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FEM SIMULATION OF A MONO-LEAF SPRING AND ITS FATIGUE LIFE PREDICTION

MKE SIMULACIJA MONO LISNATE OPRUGE I PROCENA VEKA ZAMORA

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- S/N curves
- fatigue strength
- FEM based simulation

Abstract

The fatigue life determination of a component obtained by testing the real geometry is a time consuming and expensive task. Therefore, the prediction of the fatigue life of a part by means of finite element method (FEM) is a frequent procedure of component designing. This prediction consists of: stresses, loads and strength behaviour of the component material. As an input value for the material properties S/N curves are defined, which are based on test results. Fatigue tests on notched, as well as unnotched specimens under compression-tension loading are carried out in order to obtain the S/N curves of the investigated spring steel. Two groups of specimens are prepared: longitudinal and perpendicular relative to the rolling direction, both with two different tempering temperatures. A comparison among FEM simulation and testing results on the real leaf geometry is also given.

Ključne reči
- čelik za opruge
- lisnata opruga
- S/N krive
- dinamička čvrstoća
- MKE simulacija

Izvod

Određivanje veka zamaranja komponente, koji se dobija ispitivanjem u realnim dimenzijama, je dugotrajan i skup poduhvat. Stoga je predviđanje veka zamaranja datog dela primenom metode konačnih elemenata (MKE) čest postupak u projektovanju komponente. Ova procena se sastoji iz: napona, opterećenja i ponašanja čvrstoće materijala komponente. Kao ulazna veličina za osobine materijala, definisane su S/N krive, zasnovane na rezultatima ispitivanja. Ispitivanja zamorom na zarezanim, kao i na epruvetama bez zareza pod pritisno-zateznim opterećenjem se izvode u cilju dobijanja S/N krivih za ispitivani čelik za opruge. Pripremljene su dve grupe epruveta: podužna i poprečna, u odnosu na pravac valjanja, i to sa izborom po dve različite temperature otpuštanja. Takođe je dato poređenje rezultata MKE simulacije sa rezultatima ispitivanja za realnu geometriju opruge.

INTRODUCTION

The basic function of a leaf spring is to store mechanical energy as it is initially elastically deformed and then recoup this energy after releasing the spring. Since the leaf spring is subjected to dynamic loading it is possible for failure to occur even at a stress level, considerably lower then the tensile or yield strength determined by quasi-static loading. In addition, fatigue strength of the leaf spring is also 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 process of the spring steel, as well as the spring semifinal product (plate or profile). Unfortunately, all these influencing factors often cannot be exactly taken into consideration without exact experimental investigation.

Particular care has to be taken during the spring manufacturing process (profiling, eye making, punching etc) that, along with final heat treatment, have a crucial effect on the fatigue behaviour of the spring. Among all mentioned factors that influence dynamic property of the spring, in this paper the influence of segregation orientation of alloying elements, as well as the different tempering temperature on the fatigue behaviour are examined.

EXPERIMENTAL WORK

The experimental work has involved performing compression-tension fatigue tests on notched and smooth (unnotched) specimens on servohydraulic testing rig ±259 kN INSTRON 8802 with frequency of 30 Hz. Also some additional tests are performed on the high frequency pulsator (Rumul, Switzerland) which is known as a fast and reliable method of steel quality assessment /1, 2/. The spring steel 51CrV4 that was tested is produced with a modified deoxidation technology at steel plant Štore Steel, Slovenia. The chemical composition of the selected spring steel is given in Table 1.

Table 1. Chemical composition of spring steel 51CrV4 (wt. %)
Tabela 1. Hemijski sastav čelika za opruge 51CrV4 (mas. %)

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

In order to obtain dynamic properties of the spring steel, two outmost directions of rolling, which generally correspond also to the segregation orientation, are used to prepare the testing specimens, as illustrated in Fig. 1.

