Effect of Residual Stresses and Inclusion Size on Fatigue Resistance of Parabolic Steel Springs

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Article Information

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The effect of inclusion size and residual stresses of spring steel grade 51CrV4 on fatigue lifetime in high cycle was investigated by experimental results obtained by fatigue testing. Since spring with obvious surface defects or inclusions at the surface are failed during pre-stress, the residual stress profile under surface becomes relevant for fatigue crack initiation and failure. Investigation shows that fatigue threshold for high cycle fatigue depends, besides residual stresses, on inclusion size and material hardness. In order to determine allowed size of inclusions in spring steel and the influence of residual stresses, the Murakami's and Chapetti's models and concepts have been used. The stress loading limit regarding inclusion size and applied stress has been determined for loading ratio R = -1 and 0.1 on specimens with and without residual stresses.

High strength steel grade 51CrV4 in thermomechanical treated condition is commonly used for parabolic springs of heavy vehicles. Compress residual stresses are produced by cold reverse bending. These compress residual stresses protect the spring against its tensile service loads. Besides, high surface compressive residual stress amplitude is commonly introduced by shot-peening, which improves even more to protect the spring against service loading.

Spring leaves usually fail by surface or subsurface induced fatigue failure due to an inclusion, which size is relatively large in leaf spring. The initiation location depends on different parameters associated with the fatigue mechanism initiation of crack, and then it is related with the weakest configuration of material resistance, inclusion size (the inclusion acts as a concentrator), residual stresses and loading. Properly done shot-peening generates high compress residual stresses but only to a given depth from the surface. As a result, the weakest configuration associated with the fatigue crack initiation depends on the residual stress distribution, the inclusion size, and the loading configuration.

Recently, Shiozawa and co-workers [1-3] have performed some investigations on the influence of residual stress and inclusion size on fatigue failure in very high cycle fatigue. They have shown that in case of rotating bending load fatigue cracks are usually associated with surface inclusion induced failure mode, where compressive stress relaxed and decreased at an early stage of fatigue cycling. Experience of testing carried out by spring producer shows that critical depth for inclusion initiation is more than 0.2 mm [4]. It shows that residual stress under surface is relevant for fatigue crack initiation and failure of surface which is protected by high compressive residual stress thin layer produced by shot-peening. However, how each parameter controls the fatigue process has not been quantified yet. Besides, producers of spring steels are faced with improving the quality of springs and the production of spring steel has led to a reduction of the inclusion size.

The aim of this study was to improve the knowledge about the influence of the residual stresses and the inclusion size on fatigue resistance of steel springs. The analysis is carried out by using a fracture mechanic approach and dealing with the resistance curve concept [5, 6], quantifying the applied driving force and the resistance for different configurations of residual stresses and inclusion sizes. The Murakami [7-9] and the Chapetti [10-13] models and concepts are used in order to estimate the intrinsic threshold for fatigue crack propagation in the hold crack regime (short and long cracks). The fatigue threshold of several configurations including different residual stress levels and inclusion sizes are estimated by comparing the applied driving force with the intrinsic fatigue threshold for crack propagation.

Experimental

Material. Spring steel is delivered to spring producer in hot rolled condition with bainite-perlite microstructure, which have an average grain size d = 10 μm and an average hardness of 430 HV (42 HRc ± 2 HRc). Tensile mechanical property of steel as delivered is $R_{p0.2}$ = 1050 MPa ± 36 MPa and ulitmate tensile strength is σ_u = 1270 MPa ± 21 MPa. Spring producers perform hot rolling, hot bending, eye making, and heat treatment. The goal of heat treatment is to achieving fine microstructure of tempered martensite with an average microstructure grain size of d = 5 μm and an average hardness of 590 HV (52 HRc ± 2 HRc). Tensile mechanical property of steel as delivered is $R_{p0.2}$ = 1580 MPa ± 32 MPa and ultimate tensile strength is σ_u = 1670 MPa ± 25 MPa.

Inclusions are usually sulphides (MnS), alumo-silicates and TiN. The size of inclusions varies between 35 μm to 450 μm [4].

