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FATIGUE STRENGTH AND MICROSTRUCTURAL FEATURES OF SPRING STEEL

DINAMIČKA ČVRSTOĆA I OSOBINE MIKROSTRUKTURE ČELIKA ZA OPRUGE

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Keywords
- spring steel
- S-N curves
- fatigue strength
- notch effect
- microstructure

Abstract

Knowledge about the local dynamic properties of steel, as well as the local loading conditions is absolutely necessary for the fatigue analysis and life time prediction of spring steel components. Mono-leaf and double-leaf springs of specific geometry made of 51CrV4 spring steel manufactured in the Slovenian steel plant Štore Steel are of interest in this case. Fatigue strength of the selected steel is determined in different loading modes for two different heat treatment conditions and two outmost directions of segregations of alloying elements. Microstructural characterisation of the selected steel is performed, as well as fractographic examination of fractured surfaces. The experimental results enable fatigue life prediction of spring steels using the local stress gradient concept.

Ključne reči
- čelik za opruge
- S-N krive
- dinamička čvrstoća
- uticaj zareza
- mikrostruktura

Izvod

Poznavanje lokalnih dinamičkih osobina čelika, kao i lokalnih uslova opterećenja je neophodno za analizu zamaranja i procenu veka komponenata od čelika za opruge. U našem slučaju od velikog značaja su jednolisnate i dvolisnate opruge karakteristične geometrije, napravljene od 51CrV4 čelika za opruge, proizvedenog u slovenačkoj fabrici čelika „Štore Steel". Dinamička čvrstoća izabranog čelika je određena na dva načina zamaranja za dva različita uslova termičke obrade i za dva krajnja pravca segregacija legirajućih elemenata. Izvedeno je određivanje mikrostrukture izabranog čelika kao i fraktografska ispitivanja površine loma. Rezultati dobijeni zamaranjem čelika za opruge omogućavaju procenu veka zamaranja čelika upotrebom koncepta lokalnog naponskog gradijenta.

INTRODUCTION

Spring manufacturers use different types of spring steels in the range of strength levels from 1200 up to 1800 MPa. Parabolic double and mono-leaf springs made of the highest strength, quality and safety level, are a very important market product for many spring steel producers. The highest quality level of spring steel requires the appropriate fine grained microstructure, without segregations, large inclusions and surface defects. However, the final quality of the manufactured spring does not depend on steel quality only. It also depends significantly on spring manufacture (hot forming; i.e.: profiling, eye making, punching etc), as well as final heat- and surface treatment (shot-peening). Therefore, high quality steel profile (semi product) does not necessarily mean a high quality spring (final product). Standardized dynamic (fatigue) testing on steel specimens and structural testing of springs is a time consuming and expensive task. Frequently, the information about a definite steel batch quality based on accelerated (up to approx. 2×10^5 cycles at frequency approx. 1-5 Hz) structural testing of springs is too late for the steel producer, as well as spring consumer. The testing results can generally be used only for complaint purposes. Former investigations clearly showed that the spring steel producer has to perform not only regular conventional tensile testing and hardness measurements but also dynamic testing (batch to batch) of the produced steel. It is shown that determination of fatigue bend strength on standard Charpy V-notched (CVN) samples with a high frequency pulsator is relatively fast, long-term cost acceptable and gives adequate date about steel quality /1/. It can even serve for life time assessment of springs with given or selected loading conditions based on simple stress concentration and notch-sensitivity factors approach, /2/, although geometry, surface quality and other influencing factors (roughness, shot peening, larger defects, etc.) are not taken into consideration. This simple approach considers only experimental S-N curves determined on CVN samples (cut off from the actual spring or steel profile) obtained at selected loading conditions (similar as performed with structural testing of springs) and its transfer to flat unnotched profiles. However, this approach and microstructure investigations show some incompleteness especially if larger defects (inclusions, decarburized surface /3/, strong change of segregation orientation and width) are present in the steel. A new scientific Austria-Slovenia bilateral collaboration between IMT, Ljubljana and IME, University of Leoben, Austria started last year. This is an opportunity to use a local stress gradient concept for fatigue life analysis of the selected spring steel and assess its usability for finite element method (FEM) based life-time prediction of mono-leaf and double-leaf springs of the selected size and geometry. Nowadays, FEM based analysis of mono and multi-leaf springs is very often used and it has been performed by different authors /4-8/ in the last ten years. The approaches to FEM are very different and based on different concepts. Some commercial computer codes based on the stress or strain life approach and cumulative damage analysis /9/ are already accessible (FEMFAT, Ansys, Abaqus, SolidWorks, Deform etc.) for the life time prediction of dynamically loaded structural elements. But, without adequate understanding of the problem and experimental results, these tools are useless. Recently, /10/, very interesting approach based on genetic programming and analysis of defect size at the fracture surface has also been used.

