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FATIGUE-LIFE BEHAVIOUR AND A LIFETIME ASSESSMENT OF A DOUBLE-LEAF SPRING USING FEM-BASED SOFTWARE

UTRUJANJE IN OCENA DOBE TRAJANJA DVOLISTNATIH VZMETI Z UPORABO MKE-ORODJA

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A lifetime assessment of any component by performing classical fatigue tests on real geometry is a very expensive and time-consuming task. For this reason, many efforts have been made to produce a computer software which will be able to replace this conventional fatigue testing. Although there is some dissimilarity between these two testing methods, we are free to use such a computer tool to shorten the testing time. The Finite Element Method (FEM) is one of the most frequently used methods for component designing, as well as for fatigue assessment. This assessment includes the stresses, the loads and the strength behavior of the material component. As the input values for the material properties, S/N curves were defined on the basis of the test results. The tensile and fatigue tests on the notched, as well as on the unnotched specimens under compression-tension loading were carried out in order to obtain the static and dynamic (S/N curves) properties of the investigated spring steel (51CrV4). Two groups of specimens were prepared: the longitudinal and perpendicular specimens relative to the rolling direction, both with two different heat-treatments (tempering temperatures).
The results of the performed investigation showed a clear difference between the fatigue strengths of the specimens with two outmost segregation orientations and two different tempering temperatures. In addition, other influences, such as the residual stresses due to shoot peening and machining, surface roughness and metallurgical variables, can affect the fatigue strength of a material. All these effects can be taken into account by using the FEM-based simulations.

Keywords: fatigue life, leaf spring, FEM simulation, spring steel

Ocenjevanje dobe trajanja komponent pri izvajanju klasičnega preizkusa utrujanja realne geometrije je zelo drag in dolgotrajen postopek. Zaradi tega je bil vložen velik napor, da bi pridobili računalniško podprto orodje, ki bi bilo sposobno zmanjšati število konvencionalnih preizkusov utrujanja. Čeprav realno lahko pričakujemo, da obstajajo nekatere razlike med rezultati preizkušanja na realnih preizkušancih in tistimi, dobljenimi z računalniško podprtim orodjem, je prednost slednjega nedvomna, saj močno skrajša čas do pridobitve dokaj uporabnih podatkov. Metode končnih elementov (MKE) so med najbolj uporabnimi za načrtovanje komponent tudi pri oceni vpliva utrujanja nanje za neko izbrano realno geometrijo. Ta ocena je sestavljena iz trdnostnih, obremenitvenih in napetostnih značilnosti materiala oz. komponent. Pri vzorcih iz izbranega materiala (vzmetno jeklo 51CrV4) smo določili njegovo trdoto ter statične (natezno trdnost) in dinamične (S/N-krivulje) lastnosti. Preizkusi utrujanja oz. določevanje S/N-krivulj je potekalo na zarezanih in nezarezanih vzorcih v natezno-tlačnem načinu obremenitve. Pripravljeni sta bili dve skupini vzorcev: v prečni in vzdolžni smeri glede na smer valjanja (smer izcejanja), obe skupini pa sta bili še dodatno različno toplotno obdelani (pri dveh različnih temperaturah popuščanja).
Rezultati preiskav kažejo jasno razliko med dinamično trajno trdnostjo vzorcev za izbrani orientaciji izcej in izbrani temperaturi popuščanja. Poleg tega moramo upoštevati, da tudi drugi vplivi (metalurgija izdelave jekla, zaostale napetosti zaradi peskanja in mehanske obdelave, hrapavost površine itd.) lahko vplivajo na dinamično trajno trdnost materiala. Vsi navedeni vplivi se lahko upoštevajo pri uporabi MKE-orodja.

Ključne besede: doba trajanja, listnate vzmeti, MKE-simulacije, vzmetno jeklo

1 INTRODUCTION

The basic function of a leaf spring is to store mechanical energy when it initially elastically deforms and to recoup this energy after being released. Since a leaf spring is subjected to dynamic loading it is possible for a failure to occur even at a stress level considerably lower than the tensile or the yield strengths determined by the quasi static loading. In addition, the fatigue strength of a leaf spring may be influenced by many factors such as: surface roughness, surface treatment, component size, residual stresses, corrosion, temperature, metallurgical structure, etc. In order to provide stability and safety to a vehicle, all these influences should to be taken into account in the manufacturing and designing processes of spring steel, as well as of spring semifinal products (plates or profiles). Unfortunately, all of these influencing factors often cannot be accurately taken into consideration without an exact experimental investigation.