Residual stresses. Springs after heat treatment are subjected to pre-stressing by cold reverse bending. Figure 1 shows schematically a usual pre-stressing applied to a truck spring. It is then placed in a fixture that loads it exactly as it will be loaded in service but at a level above tensile yield strength. When the load is released, it springs back to a new shape, which is that desired for assembly. However, the elastic recovery has now placed the material that yielded into a residual stress state, which will be in the opposite (compressive) direction from that of the applied load. Therefore these compressive residual stresses will act as protection of the spring against its tensile service loads. Figure 1 also indicates schematically the result of shot-peening on upper surface after pre-setting. Properly shot-peening springs can have increased fatigue strengths to the point that they will fail by yielding instead of failing by fatigue [11]. The two treatments are additive on the upper surface, affording greater protection against tensile stresses in fatigue. It should be noted that if the springs were reversely loaded in service up to yielding, the beneficial compressive stress could be relieved compromising the fatigue life of the spring. Therefore, superposition of comressive residual stress and computed (applied bending) stress determine a profile od actual stress through thickness of spring.

In order to quantify the influence of the residual stresses on fatigue strength it is necessary to know their distribution, at least along the first 0.5 mm from the surface. X-ray diffraction method was used to measure the residual stresses near the surface, at a depth of about 0.05 mm. The measured compressive residual stress on the surface was -495 MPa ±20 MPa.

In order to analyze the influence of residual stresses distribution, data from reference [14] was used, where the results of the residual stress distribution along 0.4 mm in depth is reported for four different shot-peening processes carried out on similar spring steels. Those results showed that quite similar residual stress distributions are obtained with different shot-peening procedures made with cast shot sizes between 0.3 mm and 0.8 mm, and their combination to apply double shot-peening procedures. Results showed that near the surface, at a depth of about 0.04 mm, most of the procedures give a rise of residual stresses of about 500 MPa-600 MPa (in compression), so that a value of 500 MPa, in accordance to the measured residual stress in our spring steel, can be used for estimations.

Besides, results also showed that the maximum residual stress is obtained at a depth of about 0.25 mm and is about 1100 MPa to 1200 MPa (in compression), significantly higher than the one near the surface. For higher depths the residual stress decreases and is in the range of 500 MPa-800 MPa at a depth of 0.35 mm (still in compression). For a conservatively analysis, a residual stress equal to -1100 MPa will be considered for a depth equal to 0.25 mm and -500 MPa for 0.35 mm.

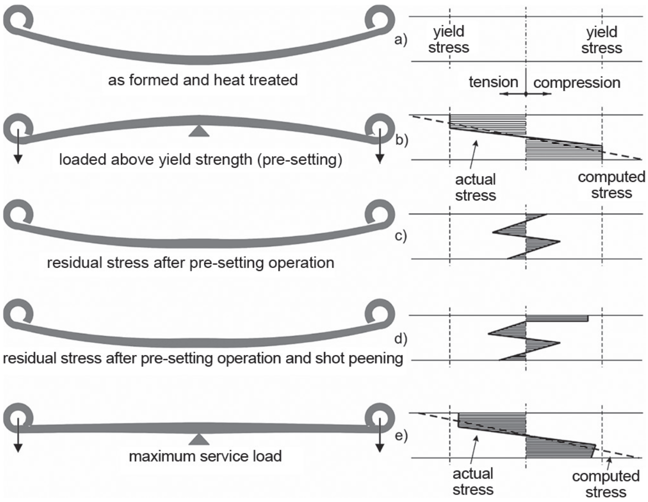

Figure 1. Residual stress profile from pre-stressing and shot-peening a leaf spring [11]