The term *clean steel* or even *super-clean steel* has become a standard in the modern production of P/M high-strength tool and high-speed steels, /11/. For spring steels one can notice a similar tendency /12/. The investigations showed, /13/, that in order to avoid the formation of larger inclusions in the production of clean steel, the following factors are very important: the proper selection and quality of insulation bricks, knowledge of the metal-slag-refractory interactions and the type of deoxidation process used during steel production. Interruptions during continuous casting (CC) of steel can also cause formation of larger inclusions /14, 15/. All these factors can drastically influence the steel quality. Metallographic control of steel can even show sound and relatively clean steel without larger inclusions. But a standard metallurgical sample for regular quality control is relatively small and can not show the real state. In some parts of large 60-tons or even larger batches, regions with extra large inclusions can be hidden. Especially if interruptions in the steel production occur, but not enough large parts of CC steel billets are refused. The complete (100%) control of steel billets is practically impossible or too expensive. Some tests have been done with ultrasonic immersion testing, /16-18/, but so far, this kind of control has been very expensive and not completely successful for large CC or hot rolled billets with insufficiently smooth and oxidized surface. An additional negative effect on fatigue strength of spring steel /19-20/ is caused by the formation of segregations. Segregations; i.e. changes of alloying element (Cr, Mn) concentrations across the cross-section of CC billets are formed because of nonuniform solidification of steel billet during CC and can not be completely removed during hot working (rolling). Some investigations have even shown that besides the segregation orientation, also thickness of negative to positive segregations has some effect on the mechanical properties of spring steel. Recently, for the reduction of segregations, the so called continuous soft reduction (CSR) devices adapted to continuous casting systems are developed. However, this demands high investment. Therefore, at the moment the only solution is very precise and in all phases as much as possible continuous well defined and controlled process of steel manufacturing. Recently, Štore Steel plant has made considerable efforts to increase the cleanliness and quality of produced spring steels. The steel manufacturing technology is modified and cleanliness of steel is significantly improved. This is confirmed by the customers' technological tests of leaf springs. The springs survived more than 2×10^5 cycles at the selected loading conditions compared to the previous tests below 10^5 cycles. This provided a good opportunity to investigate and analyse deeply the steel quality regarding fatigue.

In this paper results of fatigue strength determination of the selected spring steel manufactured with a modified technology are presented. Microstructural characterisation by light (LM) and scanning electron microscopy (SEM/ EDS) of the selected steel, as well as fractographic examination of fractured surfaces are also presented. The results enable fatigue life prediction of spring steels using the local stress gradient concept, /9/, taking into account the selected leaf spring geometry, the mechanical properties of spring steel and the conditions of fatigue.

EXPERIMENTAL WORK

The investigated spring steel is designated as standard DIN 51CrV4 (W. Nr.:1.8159, EN 10089). It is produced with a modified deoxidation technology in the steel plant Štore Steel, Slovenia. The final ladle-treatment (degassing, refinement, alloying, etc.) of liquid steel and continuous casting of steel melt into ingots of dimensions 140×140×3750 mm are performed after melting of steel scrap in a 60-ton electro-arc furnace. Finally, CC ingots are preheated, hot rolled and cut into semi finished profiles of 90×28 mm and length of either 1318 or 1618 mm. Nominal and actual chemical compositions are given in Table 1. Steel is relatively clean with low content of phosphorus (P) and sulphur (S). The content of other oligo elements (Sn, As, Sn) is below 0.01 wt. %. However, it has also a small content of Cu and Ni (0.19 wt. % of Cu and 0.13 wt. % of Ni). The aluminium content is 0.006 wt. %.

Table 1. Chemical composition of the investigated spring steel.
Tabela 1. Hemijski sastav ispitivanog čelika za opruge.

Element	C	Si	Mn	Cr	Mo	V	P	S
51CrV4	Wt. %							
Nominal	0.47–0.55	0.15–0.40	0.7–1.0	0.9–1.2	0.05–0.10	0.1–0.2	<0.015	<0.01
As analysed	0.52	0.35	0.96	0.94	0.05	0.12	0.011	0.004

The selected matrix of experiments is shown in Table 2. Specimens for mechanical testing are cut off of hot rolled profiles. As can be seen, fatigue strength (S-N curves) of the selected steel is determined in two different loading modes; i.e. tension-compression (T/C) and rotating-bending

(R/B) for two different heat treatment conditions (HT1 and HT2) and two outmost directions of alloying element segregations. For determining S-N curves, standard smooth (Fig, 1a) and notched (Fig. 1b) cylindrical specimens with different stress concentration factors are used. Fatigue testing of T/C specimens is performed at IMT, Ljubljana, with the ±250 kN Instron 8802 universal servo-hydraulic testing machine. The dynamic four-point R/B testing of smooth cylindrical specimens is performed at IME, University of Leoben, Austria, in the frame of Austria-Slovenia bilateral collaboration.

Table 2. Matrix of experiments.
Tabela 2. Matrica eksperimenata.

