applied if fracture occurs prior to reaching the yield stress. As spring steels are relatively hard (brittle) materials, they can be compared to tool steels with low ductility and toughness. For this reason LEFM can be applied over a wide range of defect sizes.

According to the literature, equation (1) is suitable for describing the fracture behaviour of tool steels for a typical crack-nucleating defect size (e.g., carbide diameter, NMI) above 10 μm to 20 μm. In the case of conventional manufactured tool steels with a banded microstructure, the width of the carbide agglomerates has to be taken as the critical defect size and it has been further noted that the fracture occurs along a path with a high carbide density. The fracture toughness of conventionally produced tool steels depends, therefore, on the specimen orientation[8]. It is highest for a crack propagation perpendicular to the rolling direction and it is lowest for a crack propagation in the rolling direction.

If the fracture stress according to equation (1) approaches the yield stress (e.g., if no larger crack-nucleating particles are present) elastic-plastic methods have to be applied. In this region the material behaviour can be described with equation[10] (2), if the ultimate fracture strength is known.

$$\sigma_f = \frac{2}{\pi}\sigma_U \cdot \cos^{-1}\left\{ \exp\left[\frac{-\pi\left(\frac{K_{Ic}}{Y}\right)^2}{8\cdot\sigma_U^2 \cdot a} \right] \right\} \tag{2}$$

σ_U final tensile fracture stress (tensile strength R_m)

For a large defect size equation (2) approximates the results from equation (1). Deviations from equation (1) are found for small defect sizes. Especially for very small defect sizes, the influence of the defect size is almost negligible. A decrease of the fracture strength is observed if a critical defect size is exceeded.

3 EXPERIMENTAL

3.1 Hardness and fracture-toughness tests

The Rockwell-C hardness (HRc) was measured on individual groups of K_{Ic}-test specimens using a Wilson 4JR hardness machine. Circumferentially notched and fatigue-precracked tensile-test specimens[11] with the dimensions indicated in **Figure 1** were used for the investigation.

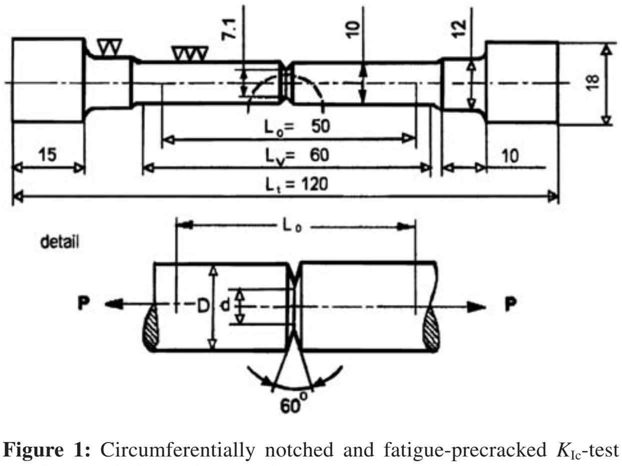

Figure 1: Circumferentially notched and fatigue-precracked K_{Ic}-test specimen. All dimensions are in mm.

Slika 1: Cilindrični natezni preizkušanec za merjenje lomne žilavosti z zarezo po obodu in utrujenostno razpoko v dnu zareze. Vse dimenzije so v milimetrih.

The advantage of the K_{Ic}-test specimens used here over standardized CT specimens (ASTM E399-90) is in the radial symmetry, which makes them particularly suitable for studying the influence of the microstructure of metallic materials on the fracture toughness. The advantage of these specimens is related to heat transfer, ensuring a completely uniform microstructure.

Due to the high notch sensitivity of hard and brittle metallic materials, such as continuous casted spring steel grade 51CrV4, it is very difficult – sometimes even almost impossible – to create a fatigue crack in the test specimen. However, with K_{Ic}-test specimens the fatigue crack can be created with rotating-bending loading before the final heat treatment[11]; the second advantage of such test specimens is that plain-strain conditions can be achieved using specimens with smaller dimensions than those of conventional CT test specimens[12].

For the linear elastic behaviour up to fracture of such specimens[13] the following equation is applied:

$$K_{IC} = \frac{P}{D^{3/2}}\left(-1.27 + 1.72\frac{D}{d}\right) \tag{3}$$

where P is the load at failure, D is the outside diameter, and d is the notched-section diameter of the test specimen, i.e., the diameter of the ligament next to the crack. Equation (3) is valid as long as the condition $0.5 < d/D < 0.8$ is fulfilled.

