Difference between mechanical properties of 51CrV4 high strength spring steel modeled by hardenability software and obtained properties by heat treatment

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Abstract - **The durability of the springs is limited by plastic deformation, fatigue and fracturing. From this point of view, the spring steel should have following properties: high ductility and toughness at operation temperatures from -40°C to + 50°C, good hardenability that provides required mechanical properties even at maximum dimensions. The information of the influence of heat treatment parameters on tensile strength R_m, yield strength $R_{p0.2}$, fracture toughness K_{Ic}, impact toughness, Charpy-V as a function of tempering temperature for a specific austenitising temperature is therefore very important for spring steel manufacturers. This paper presents the difference between the properties given by the mathematical modelling of heat treatment using the computer software *Hardenability* and the properties obtained by testing the heat treated samples.**

Keywords* - *spring steels, heat treatment, Hardenability software, mechanical properties

I. INTRODUCTION

Spring steel manufacturers must provide to their customers with technical documentation for given steel because the steels with the same chemical composition can have different mechanical properties due to different metallurgical production (due to casting, cold or hot forming, heat treatment etc.) which differs from one manufacturer to another. Among technological properties of spring steels the information concerning the heat treatment is very important. For chemical composition and initial microstructure in the normalized state (ferrite + pearlite) which are specified for steel grade 51CrMoV4, mechanical properties for specific application depend mainly on appropriately selected parameters for heat treatment. Usually, hypo-eutectoid steels, such as spring steel 51CrMoV4, are heat treated conventionally in a furnace with or without protective atmosphere at the austenizing temperature (30 to 50°C above the A_{c3} point) to obtain "homogeneous austenite", and oil cooled to the temperature of the quench oil, followed by a single tempering at the selected temperature.

Mechanical properties of the spring steel (i.e. tensile strength R_m, yield strength $R_{p0.2}$, elongation A_5 and necking Z) depend, for a specific austenizing temperature, on tempering temperature in the range 350 °C to 700 °C. Also, of great importance for this steels is the information on impact toughness, Charpy-V, and more and more users also request measured values of fracture toughness K_{Ic} for the springs after heat treatment, which for a known ultimate tensile strength allows calculation of the fracture stress σ_f and the critical defect size a_{cr} at the applied stress.

II. EXPERIMENTAL

Samples from continuous cast, high strength, spring steel grade 51CrV4, delivered as hot rolled and soft annealed bars of dimensions 100mm x 25mm x 6000mm were used in this study. The chemical composition of the steel is shown in table 1. The specimens for the standard tensile test, Charpy V notch impact test and K_{Ic}-test specimens in form of circumferentially notched and fatigue-pre-cracked tensile-test specimens in the rolling direction with the fatigue crack at the notch root in the transverse direction were cut from soft annealed bar. Also cut were the specimens for hardness measurement and microstructure characterization. The aim of the investigation was to obtain the tempering diagrams for combinations of properties i.e. fracture toughness – hardness – tempering temperature, impact toughness – hardness – tempering temperature, tensile strength – hardness – tempering temperature.

TABLE I. CHEMICAL COMPOSITION OF THE TESTED 51CRV4 STEEL (ŠTORE-STEEL)

Steel grade	%C	%Si	%Mn	%P	%S	%Cr	%Mo	%V	%Ni	%Ti	%Sn	%Ca	%N
51CrV4	0,52	0,33	0,93	0,01	0,005	0,93	0,04	0,16	0,14	0,015	0,012	0,0004	0,013

Hardness and fracture toughness For the fracture toughness measurement the circumferentially notched and fatigue-pre-cracked tensile-test specimens were used. On individual groups of K_{Ic}-test specimens the Rockwell-C hardness (HRc) was measured using a Wilson 4JR hardness machine.

For the linear elastic behaviour up to fracture of such specimens [4] the following equation is applied:

$$K_{Ic} = \frac{P}{D^{3/2}}\left(-1.27 + 1.72\frac{D}{d}\right) \qquad (1)$$

where P is the load at failure, D is the outside diameter, and d is the notched-section diameter of the test specimen. Equation (1) is valid as long as the condition $0.5 < d/D < 0.8$ is fulfilled. [5] Measurements of fracture toughness were performed using an Instron 1255 tensile-test machine. The cross-head speed of 1.0 mm/min was used for standard tensile tests on specimens with nominal 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 (1) for the tests was confirmed.

Impact toughness The impact toughness was measured by Charpy impact test known also as Charpy V-notch test (ISO 148). Measurement with an instrumented Charpy hammer allows the estimation of the total impact energy, the energy needed for crack initiation and the energy necessary for crack propagation.

Hardness HRc was measured on an Instron B 2000 device according to standard SIST EN ISO 6508-1.