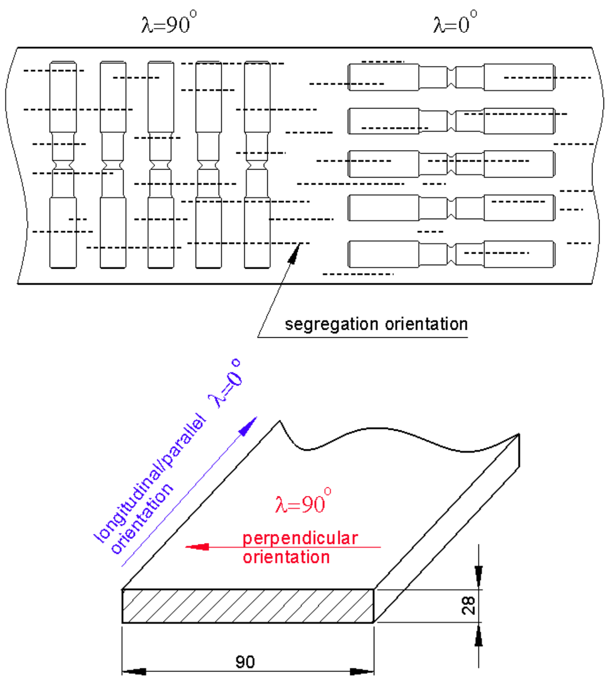


Figure 1. Orientation of specimens with respect to the rolling direction.
Slika 1. Orijentacija epruveta s obzirom na pravac valjanja

Both perpendicular (λ = 90º) and longitudinal (λ = 0º) oriented specimens relative to the rolling direction are presented in Figs. 2 and 3.

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

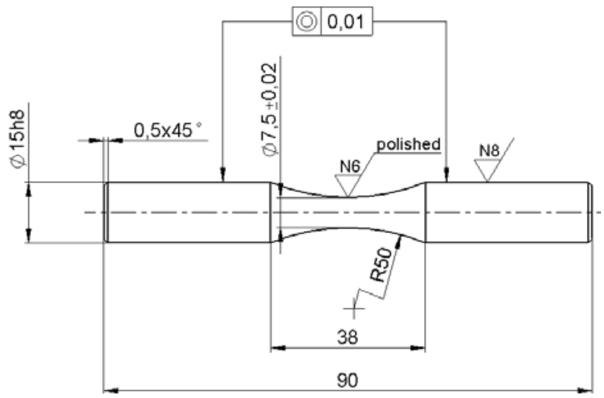


Figure 2. Standard smooth cylindrical specimen; K_t = 1.
Slika 2. Standardna glatka cilindrična epruveta; K_t = 1

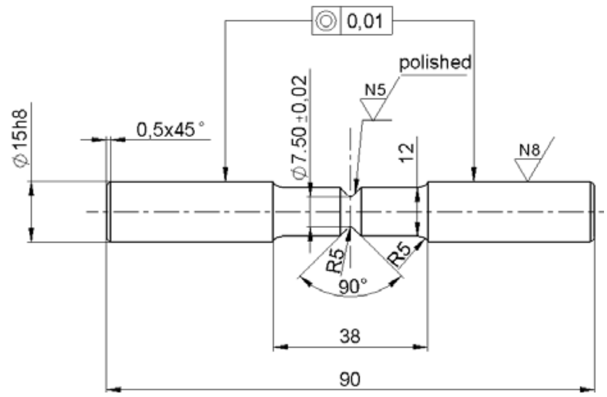


Figure 3. Standard notched cylindrical specimen; K_t = 2.
Slika 3. Standardna cilindrična epruveta sa zarezom; K_t = 2

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

RESULTS AND DISCUSION

Static test

Before the fatigue compression-tension tests, also static tensile tests are carried out using a 500 kN Instron 1255 test rig by means of extensometer. As illustrated in Table 2 it is obvious that both tensile and yield strength increase with decreasing tempering temperature. Also fracture elongation varies by changing tempering temperature. With decreasing tempering temperature, fracture elongation decreases. Ductility is also larger in the longitudinal direction compared to the perpendicular one.

Table 2. Tensile test results.

Tabela 2. Rezultati ispitivanja zatezanjem

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

Hardness measurement

A slight difference between the hardness measurement at 425°C and 475°C tempering temperatures was found. The Rockwell hardness of base material, before heat treatment, was about 30 HRC, whereas after heat treatment, the average hardness increased about 45 HRC at 425°C and 43.4 HRC at 475°C tempering temperature. Nearly the same results were obtained for both perpendicular and parallel oriented specimens.