Material	Spring steel – 51CrV4							
Heat-treatment	870°C/10′/475°C/1h				870°C/10′/425°C/1h			
Segregation orientation λ*	0°		90°		0°		90°	
Type of fatigue**	T/C	R/B	T/C	R/B	T/C	R/B	T/C	R/B
Stress gradient χ*	2.5	0.27	2.5	0.27	2.5	0.27	2.5	0.27

*0°…parallel to rolling direction, 90°…perpendicular to rolling direc.
** T/C … tension-compression, R/B …. rotating bending

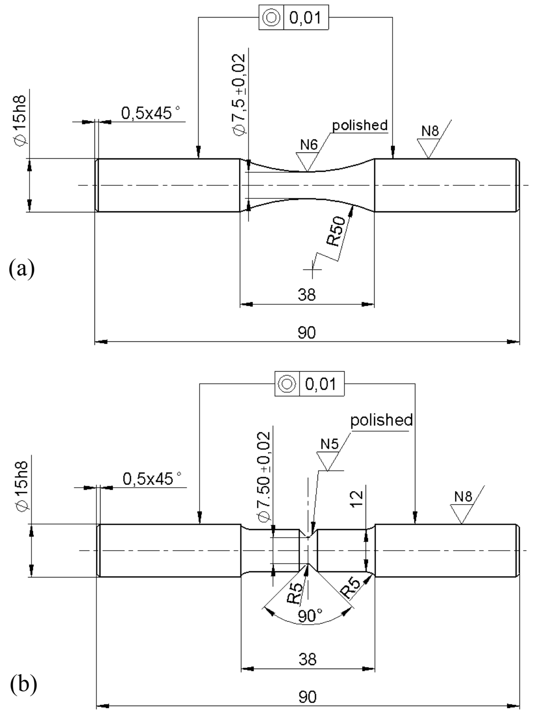


Figure 1. Standard smooth (a) and notched cylindrical specimen (b), dimensions of ϕ15/7.5×90 mm, used for determination of S-N curves of the investigated steel.
Slika 1. Standardni glatki (a) i zarezani cilindrični uzorak (b), dimenzija ϕ15/7.5×90 mm, za određivanje S-N kriva ispitivanog čelika za opruge.

For this type of steel, generally oil or water quenching from austenizing temperature, followed by the tempering in a batch furnace is performed. This gives the steel a complete tempered martensite structure. Previous investigations /2/ showed that in this case, this steel can give very high strength at an acceptable ductility ($R_m \approx 1800$ MPa, $R_{p0,2} \approx 1700$ MPa, $A \approx 8\%$ and $Z \approx 45\%$ at HRc ≈ 50 and CVN = 8–9). In the present case, vacuum heat treatment, /21/, is used. This enabled easier mechanical preparation of specimens and only surface mechanical polishing of specimens is performed after heat treatment. In this case, the cooling rate ($t_{8/5} \approx$ 42–46”) during fast cooling in nitrogen (5 bar) is lower. The result is presence of a small content of lower bainite in tempered martensite structure. Therefore, a little lower tensile strength and yield point are obtained, but they are still within the required strength region (1400–1600 MPa). One author, /22/, even suggests improvement of dynamic properties if a small amount of bainite is present in the steel matrix.

Standard metallographic samples are prepared for microstructural and micro-chemical investigations of steel matrix and inclusions under light- (LM) and scanning electron microscope (FE SEM/EDS). Microstructures are observed at different magnifications in the rolling and perpendicular directions. SEM fractographic examinations of characteristic broken specimens after fatigue were also made.

RESULTS AND DISCUSSION

In Table 3 the results of tensile tests and hardness measurements of the investigated steel are given. Tensile tests are performed on standard cylindrical specimens with dimensions of M12/ϕ8×75/48 mm with the Instron 1255/8800 universal servo-hydraulic testing machine.

Table 3. Average tensile properties and hardness of the investigated steel.
Tabela 3. Prosečne vrednosti ispitivanja na zatezanje i tvrdoće ispitivanog čelika.

Specimen orientation	Heat treatment	Yield strength	Tensile strength	Fracture elongation	Fracture contraction	Hardness HRc
		[MPa]		[%]		
Perpendicular ($\lambda = 90°$)	HT1	1502	1591	5.16	15.8	45.8
	HT2	1373	1448	7.04	24.6	43.0
Longitudinal ($\lambda = 0°$)	HT1	1502	1606	9.9	42	45.0
	HT2	1366	1442	10.6	41	43.4

Heat-treatment HT1 (austenizing at 870°C for 10 min., fast cooling in N_2 and tempering at 425°C for 1 hour) gives higher Rockwell hardness (HRc), tensile strength (R_m) and yield point ($R_{p0.2}$) but lower ductility (A and Z) compared to HT2 (austenizing at 870°C for 10 min., fast cooling in N2 and tempering at 475°C for 1 hour). As can be seen, with two different tempering conditions, two different strength levels (1450 and 1600 MPa) of spring steel are obtained. However, segregation orientation does not influence significantly the static mechanical properties of the investigated steel.

Figures 2 and 3 show S-N curves obtained in T/C fatigue regime on notched cylindrical samples for two different heat treatment conditions and segregation orientation. It can be seen that the fatigue strength of longitudinally oriented material is higher. HT1 also gives a little higher fatigue limit compared to HT2. Interestingly, in both cases the slopes of S-N curves are almost the same for the same heat treatment, independently of the segregation orientation.