Tensile test The standard tensile test (SIST EN ISO 6892-1) was applied to measure Tensile strength R_m, MPa, Yield stress $R_{p0.2}$, MPa, Elongation A_5, % and Necking Z, %.

Heat treatment of samples For the selected austenizing temperature of 870 °C, first, the modelling of TTT diagrams and tempering diagrams were done using *Hardenability* software.

The test specimens were heat treated in a horizontal vacuum furnace with uniform high-pressure gas-quenching using nitrogen (N_2) at pressure of 5 bar. After first preheat (650 °C) the specimens were heated at the rate of 10°C/min to austenitising temperature of 870 °C, soaked for 10 minutes, gas quenched to 80 °C, and then single tempered for one hour at different temperatures between 300 °C and 700 °C. At each tempering temperature 16 test specimens for tensile test (R_m-specimen), for determination of fracture toughness (K_{Ic}-specimen) as well as two metallographic samples Φ 19 x 9 mm were heat treated.

The Charpy-V toughness CVN-specimens were tempered between 200 °C to 625 °C.

III. RESULTS AND DISCUSSION

For the presented chemical composition of 51CrV4 spring steel modelling using *Hardenability* software was done. TTT diagrams with cooling curves for cooling in nitrogen at pressure of 5 bar, transformation temperatures and tempering diagrams were modelled. Figures 1, 2 and 3 shows TTT diagram with the selected cooling curve, transformation temperature diagram and tempering diagram for the steel 51CrV4 with chemical composition presented at table 1 from the selected austenitising temperature of 870 °C.

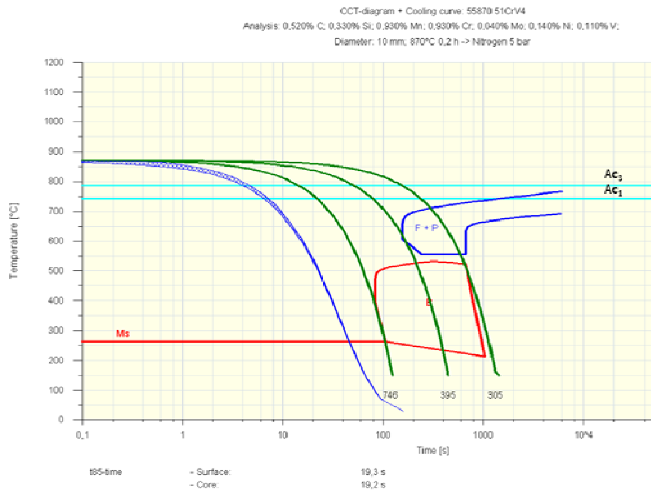

Figure 1: TTT diagram of spring steel grade 51CrV4 with marked cooling curve from austenitising temperature of 870 °C modelled in Hardenability software

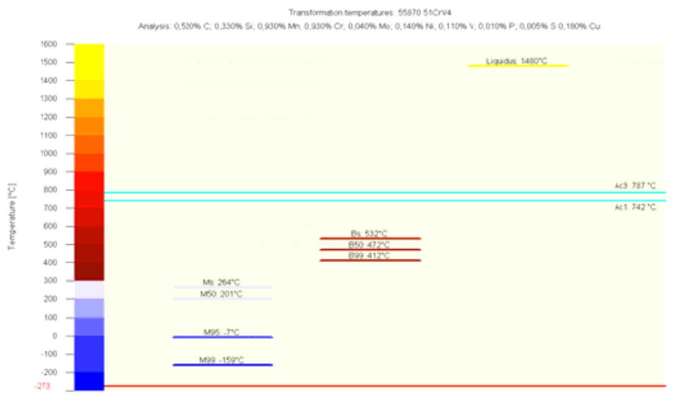

Fig2: Transformation temperature for spring steel grade 51CrV4 modelled in Hardenability software

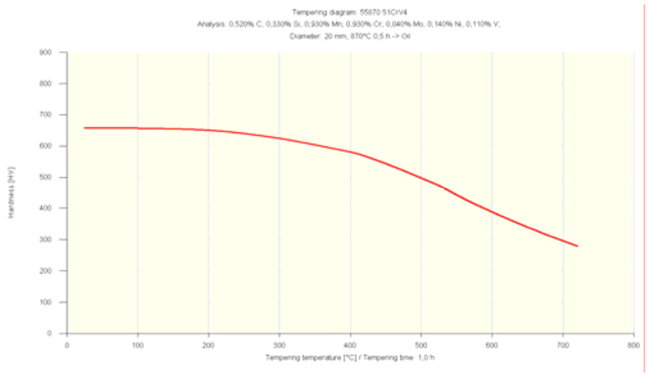

Fig.3 : Tempering diagram (hardness – tempering temperature) for spring steel grade 51CrV4 modelled in Hardenability software

Fig 4. shows tempering diagram mechanical properties (tensile strength, *Rm*, MPa, yield strength, $Rp_{0,2}$, MPa, elongation *A*, % and necking, *Z*, %) - tempering temperature modelled using *Hardenability* software for vacuum heat treatment of the specified spring steel.