Measurements of the fracture toughness were performed at room temperature using an Instron 1255 tensile-test machine. The cross-head speed was 1.0 mm/min for standard tensile tests on specimens with a nominal

Table 1: Chemical composition of continuous-cast spring steel grade 51CrV4 in mass fractions, *w*/%
Tabela 1: Kemična sestava kontinuirno litega vzmetnega jekla 51CrV4 v masnih deležih, *w*/%

Steel grades 51CrMoV4	C	Si	Mn	P		Cr	Mo	V	Ni	AL	Cu	Ti	Sn	Ca	N
Heat 1	0.49	0.30	0.93	0.008	0.004	0.97	0.08	0.1	0.11	0.006	0.17	0.018	0.011	0,0010	0.013
Heat 2	0.50	0.33	0.94		0.008	1.00			0.14	0.009	0.20	0.019	0.010	0.0015	

test length of 100 mm. In the tests two specially prepared cardan fixed jaws, ensuring the axiality of the tensile load, were used. During the tests the tensile-load/ displacement relationship until failure was recorded. In all cases this relationship was linear, and the validity of equation (3) for the tests was confirmed.

3.2 Material, sampling and vacuum heat treatment

Commercial, continuous-cast spring steel grade 51CrV4, delivered as rolled bars of dimensions (20 ×100 × 4000) mm from two heats with similar chemical compositions (**Table 1**) were used. As can be seen from the table there is no difference in the chemical composition of the two heats. The rolled bars were delivered after hot plastic deformation in the as-rolled condition with a mixed martensitic-bainitic microstructure and a hardness of HRc 42–45. Before the sampling, the bars were soft annealed. The bars of each heat were selected at the beginning, middle and end of the rolling.

K_{Ic}-test specimens in the form of circumferentially notched and fatigue-precracked tensile-test specimens were cut from soft annealed bars with $HB_{2.5/187.5}$274–277 in the rolling direction with the fatigue crack at the notch root in the transverse direction.

The specimens were heat treated in a horizontal vacuum furnace with uniform high-pressure gas-quenching using nitrogen (N_2) at a pressure of 5 bar. After the first preheat (650 °C) the specimens were heated (10 °C/min) to the austenitizing temperature of 870 °C, soaked for 10 min, gas quenched to a temperature of 80 °C, and then single tempered for one hour at different temperatures between 200 °C and 575 °C, as shown in **Figure 2**. Sixteen K_{Ic}-test specimens were tested for each tempering temperature.

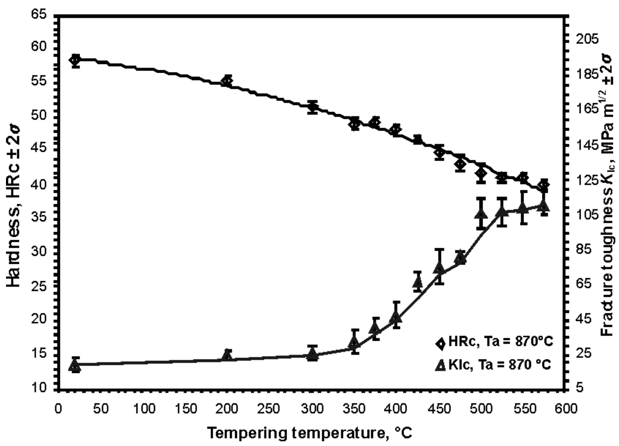

Figure 2: Tempering diagram for two heats of continuous-cast spring steel grade 51CrV4
Slika 2: Diagram popuščanja za dve šarži kontinuirno litega vzmetnega jekla 51CrV4

4 RESULTS AND DISCUSSION

The average measured hardness and fracture-toughness data are shown for the range of hardness (HRc 30–56 ; i.e. R_m = 1275–2161 MPa) in a so-called combined tempering diagram (Rockwell-C hardness – Fracture toughness K_{Ic} – Tempering temperature for austenitizing temperature 870 °C) in **Figure 2**.