Figure 4 shows the S-N curve obtained in the R/B regime on smooth cylindrical samples for two different heat treatment conditions and longitudinal segregation orientation. As one can see, the fatigue strength of the HT1 material is significantly higher. Again, the slopes for both heat treatment conditions are similar to the slopes obtained in the T/C fatigue mode.

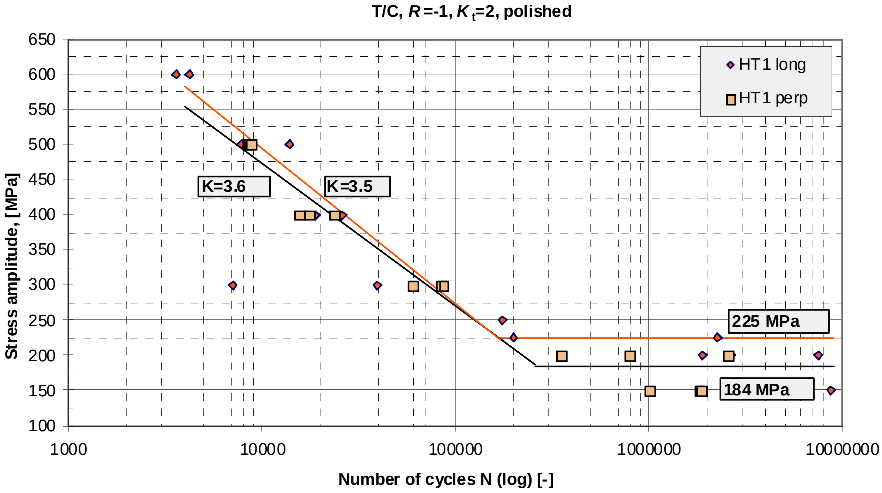


Figure 2. S-N curves of HT1 material for T/C fatigue mode ($R = -1$) obtained on notched samples with 2 different orientations of segregations.
Slika 2. S-N krive za HT1 materijal za T/C režim zamora ($R = -1$), dobijene sa uzoraka sa zarezom, uzetim u 2 segregacijska pravca.

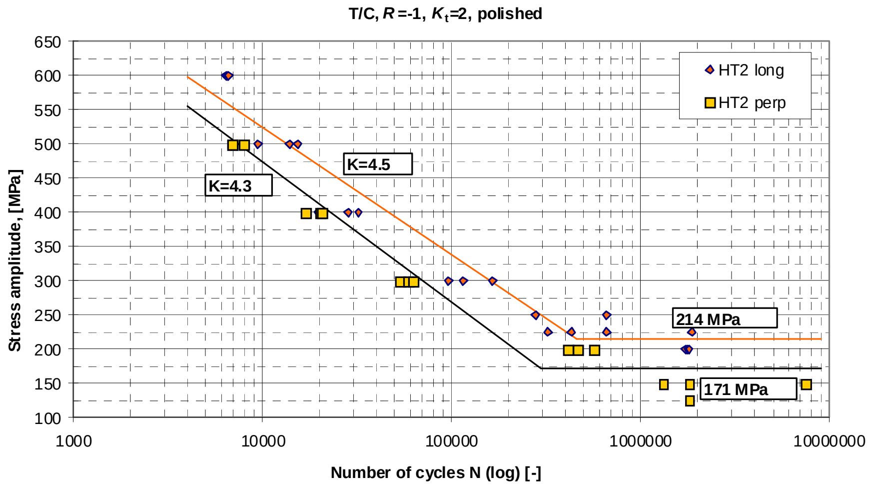


Figure 3. S-N curves of HT2 material for T/C fatigue mode ($R = -1$), obtained on notched samples with 2 different orientations of segregations.
Slika 3. S-N krive za HT2 materijal za T/C režim zamora ($R = -1$), dobijene sa uzoraka sa zarezom, uzetim u 2 segregacijska pravca.

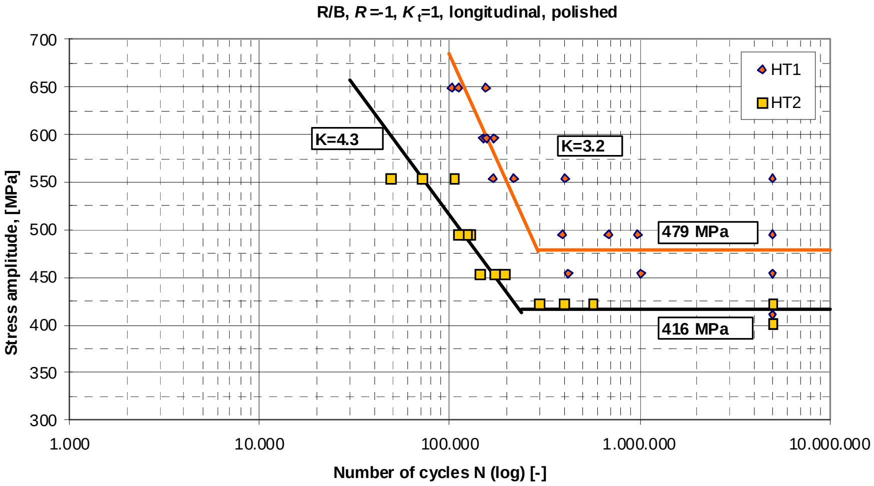


Figure 4. S-N curves of HT1 and HT2 materials for R/B fatigue mode ($R = -1$), obtained on smooth samples with longitudinal segregations.
Slika 4. S-N krive za HT1 i HT2 materijal za R/B režim zamora ($R = -1$), dobijene sa glatkih uzoraka, uzetim u uzdužnom pravcu segregacija.