Particular care has to be taken during a spring-manufacturing process (profiling, eye making, punching, etc) that, together with the final heat-treatment, has a crucial effect on the fatigue behavior of a spring. Among all the mentioned factors that influence the dynamic property of a spring, in this paper the influences of the intensities of the alloying elements, as well as of different tempering temperatures, on the fatigue behavior were examined.

2 EXPERIMENTAL WORK

The experimental work consisted of the compression-tension fatigue tests carried out on the notched and smooth (unnotched) specimens on a servo-hydraulic testing rig ±250 kN INSTRON 8802 at the frequency of 30 Hz. Some additional tests were also performed on a high-frequency pulsator (Rumul, Switzerland) that is known for providing a fast and reliable method of steel-quality assessment[1,2]. The tested spring steel 51CrV4 was produced with a modified deoxidation technology at the steel plant Štore Steel, Slovenia. The chemical composition of the selected spring steel is given in **Table 1**.

To determine the dynamic properties of the spring steel two groups of specimens were prepared and tested. As it is illustrated in **Figure 1**, one group of specimens is oriented along the rolling direction, while another group is perpendicular to the rolling direction.

Both the perpendicularly (λ = 90°) and longitudinally (λ = 0°) oriented specimens relative to the rolling direction are presented in **Figures 2** and **3**.

For the purpose of both static-tensile test and dynamic-loading test, all specimens are cut off from the base spring-steel material in the as-delivered condition (a flat profile with the dimensions of 90 mm × 28 mm). After cutting and machining, the specimens were heat-treated, quenched in nitrogen at 5 bar of overpressure and then tempered at two different temperatures. Both perpendicular and longitudinal specimens were divided into these two groups of tempering temperatures: 425 °C (HT1) and 475 °C (HT2).

At the end of the experiment, an FEM simulation of the dynamic loading (fatigue) of a double-leaf spring with a selected geometry was carried out with the use of the experimental testing results. Among the many accessible computer codes based on the stress or strain-life approaches[3–7] and on a cumulative-damage analysis[8] relating to the fatigue-life prediction of the double-leaf spring, ANSYS computer software was used. The presented FEM simulation was based on the high-cycle fatigue approach and the S/N curves for the investigated spring steel 51CrV4 obtained with the compression-tension tests of differently oriented specimens at both tempering temperatures. The used computer tool was first successfully tested by performing an FEM simulation on the smooth and notched cylindrical specimens during the mechanical testing.

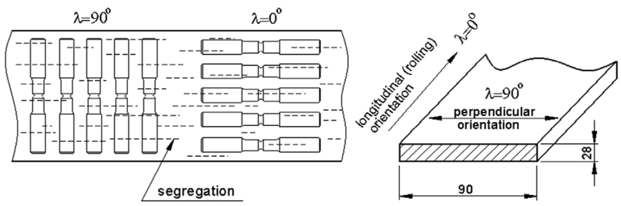

Figure 1: Orientation of the specimens with respect to the rolling direction
Slika 1: Orientacija preizkušancev glede na smer valjanja

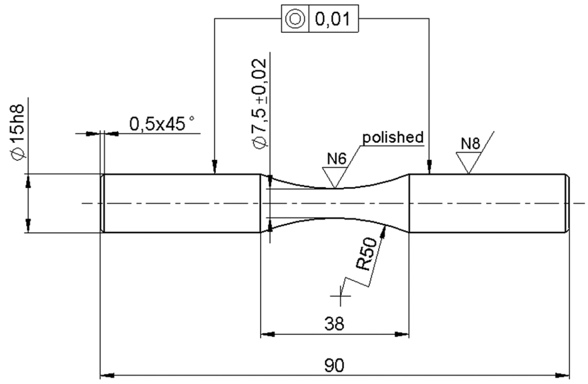

Figure 2: Standard smooth cylindrical specimen; *Kt* = 1 (calculated with ANSYS)
Slika 2: Standardni cilindrični preizkušanec brez zareze; *Kt* = 1 (izračunan v ANSYS-u)