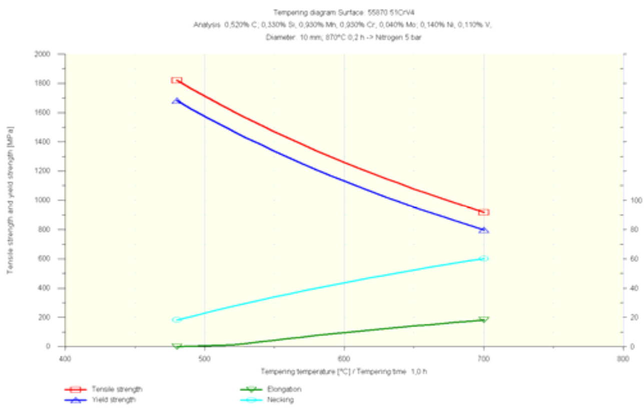

Fig. 4: Tempering diagram for spring steel 51CrV4 modelled in Hardenability software

Tempering diagram of mechanical properties Rm, $R_{p0.2}$, , A and Z as a function of tempering temperature

Figure 5. shows classic tempering diagram of the average measured values of mechanical properties (tensile strength R_m (MPa), yield strength $R_{p0.2}$ (MPa), elongation A_5 (%) - necking Z (%)) as a function of tempering temperature in range between 300 – 700 °C for an austenitising temperature of 870 °C.

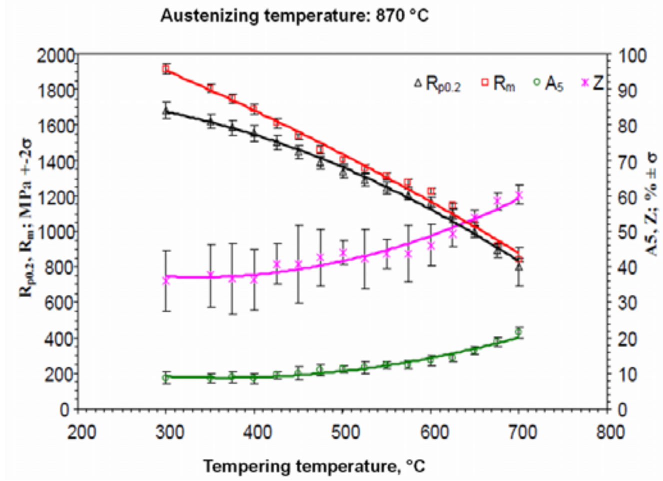

Fig. 5: Classic tempering diagram for continuous cast hot rolled flat spring steel 51CrV4, austenitising temperature 870 °C.

For each tempering temperature tensile tests were performed on a statistically relevant number of R_m-specimens so the results were subjected to statistical analysis. As can be seen from the diagram, the minimum variation of results is within ± 2σ in the whole range of selected tempering temperatures for tensile strength and elongation, while it is higher only for necking. In comparison with modelled tempering diagram the mean value of tensile strength, Rm, for the tempering temperature of 500 °C is smaller by 219 MPa, and yield strength Rp0,2 by 144 MPa. For the tempering temperature of 650 °C measured mean value of tensile strength, Rm, is higher by 28 MPa, and $Rp_{0,2}$ is higher by 112 MPa.

The measured contraction Is higher by 16 % and necking by 11,2 % comparing to values given by *Hardenability* model. Comparing the results with the modelled values, for a tempering temperature of 500 °C, the measured value of tensile strength, Rm, was 1402 MPa, and in the model, the specified Rm value was given at a tempering temperature of 547 °C.

Tempering diagram hardness HRC – fracture toughness, K_{IC} – tempering temperature

High strength spring steels are very notch sensitive, so it is very important to measure fracture toughness $\boldsymbol{K}_{Ic}$, which can be described as the ability of the material to resist the propagation of existing crack under tensile stress. Tempering diagram Hardness HRc – Fracture toughness $\boldsymbol{K}_{Ic}$ – Tempering temperature for the selected austenitising temperature 870 °C and selected tempering temperature in the range of 200 °C to 625 °C for the steel grade 51CrV4 is shown in Figure 6.