Table 3. Hardness depending on heat treatment condition and orientation of segregation.

Tabela 3. Tvrdoća u zavisnosti od stanja termičke obrade i orijentacije segregacije

Longitudinal ($\lambda = 0°$)		Perpendicular ($\lambda = 90°$)	
425ºC	475ºC	425ºC	475 ºC
45.0 HRC	43.4 HRC	45.8 HRC	43.0 HRC

Dynamic test

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

The S/N curves obtained by compression-tension fatigue tests on notched, as well as on smooth specimens are presented in the diagram in Figs. 4 and 5, respectively. All specimens, as given in Figs. 2 and 3 are polished after the heat-treatment process in order to achieve the required surface roughness.

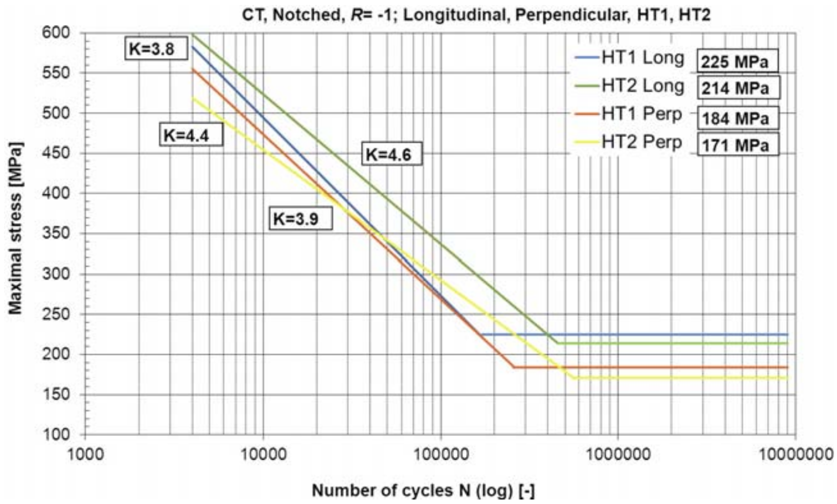


Figure 4. S/N curves for notched specimens of both segregation orientations.
Slika 4. S/N krive epruveta sa zarezom za obe orijentacije segregacija

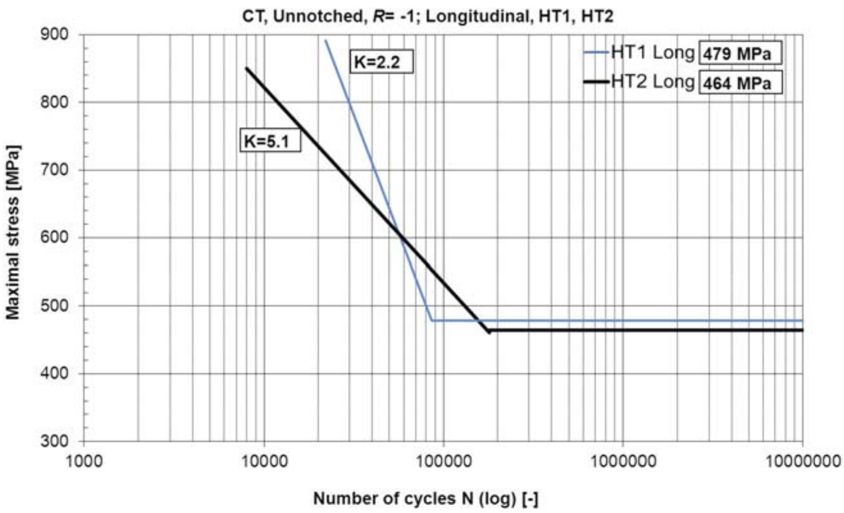


Figure 5. S/N curves for smooth longitudinal orientated specimens.
Slika 5. S/N krive za glatke podužno orijentisane epruvete

As it can be seen from Figs. 4 and 5 that fatigue strength of specimens tempered at 425ºC is slightly higher compared to specimens tempered at 475ºC. It is also clear that the fatigue strength of longitudinal oriented specimens is significantly higher than the fatigue strength of perpendicular oriented specimens. Fatigue testing needs still to be accomplished for smooth perpendicular oriented specimens of both tempering temperature to receive more information about the influence of the notch on the fatigue strength. A tabular review of the fatigue strength depending on segregation orientation and heat treatment conditions for both notched and smooth specimens is given in Table 4.