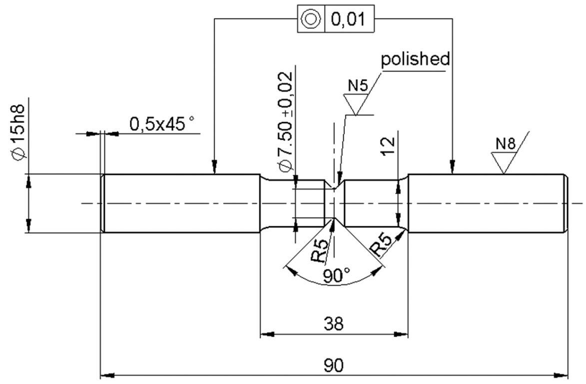

Figure 3: Standard notched cylindrical specimen; *Kt* = 2 (calculated with ANSYS)
Slika 3: Standardni cilindrični preizkušanec z zarezo; *Kt* = 2 (izračunan v ANSYS-u)

3 RESULTS AND DISCUSION

3.1 Static test

Before the compression-tension fatigue testing, the static-tensile tests were also carried out using a 500-kN Instron 1255 test rig with an extensometer. As illustrated in **Table 2** it is obvious that both tensile and yield strengths increase with a decrease in the tempering

Table 1: Chemical composition of the spring steel 51CrV4 in mass fraction (*w*/%)
Tabela 1: Kemijska sestava vzmetnega jekla 51CrV4 v masnih deležih (*w*/%)

Chemical element	C	Si	Mn	P	S	Cr	Mo	Ni	V
Composition	0.52	0.35	0.96	0.011	0.004	0.94	0.05	0.13	0.12

Table 2: Tensile-test results
Tabela 2: Rezultati nateznega preizkusa

Orientation	Tempering temperature	Yield strength (MPa)	Tensile strength (MPa)	Fracture elongation (%)	Fracture contraction (%)
Perpendicular (λ = 90°)	475 °C/1 h	1373	1448	7.04	24.6
	425 °C/1 h	1502	1591	5.16	15.8
Longitudinal (λ = 0°)	475 °C/1 h	1366	1442	10.6	41
	425 °C/1 h	1502	1606	9.9	42

temperature. The fracture elongation also varies with the changes in the tempering temperature. When the tempering temperature decreases the fracture elongation decreases as well. Ductility is larger in the longitudinal direction than in the perpendicular one.

3.2 Hardness measurement

A slight difference between the hardness measurements at 425 °C and at 475 °C of the tempering temperature was also found (**Table 3**). Before the heat treatment, the base material had the Rockwell hardness of about 30 HRC, whereas after the heat treatment the average hardness increased to about 45 HRC at 425 °C and to 43 HRC at the tempering temperature of 475°C. Nearly the same results were obtained for both the perpendicularly and parallelly oriented specimens.

Table 3: Hardness in dependence of the heat-treatment condition and the segregation orientation
Tabela 3: Trdota v odvisnosti od pogojev toplotne obdelave in orientacije izcej

Longitudinal (λ = 0°)		Perpendicular (λ = 90°)	
425 °C	475 °C	425 °C	475 °C
45.0 HRC	43.4 HRC	45.8 HRC	43.0 HRC

3.3 Dynamic test

The influences of the heat treatment and the segregation orientation under the compression-tension dynamic loading were investigated. These experiments were performed at the Institute of Metals and Technology (IMT), Ljubljana, Slovenia, using a compression-tension testing machine Instron 8802 of ±250 kN with the operating frequency of 30 Hz.

The S/N curves obtained with the compression-tension fatigue tests on the notched, as well as on the smooth specimens are presented in the diagrams in **Figures 4** and **5**, respectively. The specimens shown in **Figures 2** and **3** were mechanically polished (fine metallographic grinding; final paper 800) after the heat treatment in order to achieve the required surface roughness.

Figures 4 and **5** show that the fatigue strength of the specimens tempered at 425 °C is slightly higher than that of the specimens tempered at 475 °C. It is also clear that the fatigue strength of the longitudinally oriented specimens is significantly higher than the fatigue strength of the perpendicularly oriented specimens. We still need to finish the fatigue testing on the smooth, perpendicularly oriented specimens tempered at 475 °C to get more information about the influence of the notch on the fatigue strength. A tabular review of the fatigue-strength dependence on the segregation orientation and the heat-treatment conditions, for both notched and smooth specimens, is given in **Table 4**.