Fatigue strength obtained on smooth samples in the R/B regime is approximately two times higher compared to the fatigue strength obtained in the T/C regime on notched samples. It is in good agreement with the theoretical notch sensitivity factor of used specimens ($K_t = 1$ and $K_t = 2$) neglecting the mode of fatigue.

Initial fatigue testing in the R/B mode is performed on smooth but only grinded (unpolished) samples. The results show a big influence of surface roughness. The influence of heat treatment is almost lost (Fig. 5) and the fatigue strength is almost 25% lower compared to the smooth polished longitudinal specimens.

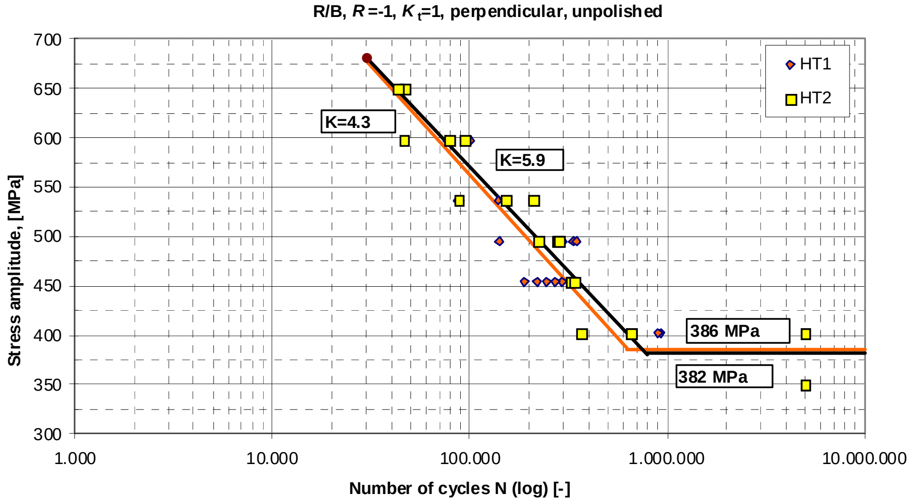


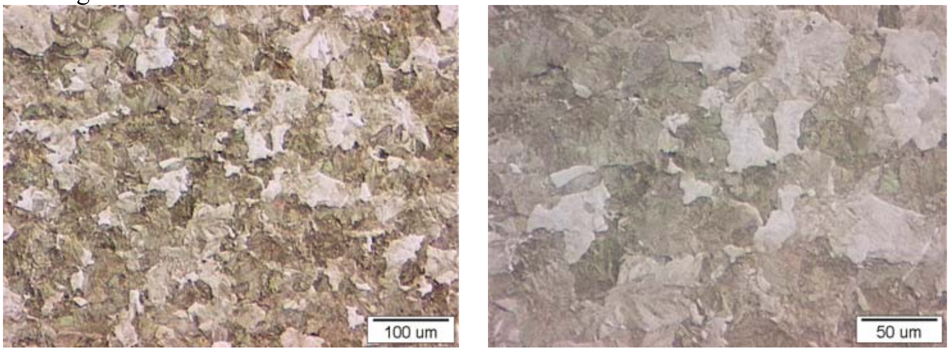
Figure 5. S-N curves of HT1 and HT2 material for R/B fatigue mode ($R = -1$), obtained on grinded (unpolished) samples with perpendicular orientation of segregations.

Slika 5. S-N krive za HT1 i HT2 materijal za R/B režim zamora ($R = -1$), dobijenih na brušenim uzorcima, uzetim poprečno u odnosu na pravac segregacija.

Fatigue testing has shown a relatively large scatter of results. In some cases fatigue failure occurred at an unexpectedly low number of cycles. Therefore, microstructural and micrographic analysis of characteristic samples is performed.

Figures 6a and 6b show a typical ferrite-pearlite microstructure of the investigated spring steel in the as-delivered (hot rolled) condition. The microstructure changes to a mainly fine tempered martensite structure after vacuum heat treatment (Figs. 7a and 7b). This gives the steel the required strength and toughness.