The slope of 2.2 of the S/N curve for the longitudinal oriented specimens of HT1 is surprisingly lower than all the other S/N slopes. For more accurate findings, this fatigue test has to be repeated.

Table 4. Fatigue limit of tested specimens.
Tabela 4. Dinamička čvrstoća ispitivanih epruveta

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

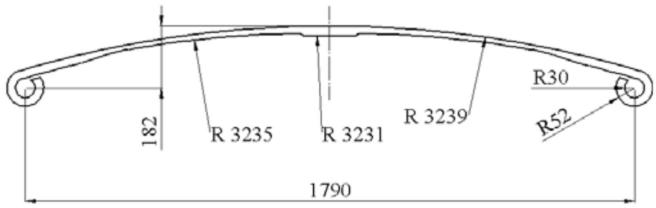
* still needs to be performed

From fatigue limit values of smooth and notched specimens it is evident that fatigue limits of notched specimens are nearly reduced as the theoretical stress concentration factor indicates, compared to the fatigue limits of smooth specimens (Figs. 2 and 3). These reductions of longitudinal oriented specimens for HT1 and HT2 are K_f = 2.12 and K_f = 2.16, respectively. This is typical for high strength steel where the fatigue stress reduction factor is larger than the theoretical (geometrical) stress concentration factor ($K_f > K_t$).

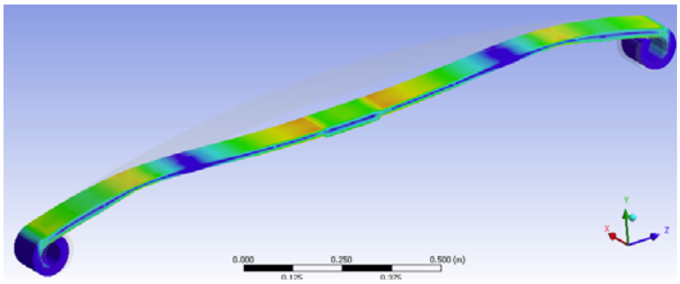
Mono-leaf spring simulation using ANSYS software

Fatigue simulations of the mono-leaf spring with the selected geometry are performed using three standard loading conditions used at spring manufacturers for structural testing of springs (Table 5). The basis for fatigue simulations are also the results of the above described mechanical testing. All specimens are first generated in the SOLID WORKS 3D computer programme. After exporting, specimen models are further prepared (meshed, constrained, loaded etc) and finally simulated by ANSYS computer programme, using fatigue module. No remarkable difference is found in a number of cycles (the fatigue limit) between mechanically tested specimens and computer simulated specimens using ANSYS software with corresponding S/N curves. One model of the monoleaf spring is presented in Fig. 6.

For the fatigue simulation of mono-leaf spring, three different loading conditions are used. The ANSYS material database is created with one new spring steel material of needed static properties with six S/N curves obtained by dynamical tests. By variation of parameters (segregation orientation, heat treatment, notch effect), during ANSYS simulation next fatigue life results of the mono-leaf spring are gathered, Table 5. During the fatigue simulation, 1632 mesh elements, each with the size of 15 mm are created. The mono-leaf spring model is loaded with free displacement in one direction (z) and is constrained in the other two directions (x and y), Fig. 6a.