The 5.2 slope of the S/N curve for the perpendicularly oriented HT2 specimens is surprisingly lower than the 5.9 slope of the HT1-S/N curve. For more accurate findings, this fatigue test has to be repeated.

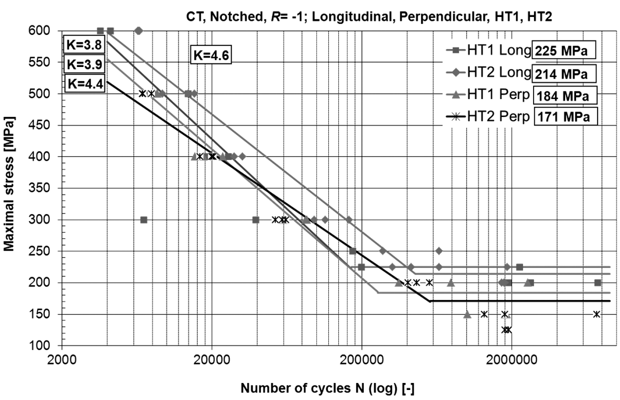

Figure 4: S/N curves for the notched specimens of both segregation orientations
Slika 4: S/N-krivulje zarezanih preizkušancev za obe orientaciji izcej

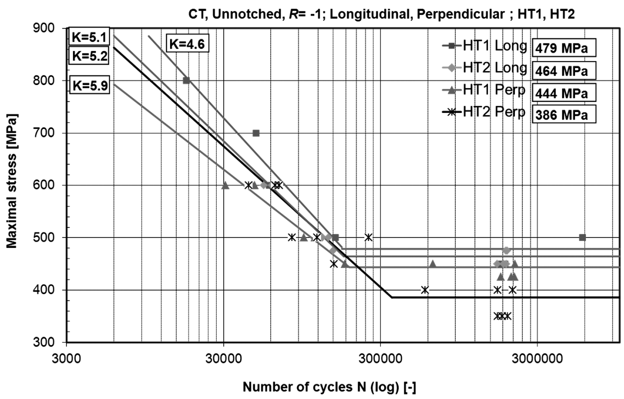

Figure 5: S/N curves for the smooth, longitudinally orientated specimens
Slika 5: S/N-krivulje nezarezanih preizkušancev za obe orientaciji izcej

Table 4: Fatigue limits of the tested specimens
Tabela 4: Trajna dinamična trdnost preizkušancev

Segregation orientation	Tempering temperature	Notched specimens	Smooth specimens
Perpendicular (λ = 90°)	HT1 (425 °C)	184 MPa	444 MPa
	HT2 (475 °C)	171 MPa	386 MPa
Longitudinal (λ = 0°)	HT1 (425 °C)	225 MPa	479 MPa
	HT2 (475 °C)	214 MPa	464 MPa

From the fatigue-limit values for the smooth and notched specimens it is evident that the fatigue limits of the notched specimens are nearly reduced by the theoretical stress-concentration factor (Kt = 2 for the notched specimens).

3.4 Double-leaf-spring simulation using FEM-based software

Fatigue simulations of the double-leaf spring with the selected geometry were performed using three standard loading conditions that the spring manufacturers normally use for the structural testing of leaf springs (**Figure 7**). The fatigue simulations were also based on the results of the above described mechanical testing. First, the simulations on the specimens were performed in order to evaluate the usability of ANSYS software for the double-leaf spring. All specimens were first generated in Solid Works 3D computer programme. After exporting, the specimen models were further prepared (meshed, constrained, loaded, etc) and finally simulated with ANSYS computer programme using the fatigue module. No remarkable difference was found in the number of cycles between the mechanically tested specimens and the computer-simulated specimens using ANSYS software with the corresponding S/N curves. Afterwards the fatigue simulations using the ANSYS computer tool were carried out on the double-leaf spring. One model of the double-leaf spring is presented in **Figure 6**.

The ANSYS material database was created using a new spring-steel material with the required static properties, forming six S/N curves obtained with the dynamical testing. The fatigue-life results for the double-leaf spring obtained with the ANSYS simulation are gathered in **Figure 7**. The results are based on the variation of different parameters, i.e., the segregation orientation, the heat treatment and the notch effect. The double-leaf-spring model was loaded in the case of a free displacement in one direction (z) and constrained in the other two directions (x and y), **Figure 6a**.