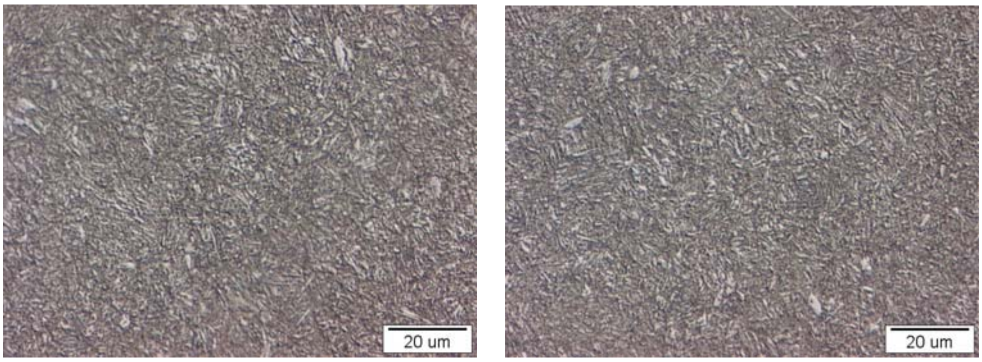
Differences between parallel and perpendicular rolling directions in microstructure are not visible at higher magnification. However, the segregation orientation can be clearly noticed only at lower magnifications under LM (Figs. 8). The differences in segregation morphology are also noticed. In some cases very thin and evenly distributed segregations (Fig. 8a) are noticed. On the other side, thicker and wider segregations (Fig. 8b) are visible. In Fig. 8b, also some smaller spherical inclusions in the steel matrix can be noticed.



(a) (b)

Figure 6. Typical microstructure of investigated spring steel, in hot-rolled condition: magnification 100× (a) and 200× (b); perpendicular to the rolling direction LM, etched in nital.

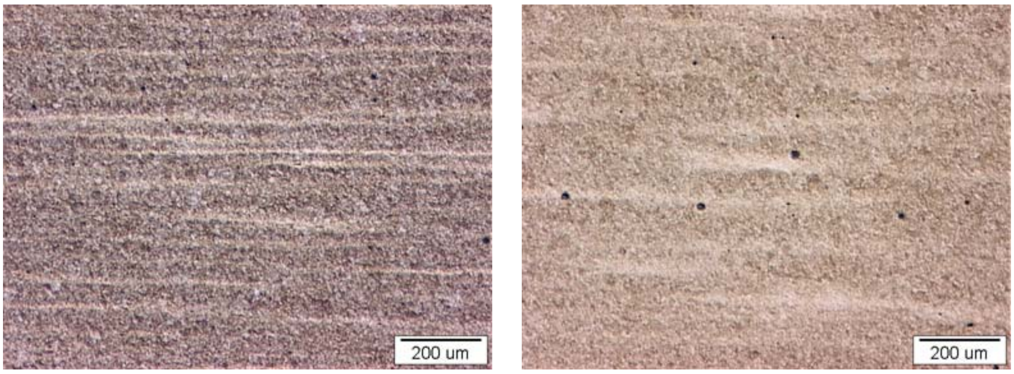
Slika 6. Karakteristična mikrostruktura ispitivanog čelika za opruge u toplo valjanom stanju: uvećanje 100× (a) i 200× (b); poprečno u odnosu na pravac valjanja (segregacija), optički mikroskop, nagriženo u nitalu.



(a) (b)

Figure 7. Typical fine martensitic microstructure of investigated spring steel in heat treated condition; magnification 500×; perpendicular (a) and longitudinal to the rolling direction (b); LM, etched in nital.

Slika 7. Klasična mikrostruktura finog martenzita ispitivanog termički obrađenog čelika za opruge, uvećanje 500×; poprečno (a) i uzdužno (b) u odnosu na pravac valjanja (segregacija), optički mikroskop, nagriženo u nitalu.



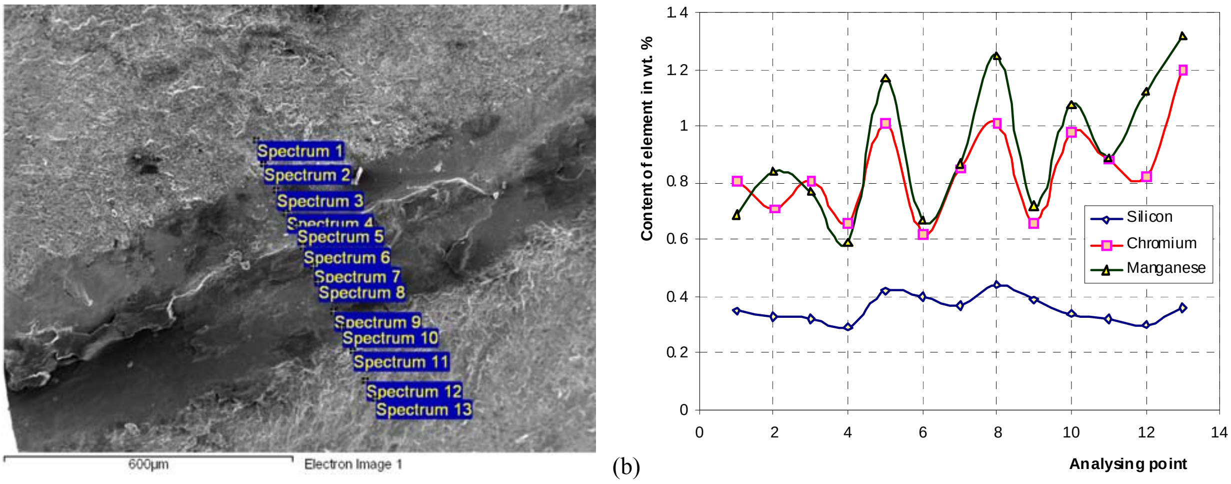
(a) (b)

Figure 8. Microstructure of investigated spring steel in heat treated condition with well visible morphology of segregations; magnification 50×; parallel to rolling direction: fine (a) and thicker (b) strings of positive and negative segregations; LM, etched in nital.