(a)



(b)

Figure 6. Basic dimensions of mono-leaf spring generated by Solid Works (a); and ANSYS fatigue simulation of the mono-leaf spring (b).
Slika 6. Osnovne dimenzije mono lisnate opruge, generisane u Solid Works (a); i ANSYS simulacija zamora mono lisnate opruge (b)

Table 5. Fatigue limit of tested mono-leaf spring.
Tabela 5. Dinamička čvrstoća ispitivane mono lisnate opruge

Fatigue life of monoleaf spring	760±440 MPa	720±630 MPa	800±650 MPa
Orientation/Heat treatment	Number of Cycles		
Long HT1 Smooth	$2\cdot10^6$	52481	49081
Long HT2 Smooth	$2\cdot10^6$	46458	39609
Long HT1 Notched	17707	2447	1989
Long HT2 Notched	27977	2699	2109
Perp HT1 Notched	14617	1727	1380
Perp HT2 Notched	12247	827	623

From the fatigue simulation it is clear that the best fatigue life of monoleaf spring is obtained using dynamic properties of longitudinal oriented specimens, tempered at 425°C, simulated under load condition I (760 ± 440) MPa. S/N curves obtained by fatigue testing of notched specimens are intentionally used during simulation of mono-leaf spring without the correction of their fatigue limits. Normally, the S/N curves should be corrected and the fatigue limits of notched specimens should by multiplied by the fatigue notch factor (K_f) in order to have valid simulations.

The expected life of mono-leaf spring is above $1.5\cdot10^5$ cycles. It is evident that this condition is fulfilled at the lowest loading condition, only. Accordingly, the suspension system of the truck has to be designed in the 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 (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 testing condition seems problematic and non-adequate.

CONCLUSION

The investigations have shown scattered results in the fatigue testing performed at a certain stress. These disperse results, among repeated specimens are mainly influenced by different nonmetallic inclusions /9/ in spring steel (MnS, CaS, Al_2O_3). Also an insufficient polishing quality after the heat treatment of the specimen surface can lead to a lower number of cycles than expected, ending with lower fatigue strength of the investigated steel. In general, for the selected spring steel 51CrV4, the fatigue strength of perpendicular oriented specimens decreases for about 25%, compared to longitudinal oriented specimens accompanied with lower tensile and yield strength, as well as lower hardness. Regarding the different stress concentration factor for notched and smooth specimens it is shown that the fatigue strength of notched specimens is effectively lower as the stress concentration factor indicates.

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

REFERENCES

1. Šuštaršič, B., Senčič, B., Arzenšek, B., Jodin, P., *The notch effect on the fatigue strength of 51CrV4Mo spring steel*, Materials and Technology, 41 (2007) 1, pp.29-34.
2. Šuštaršič, B., Senčič, B., Leskovšek, V., *Fatigue strength of spring steels and life-time prediction of leaf springs*, Assessment of reliability of materials and structures (RELMAS'2008), St. Petersburg, Russia, 2008, Int. Conf. Volume 1, St. Petersburg, Polytechnic Publishing House, 2008, pp.361-366.
3. Tavakkoli, S., Aslani, F., et al., Analytical Prediction of Leaf Spring Bushing Loads Using MSC/NASTRAN and MDI/ADAMS, http://www.mscsoftware.com/support/library/conf/wuc96-/11b_asla.pdf
4. Kumar, M.S., Vijayarangan, S., *Static analysis and fatigue life prediction of steel and composite leaf spring for light passenger vehicles*, Journal of Scientific and Industrial research, 66 (2007) 2, pp.128-134.
5. Refngah, F.N.A., Abdullah, S., Jalar, A., Chua, L.B., *Fatigue life evaluation of two types of steel leaf springs*, Int J Mech. and Materials Engng. (IJMME), 4 (2009) 2, pp.136-140.
6. Niklas, Philipson: Leaf spring modeling http://www.modelica.org/events/modelica2006/Proceedings/sessions/Session2d1.pdf
7. Shankar, G.S.S., Vijayarangan, S., Mono Composite Leaf Spring for Light Weight Vehicle - Design, End Joint Analysis and Testing, ISSN 1392–1320 Materials Science (Medžiagotyra). 12 (2006) 3, pp.220-225.
8. Eichlseder, W., *Enhanced Fatigue Analysis – Incorporating Downstream Manufacturing Processes*, Materials and Technology, 44 (2010) 4, pp.185-192.
9. Kovačič, M., Senčič, S., *Critical inclusion size in spring steel and genetic programming*, RMZ - Materials and Geoenvironment, 2010, pp.17-23.