From the diagram it is clear that the highest hardness of HRc 58 and the associated fracture toughness K_{Ic} i.e., 18.8 MPa m$^{1/2}$, are achieved in the as-quenched condition after vacuum quenching from the austenitizing temperature of 870 °C. In examining the course of tempering, it is observed that the minimum scatter of results within $\pm 2\sigma$ = 3.2 MPa m$^{1/2}$ is in the as-quenched state and after single tempering at 200 °C. At higher tempering temperatures between 300 °C and 575 °C, the scattering of the K_{Ic} results slightly increased up to $\pm 2\sigma$ = 9.4 MPa m$^{1/2}$, while the scatter of the Rockwell-C hardness is up to $\pm 2\sigma$ = 1.2 HRc in the whole range of used tempering temperatures. Within each group of K_{Ic}-specimens, which were quenched and tempered at the same temperature, this can be attributed to the kinetics of carbide precipitation during tempering at selected temperatures as well as to the heterogeneity of the investigated steel. Since the differences in chemical composition (**Table 1**) are minimal and the austenitizing temperature is the same, it is clear that the fracture toughness K_{Ic} is a very selective mechanical property with regard to the tempering temperature. It should be noted that the K_{Ic}-test specimens were taken from the middle of the bar, and therefore the microstructures of the K_{Ic}-test specimens with the lowest and highest fracture toughness are comparable.

In the as-quenched condition the microstructure consists of untempered martensite and bainite, **Figure 3**. Grain boundaries of the prior austenite grains are not pronounced, and therefore the determination of the austenite grain size according to ASTM E112 was not possible.

Strong positive (bright) and negative (dark) segregations are visible due to the lower etching intensity of the untempered martensite.

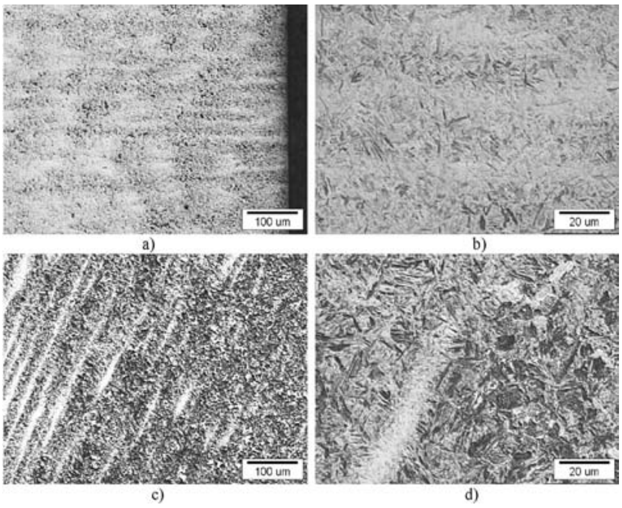

Figure 3: The microstructure of the K_{Ic}-test specimen in the as-quenched condition: a, b) specimen with the lowest fracture toughness (K_{Ic} = 16.2 MPa $m^{1/2}$ and HRc 58.9) c, d) specimen with the highest fracture toughness (K_{Ic} = 22.3 MPa $m^{1/2}$ and HRc 58.1), transverse direction, natal

Slika 3: Mikrostruktura K_{Ic}-preizkušanca v kaljenem stanju: a, b) z najmanjšo lomno žilavostjo (K_{Ic}= 16,2 MPa $m^{1/2}$ in HRc 58,9) c, d) z največjo lomno žilavostjo(K_{Ic} = 22,3 MPa $m^{1/2}$ in HRc 58,1), prečna smer

The fractured surface of the K_{Ic}-test specimens from the same heat with the highest and lowest fracture toughness tempered at 457 °C examined in binocular at 16-times magnification, Figure 4.

From **Figure 4**, it is evident that on the fractured surface of the K_{Ic}-test specimen the highest fracture toughness is higher with the density of positive segregations (black features), the size of segregation is smaller and the distribution is more even in comparison to the

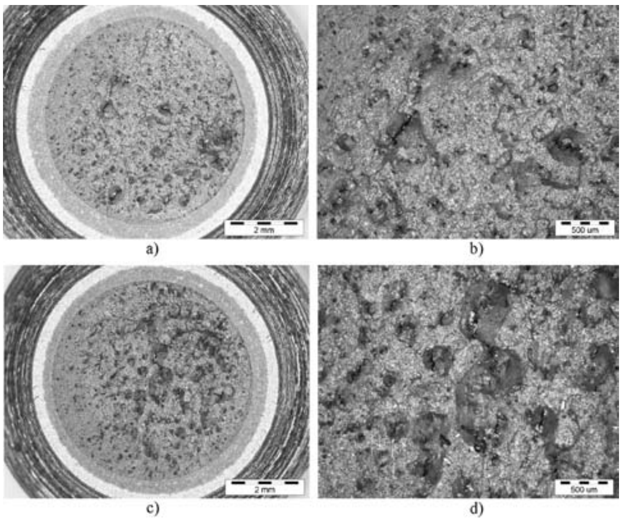

Figure 4: Fractured surfaces of K_{Ic}-test specimen, tempered at 475 °C: a, b) specimen with the lowest fracture toughness (K_{Ic} = 75.7 MPa $m^{1/2}$, HRc 43.8) c, d) specimen with the highest fracture toughness (K_{Ic} = 82.2 MPa $m^{1/2}$, HRc 43.2)