Slika 8. Mikrostruktura ispitivanog termički obrađenog čelika za opruge sa karakterističnom morfologijom segregacija; uvećanje 50×; uzdužno sa pravcem valjanja: sa užim (a) i debljim (b) trakama pozitivnih i negativnih segregacija; optički mikroskop, nagriženo u nitalu.

This inhomogeneous microstructure contributes to the larger scatter of mechanical properties of the steel. The significant influence of segregation on fatigue strength is proved by SEM/EDS microanalyses. The fracture surface of sample after the T/C fatigue experiment with unexpectedly low cycles to failure is investigated. The fractography and analysis show that fracture initiation starts and proceeds in the region of large segregation (Fig. 9). The analysed points with higher concentration of alloying elements have also higher oxygen content. This is natural because of high affinity of Si, Mn and Cr to oxygen.

Detailed microstructural and microchemical investigations show that different types of, mainly oxide based inclusions are present in the steel. Figures 10 to 12 show the typical size and shape of the inclusions.



(a) (b)

Figure 9. (a) SEM/EDS linear point analysis across the fracture initiation site (segregation), and (b) change of main alloying elements concentration.

Slika 9. (a) SEM/EDS linearna tačkasta analiza preko mesta inicijacije prsline (segregacije) i (b) promena koncentracije glavnih legirajućih elemenata.

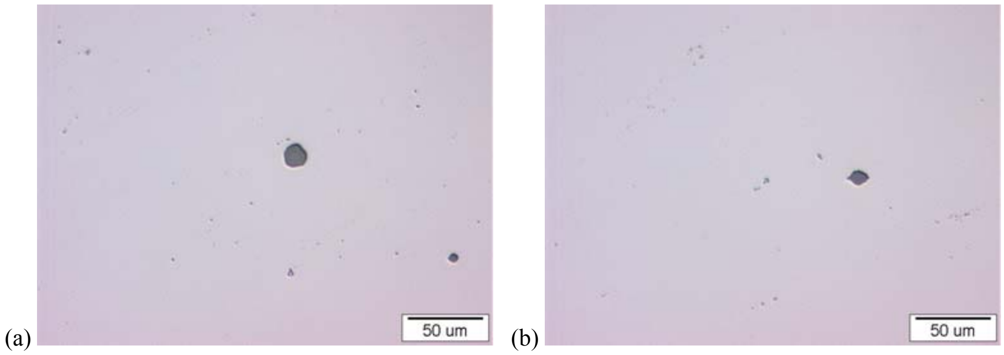


Figure 10. Typical morphology of inclusions in the tested spring steel; 200×; spherical (a) and spherical with typical tails (b); LM, polished only.
Slika 10. Karakteristična morfologija uključaka u ispitivanom čeliku za opruge; 200× (a) i okrugli uključak sa karakterističnim repovima (b); OM, samo polirano.

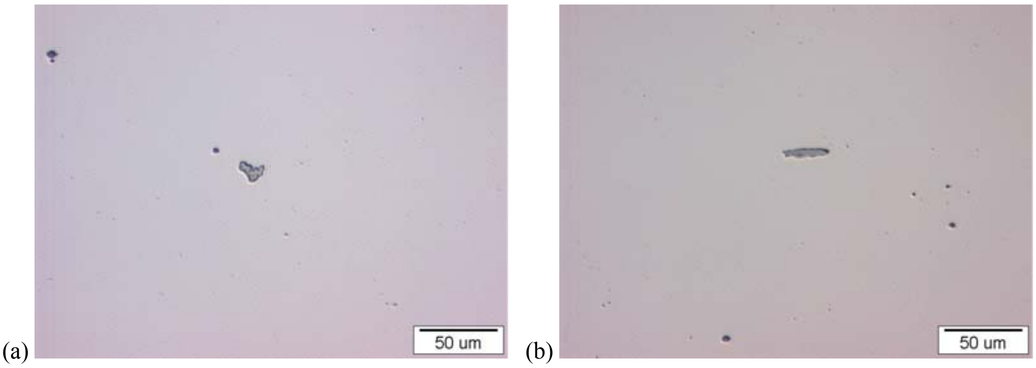


Figure 11. Typical morphology of inclusions in the tested spring steel; 200×; irregular (a) and elongated (b); LM, polished only.
Slika 11. Karakteristična morfologija uključaka u ispitivanom čeliku za opruge; 200×; neregularan (a) i izdužen oblik (b); OM, samo polirano.