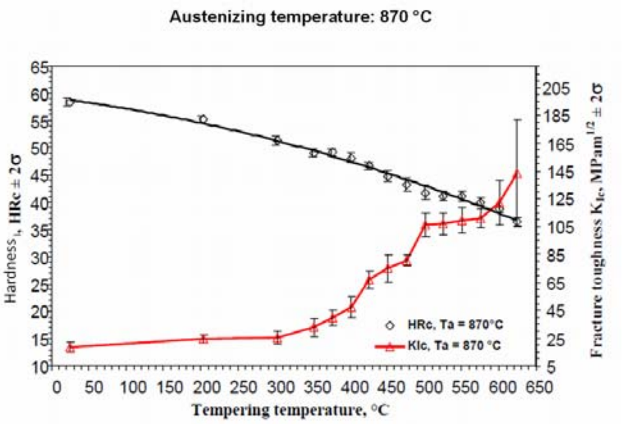

Figure 6: Effect of tempering temperature on the hardness HRc and fracture toughness K_{Ic} of spring steel 51CrV4.

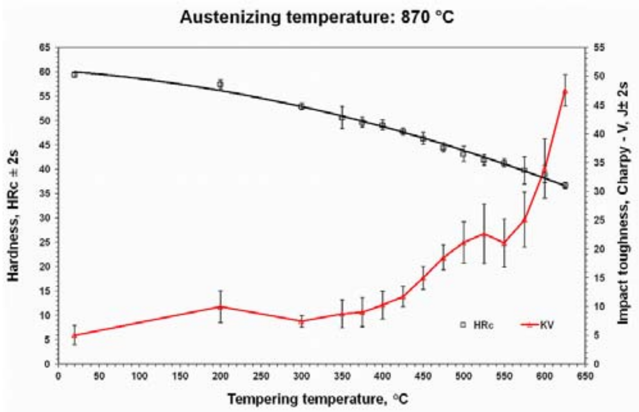

Figure 7: Effect of tempering temperature on hardness HRc and impact toughness Charpy-V of continuous cast hot rolled flat spring steel 51CrV4.

It can be seen that the minimum variation of results within ± 2s is in the quenched state and in $\boldsymbol{K}_{Ic}$-specimens, which were quenched and tempered at 200 °C. At higher tempering temperatures between 300 °C and 525 °C, the results scattering is slightly higher. This can be attributed to the kinetics of precipitation during tempering which affected the heterogeneity of the investigated steel. In the range between 500 °C and 575 °C there was no increase in fracture toughness from which one could conclude that we are in the area of irreversible temper brittleness which should be further investigated [6].

Tempering diagram Hardness HRc - Charpy-V - tempering temperature

For obtaining this diagram the impact toughness was measured by Charpy impact test known also as Charpy V-notch test (ISO 148). Measurement with an instrumented Charpy hammer allows the estimation of the total impact energy, the energy needed for crack initiation and the energy necessary for crack propagation. The tempering diagram obtained for selected tempering temperatures in the range of 200 °C to 625 °C for high strength steel 51CrV4 is shown in Figure 7.

The diagram shows that the curves of hardness and impact toughness Charpy-V over the entire range of tempering temperature are similar to the curves of hardness and fracture toughness K_{Ic} in the tempering diagram shown in Figure 7. Similarly, for fracture toughness the impact toughness also increases to a temperature of 525 °C. In the range from 500 °C to 550 °C the impact toughness is approximately equal, then it increases again. This trend can be attributed to the kinetics of precipitation during tempering. In the diagram, the variation of results within ± 2s in the quenched and tempered condition by a temperature of 475 °C is of the same magnitude, after that it is increased for tempering temperature above 500 °C. In the tempering temperature range of 525 °C - 575 °C results show that toughness is reduced, which confirms the observations made in measuring the fracture toughness, when the assumption that this is the area of irreversible temper embrittlement was made [5,6].

IV. CONCLUSION

On the basis of the experimental investigation conducted it can be concluded that the high-strength spring steel 51CrV4 can successfully be heat-treated in a horizontal vacuum furnace with uniform high-pressure gas-quenching using nitrogen (N_2) at a pressure of 5 bar. Achieved hardness after quenching was 58.4 ± 0.8 HRC which is enough for this steel to obtain the required hardness of 30-50 HRC after single tempering.

The investigation also showed that standardized fracture-toughness testing (ASTM E399-90), could be replaced with a non-standard testing method using circumferentially notched and fatigue-pre-cracked tensile specimens ($\boldsymbol{K}_{Ic}$-test specimen). The results of this innovative approach of 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 $\boldsymbol{K}_{Ic}$ – Tempering temperature) for vacuum-heat-treated high strength spring steel grade 51CrV4.

According to tempering diagrams Tensile strength R_m-Yield stress $R_{p0.2}$-Elongation A_5(%)-Necking Z(%)-Tempering temperature and tempering diagram Hardness HRc – Impact toughness Charpy-V - Tempering temperature we can conclude that the investigated spring steel 51CrV4 is suitable for production of high strength springs when proper heat treatment is performed.

Although some values of mechanical properties of investigated steel were for approx. 10 – 15 % higher when modelled in Hardenability software it can be concluded that Hardenability software is very good tool for assessment of heat treatment parameters.

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