Slika 4: Prelomna površina K_{Ic}preizkušancev, popuščenih na 475 °C: a, b) z najmanjšo lomno žilavostjo (K_{Ic} = 75,7 MPa $m^{1/2}$ in HRc 43,8) c, d) z največjo lomno žilavostjo(K_{Ic} = 82,2 MPa $m^{1/2}$ in HRc 43,2)

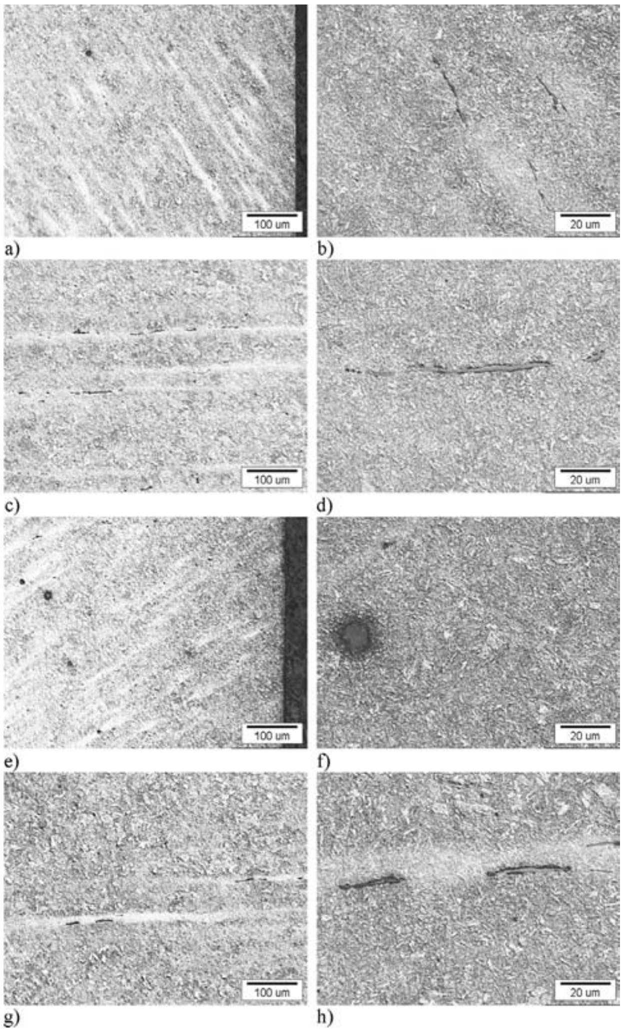

Figure 5: Typical microstructure of K_{Ic}-test specimens a, b) specimen with the lowest fracture toughness (K_{Ic} = 75.7 MPa $m^{1/2}$, HRc 43.8) in transverse direction and c, d) in longitudinal direction and e, f) specimen with the highest fracture toughness (K_{Ic} = 82.2 MPa $m^{1/2}$, HRc 43.2) in transverse direction and g, h) in longitudinal direction

Slika 5: Značilna mikrostruktura K_{Ic} -preizkušanca: a, b) z najmanjšo lomno žilavostjo (K_{Ic} = 75,7 MPa $m^{1/2}$ in HRc 43,8), prečna smer c, d) vzdolžna smer; e, f) z največjo lomno žilavostjo (K_{Ic} = 82,2 MPa $m^{1/2}$ in HRc 43,2), prečna smer; g, h) vzdolžna smer

fractured surface of the K_{Ic}-test specimen with the lowest fracture toughness with nearly the same hardness.

The microstructure of the same K_{Ic}-specimens just below the fractured surface was examined in the optical microscope, **Figure 5**.

The microstructure in the quenched and tempered condition consists of tempered martensite and bainite (≈ 20 %). In the microstructure, non-metallic inclusions of the sulphide type can be observed that are located in positive segregations and oriented in the rolling direction.