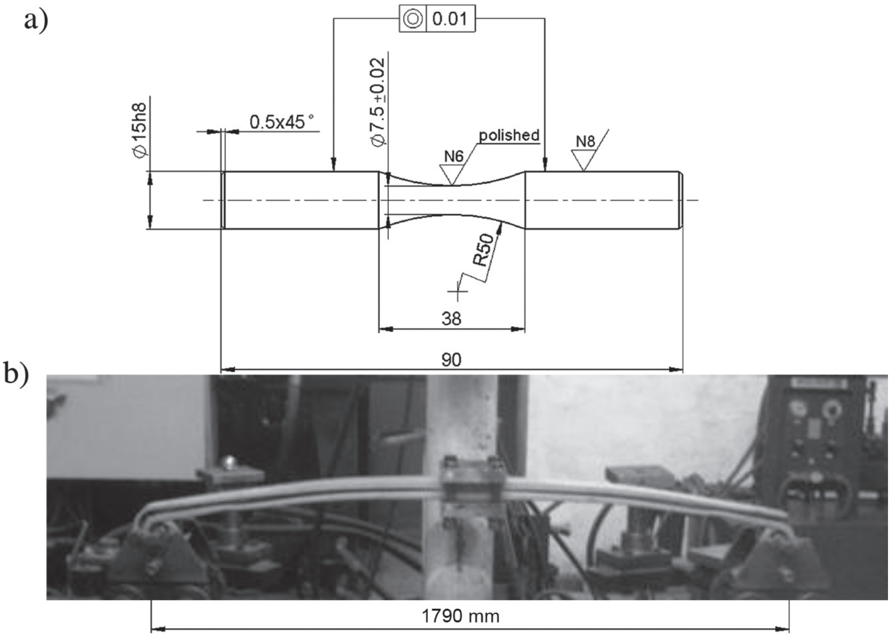

Figure 2. a) Rotating bending test specimen, b) example of spring test setting

In reference [14] it is stated that for a given shot-peening procedure the fatigue properties was improved due to some different observed residual stresses near the surface (-500 MPa to -600 MPa) which directly influences the fatigue crack nucleation. The residual stresses induced by shot-peening in larger depths have no influence on fatigue life and on crack propagation is not affected by the induced residual stresses. However, these conclusions were not demonstrated and, even more important, could be in contradiction with the mechanism that define the fatigue resistance.

Fatigue testing. Two groups of experimental results were obtained from representative specimens made from steel with hardness of 590 HV under quenched and tempered condition. First group of tests is performed on hourglass specimens at room temperature using a four-axis cantilever type rotary bending fatigue machine. Twelve hourglass shaped specimens with a grip diameter of 20 mm and a minimum diameter of 6 mm were used (see Figure 2a). In order to induce minimum compress residual stress, the specimens were grinded and electro-polished in order to remove a layer of the surface of about 10 µm thickness. This specimens have no residual stresses and are tested at a stress ratio of R = -1.

Second group of specimens includes the single leaf of original spring for heavy tracks. Six tests were performed by spring producer as part of regular quality insurance of products. The springs were tested by bending with applied stress amplitude of 1250 MPa (see Figure 2b). Testing was performed in factory by frequency of 1 Hz. These springs had residual stresses and were tested at stress ratio of R = 0.1.

Estimation of fatigue resistance. Even though there are several models and approaches proposed to analyze the fatigue resistance when dealing with materials with defects or inclusions, in the last two decades Murakami's model has been usually used due to its simplicity for the estimation of the threshold ΔK_{th} as function of area$^{1/2}$, when the effect of inclusion is studied [7-9]:

$$\Delta K_{th} = 3.3 \cdot 10^{-3} \cdot (HV + 120) \cdot (\sqrt{area})^{1/3} \qquad (1)$$

where HV is the Vickers hardness, in kgf/mm^2, and area$^{1/2}$ is in µm, giving ΔK_{th} in MPa × m$^{1/2}$.

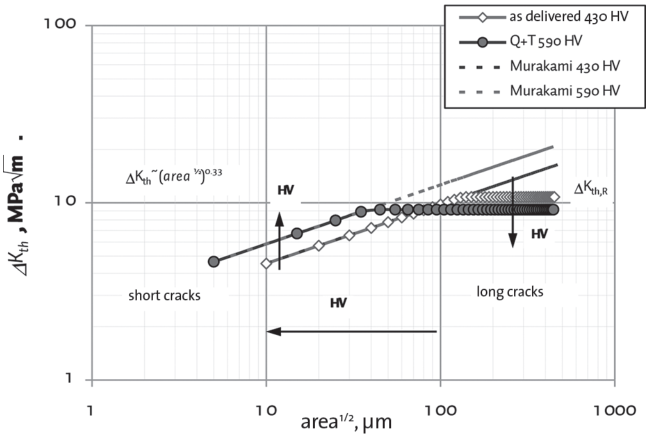

Figure 3. Fatigue threshold as a function of area1/2 parameter for 51CrV4 steels: with hardness 430 HV as delivered and with hardness 590 HV under quenched and tempered condition