From the fatigue simulation it is clear that the longest fatigue life of the double-leaf spring was obtained by using the dynamic properties of the smooth, longitudinally oriented specimens, tempered at 425 °C. For the lowest loading condition it can be seen that all three S/N curves relating to the smooth specimens give a fatigue lifetime of more than 5 million cycles, which is already in the range of the fatigue limit. The S/N curves obtained with the fatigue testing of the notched specimens were corrected with the stress-concentration factor to avoid the influence of the notch.

The expected life of the double-leaf spring is above $1.5 \cdot 10^5$ cycles. It is evident that this expectation is fulfilled only at the lowest loading condition. Accordingly, the suspension system of a truck has to be designed in such a way that this dynamic loading condition is not exceeded. One can also notice that the highest prescribed testing conditions are already in the low-cycle fatigue region (the regime of loading very close to, or even above, the yield point of the selected spring steel; **Table 2**). From this point of view the selected structural testing condition seems problematic and inadequate.

4 CONCLUSION

The investigations have shown scattered results of the fatigue testing performed at a certain stress level. This dispersion of the results among the repeated specimens is

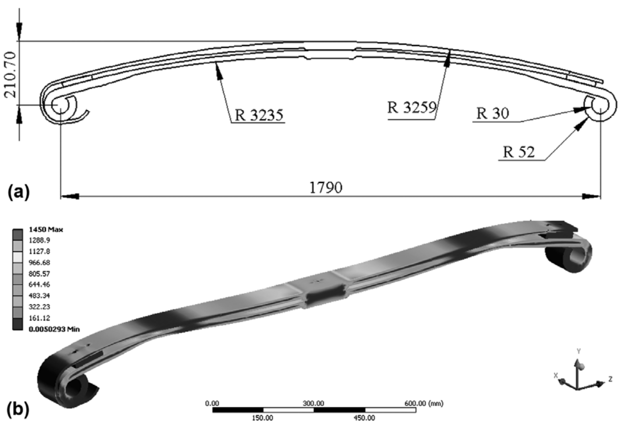

Figure 6: a) Basic dimensions of the double-leaf spring generated with Solid Works and b) an ANSYS fatigue simulation of the double-leaf spring
Slika 6: a) Osnovne dimenzije dvolistnate vzmeti, modelirane v Solid Worksu in b) ANSYS-simulacije utrujanja dvolistnate vzmeti

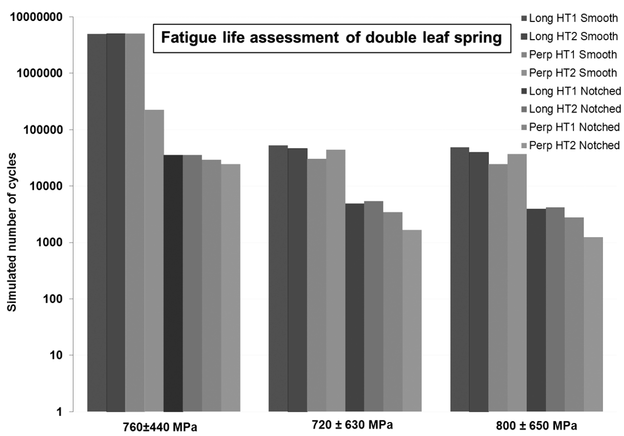

Figure 7: Simulated fatigue lifetime of the tested double-leaf spring
Slika 7: Simulacijska doba trajanja preizkušanih dvolistnatih vzmeti

mainly influenced by different nonmetallic inclusions[9] in the spring steel (MnS, CaS, Al_2O_3). Insufficient polishing quality after the heat treatment of the specimen surface can also lead to the number of cycles being lower than expected, causing a lower fatigue strength of the investigated steel. In general, in the case of the selected spring steel 51CrV4, the fatigue strength of the perpendicularly oriented specimens decreases by about 25 % more than the strength of the longitudinally oriented specimens, accompanied with the lower tensile and yield strengths. Considering different stress-concentration factors relating to the notched and smooth specimens, it is shown that the fatigue strength of the notched specimens is effectively lower, as indicated by the stress-concentration factor.

Generally speaking, when dealing with a fatigue-module simulation, one has to take into consideration not only the metallurgical and manufacturing effects, but also the other effects related to the used software, such as the type and the size of the mesh element (tetrahedral, hexahedral etc), the input file (IGES, STEP, SLDPRT etc), the boundary conditions and the constraint type.

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