The microhardness $HV_{0.025}$ on the positive (bright) and negative (dark) segregations of the K_{Ic}-test specimens with the highest fracture toughness is shown in **Figure 6**. The microhardness in the positive segregations

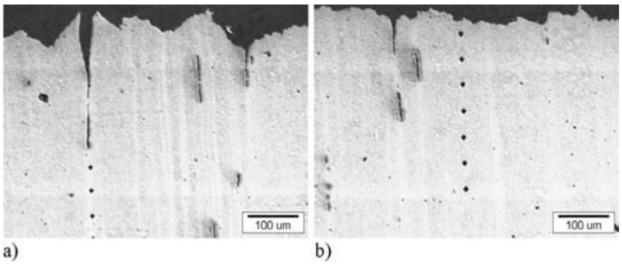

Figure 6: Microhardness measurements on positive (bright) a) and negative (darker), b) segregations of the K_{Ic} -test specimens with the highest fracture toughness
Slika 6: Mikrotrdota a) na pozitivnih (svetli pasovi) in b) na negativnih (temnejši pasovi) izcejah K_{Ic}-preizkušanca z največjo lomno žilavostjo

was 554–584 $HV_{0.025}$, in negative segregations it was ≈458 $HV_{0.025}$. From the difference of the microhardness one can conclude that the microstructure in positive segregations consists of tempered martensite and in negative segregations with a lower microhardness of martensite and bainite.

The microstructure of the K_{Ic} -test specimens with the highest fracture toughness was examined in the SEM on positive and negative segregations in the longitudinal direction, **Figure 7**.

At higher magnification it can be seen that the microstructure in the positive segregations consist of tempered martensite and in negative of tempered martensite with islands of bainite, **Figure 8**.

From the comparison of the microstructures of the K_{Ic}-test specimens with the lowest and highest fracture toughness from the same heat and nearly the same hardness and fracture toughnesses, it can be concluded that the density, the size and the distribution of segregations have a significant influence on the fracture toughness. The increase in the fracture toughness can be ascribed to the presence of bainite in the negative segregations.

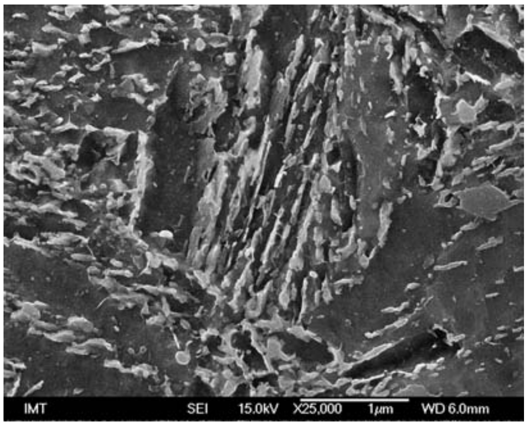

Figure 8: Bainite grain from **Figure 7**
Slika 8: Kristalno zrno bainita s **slike 7**

As mentioned above, if the fracture stress according to equation (1) approaches the yield stress (e.g., if no larger crack-nucleating particles are present), elastic-plastic methods have to be applied. In this region the material behaviour can be described with equation (2), if the ultimate fracture strength is known, **Figure 9**.

In the diagram the decrease of the fracture strength is observed when the critical defect size a_{cr} is exceeded, i.e., a_{cr} = 50 μm and 100 μm, respectively.

5 CONCLUSIONS

The investigated spring steel grade 51CrV4 was successfully vacuum quenched in a horizontal vacuum furnace with uniform high-pressure gas-quenching using nitrogen (N_2) at a pressure of 5 bar. The obtained as-quenched Rockwell-C hardness was HRc 58.4 ± 0.8,