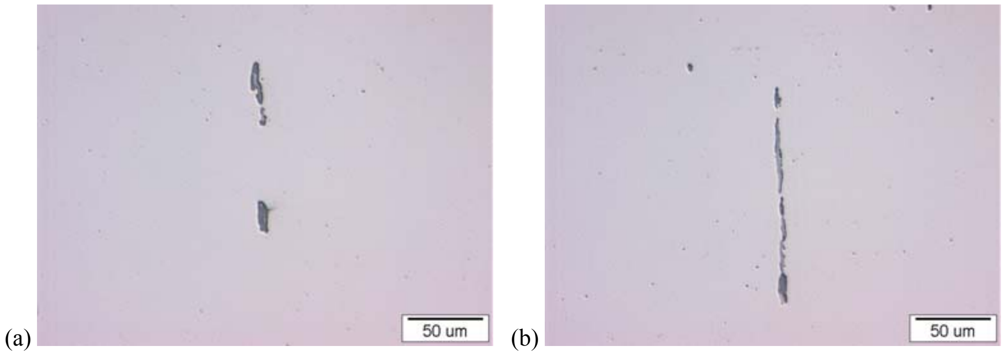


Figure 12. Typical morphology of inclusions in the tested spring steel; 200×; individual elongated complex (a) and stringers (b) parallel to rolling (segregation) direction; LM, polished only.
Slika 12. Karakteristična morfologija uključaka u ispitivanom čeliku za opruge; 200×: pojedinačni izduženi kompleksni (a) i trakasti (b) uzdužno u odnosu na pravac valjanja (segregacije); OM, samo polirano.

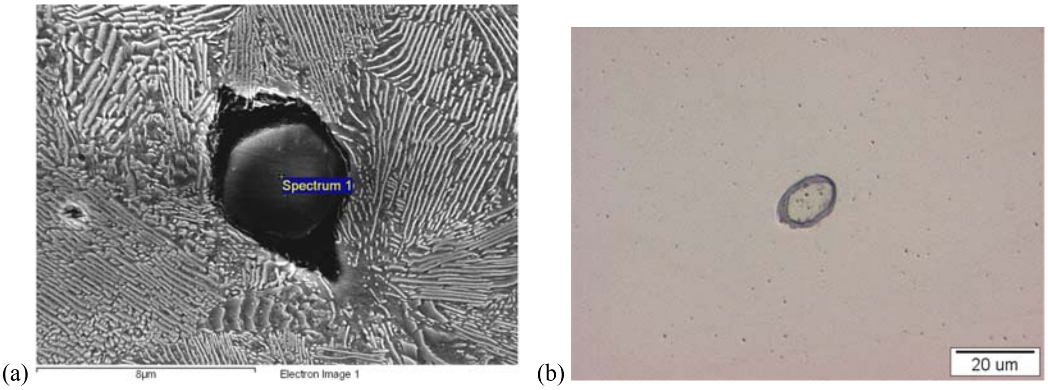


Figure 13. Complex inclusions in steel matrix: fine (Al, Mg, Mn)$_x$O$_y$ based inclusion in a pearlite structure, SEM/EDS-BS (a) and two-component inclusion; MnS outer and Ca-Al based oxide inner (b), LM, polished only.
Slika 13. Kompleksni uključci u čeličnoj osnovi: sitni uključci na osnovu (Al, Mg, Mn)$_x$O$_y$ u perlitnoj strukturi, SEM/EDS-BS (a) i dvokomponentni uključci; MnS je spoljašnji, i oksid na bazi Ca-Al u sredini uključka (b), OM, samo polirano.

Image analyses show that the largest spherical inclusions have a diameter below 50 μm, but elongated thinner stringers have length even up to 400 μm. SEM/EDS microanalyses show that sulphide (MnS), calcium-alumo-silicate and other complex, mainly oxide inclusions, are present. Some of them are chemically inhomogeneous (Figs. 13). These defects can also significantly contribute to a larger scatter and lower fatigue strength of the investigated steel.

CONCLUSIONS

Our investigations have shown that the modified steel technology still does not give super clean steel. The investigated steel seems metallographically sound, without larger inclusions. The largest globular inclusions are the order of 50 μm. This could be already above critical size for crack initiation. In our case, the highest influence on dynamic properties of the investigated steel have the segregations of alloying elements. The fatigue strength is almost 25% higher in the longitudinal, compared to the perpendicular orientation of segregation.

Appropriate heat treatment can also contribute to the increase of the steel's fatigue strength. In our case, lower tempering temperature results in higher hardness, static tensile, as well as dynamic properties. But ductility is slightly decreased. As expected, steel with higher hardness, higher tensile strength and yield point has higher (by approx. 8%) fatigue strength. The notched cylindrical specimens ($K_t = 2$) have an adequately lower fatigue limit compared to the smooth cylindrical samples ($K_t = 1$) considering the selected fatigue testing mode and the type of specimens. The T/C mode fatigue testing on smooth specimens still has to be performed in order to obtain a more complete figure of the dynamic properties of the investigated steel. The investigations have shown that inappropriate preparation of surface (grinded only - unpolished) can completely hide the influence of heat treatment conditions and decrease fatigue strength of investigated material. The obtained experimental results will enable a better FEM-based fatigue life prediction of leaf springs of the selected geometry using the local stress gradient concept and taking into account loading conditions and experimentally determined dynamic properties of spring steel.

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