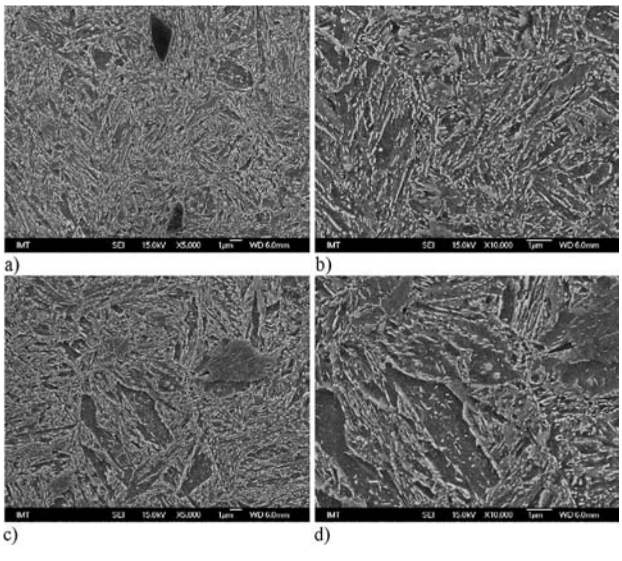

Figure 7: SEM Microstructure of the K_{Ic}-test specimens with the highest fracture toughness: a, b) positive segregations and c, d) negative segregations, longitudinal direction
Slika 7: SEM-mikrostruktura K_{Ic}-preizkušanca z največjo lomno žilavostjo: a, b) pozitivna izceja, c, d) negativna izceja

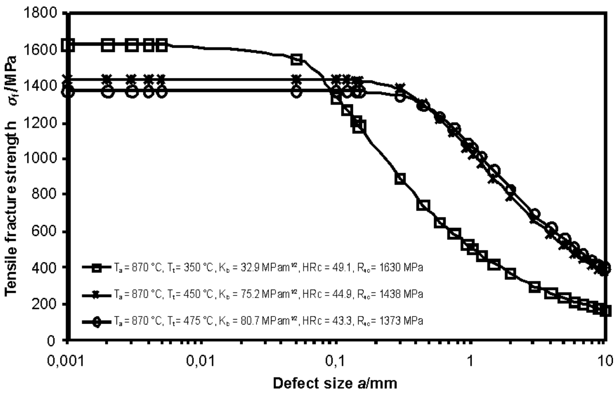

Figure 9: Fracture stress σ_f calculation for the investigated spring steel tempered at various temperatures, ultimate fracture strength (σ_u = R_{uc}) was calculated from the Rockwell-C hardness according to DIN 50150.
Slika 9: Lomna napetost σ_f za preiskovano vzmetno jeklo, popuščeno pri različnih temperaturah; končna natezna napetost (σ_u = R_{uc}) izračunana iz trdote Rockwell-C, DIN 50150

i.e., high enough to obtain, after a single tempering, the required hardnesses from HRc 30 to HRc 50.

The obtained microstructure consists of tempered martensite and bainite (≈ 20 %). Such a microstructure is allowed according to the criteria TB1402 (Scania Standard STD512090 and STD4153) permitting that the microstructure consists of volume fraction $\varphi \approx 80$ % of martensite in the middle of the spring. This condition was met for the investigated spring steel. From the results we can conclude that the investigated spring steel 51CrV4 with a thickness up to 20 mm is suitable for heat treatment in a vacuum furnace with uniform high-pressure gas-quenching using nitrogen (N_2) at a pressure of 5 bar or higher.

The fracture toughness of the steel was determined with a non-standard circumferentially notched and fatigue-precracked tensile-test specimen (K_{Ic}-test specimen). In all cases the load-displacement relationship was linear and the validity of equation (3) for the tests was confirmed. Because of the radial symmetry of the heat transfer, the microstructure of the metallic material along the circumferential area is completely uniform; therefore, the scatter of the fracture toughness could be ascribed to the heterogeneity of the investigated steel only.

For three tempering temperatures and the associated ultimate fracture strength calculated from the Rockwell-C hardness according to DIN 50150, the critical defect size a_{cr} was estimated, i.e., a_{cr} = 50–100 µm, respectively.

The fractured surfaces of the K_{Ic}-test specimens show positive segregations (black features) and confirmed with metallographic analyses as well as with the microhardness $HV_{0.025}$ measurements. The microstructure of the positive segregations consists of tempered martensite with a microhardness $HV_{0.025}$554–584. In the microstructure, non-metallic inclusions of the sulphide type can be observed, which are located in the positive segregations and oriented in the rolling direction. The microstructure in the negative segregations with a lower microhardness consists of low-alloyed tempered martensite and bainite.

In analyzing the fracture surfaces of the K_{Ic}-test specimens of the same heat with the highest and lowest fracture toughness, tempered at the same tempering temperature, as well as from the examined microstructure, which confirmed the presence of positive and negative segregations, we found that specimens with a higher density of positive segregations (black features), which are smaller in size and evenly distributed over the fractured surface, exhibit up to 27 % higher fracture toughness. This finding, which is also very interesting for the automotive industry, will be the subject of a further investigation.

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