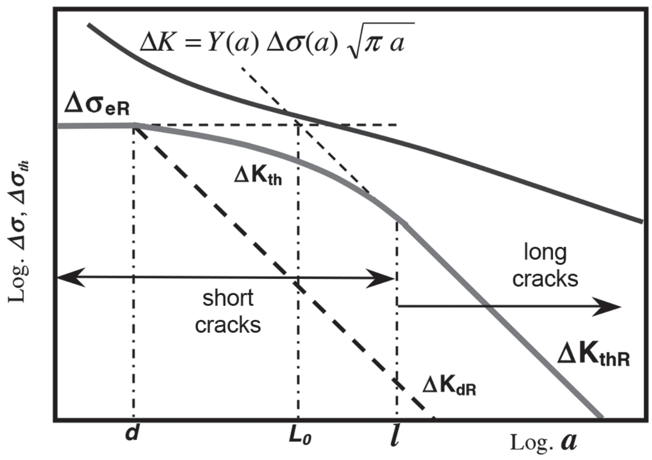

Figure 4. Threshold curve concept in terms of stress intensity factor range

The Murakami model needs only the hardness and the inclusion or defect size to estimate the fatigue resistance of a given configuration, so that it becomes a simple method for engineering applications to estimate fatigue endurance of steels with small defects or inclusions. Stress ratio can also be considered by modifying expression (1) [8, 9].

However, Murakami's model works well only until ΔK_{th} equals the threshold for long cracks, ΔK_{thR}, which depends on the microstructure properties of material. It seems that the Murakami expression (1) works well till a value of area$^{1/2}$ of 1 mm for low strength steel is reached, where fatigue threshold equals the one for long crack. The value of area$^{1/2}$ can be related to inclusion size, as first iteration for initial fatigue crack length. Equation (1) shows also that the threshold for crack propagation increases with hardness. Therefore, it seems that with increasing inclusion size and hardness of high strength material a higher fatigue threshold ΔK_{th} value can be obtained. Unfortunately, nocent of failures of springs steel are caused by inclusions of different sizes, diameters from 0.1 mm until 1.5 mm, where spring last for only a few or couple of thousand cycles [15], so that model could not be used for all those cases.

Chapetti showed that the opposite trend for fatigue threshold for long crack appears, as it is shown in Figure 3 [12]. For long cracks the threshold decreases with hardness, and is independent of crack length for a given R ratio. Besides, it is easy to realize that with the Murakami model it is not possible to estimate fatigue life to failure for a given applied nominal stress (fatigue resistance).

For the estimation of the fatigue resistance an integrated fracture mechanics approach is applied by using the resistance curve concept [10-13]. This approach is not so easy to apply like Murakami's model but allow us to deal with most of the parameters that influence the fatigue mechanisms. Then, it allows us to quantify the influence of many geometrical, material and loading parameters on the definition of the fatigue behaviour of the analyzed component.

In this approach the difference between the total applied driving force and the material threshold for crack propagation defines the effective driving force applied to the crack, as schematically shown in Figure 4 [10-13]. The initial crack length is given by the position of the brittle microstructural barrier if the material was free of cracks or crack like flaws, or by the greatest defects that act as a fatigue initiator. The short crack is size of few grains (2-20 μm) while a long crack is usually more than 100 μm. The minimum threshold for fatigue crack propagation is associated with the microstructural barrier that defines the plain fatigue limit and represents the microstructural threshold for crack propagation, as [10]:

$$\Delta K_{dR} = Y \cdot \Delta\sigma_{eR} \sqrt{\pi \cdot d} \qquad (2)$$

where Y is the geometrical correction factor. In most cases the nucleated microstructurally short surface cracks are considered semicircular, and the value of Y then would be 0.65. Because the plain fatigue limit depends on the stress ratio R, the microstructural threshold also does. The value of d is usually given by the microstructural characteristic dimension, as grain size, e. g., for the steel in as-delivered condition d = 10 μm, and Q+T conditions d = 5 μm.

A total extrinsic threshold to crack propagation, ΔK_{CR}, is then defined by the difference between the crack propagation threshold for long cracks, ΔK_{thR}, and the microstructural threshold, ΔK_{dR} [10]. The development of the extrinsic component is considered to be exponential and a development parameter k is estimated as a function of the same microstructural and mechanical parameter used to define the material threshold for crack propagation. The material threshold for crack propagation as a function of the crack length, ΔK_{th}, is then defined as [10]:

$$\Delta K_{th} = \Delta K_{dR} + \left(\Delta K_{thR} - \Delta K_{dR}\right)\left[1 - e^{-k(a-d)}\right]$$

$$= Y\,\Delta\sigma_{th}\sqrt{\pi\,a} \quad a \ge d \qquad (3)$$

where the parameter k is given by:

$$k = \frac{1}{4d}\frac{\Delta K_{dr}}{\left(\Delta K_{thR} - \Delta K_{dr}\right)} \qquad (4)$$

The pure fatigue crack propagation threshold for long cracks $\Delta K_{th,R=-1}$ can be estimated by using the following expression [12]:

$$\Delta K_{th,R=-1} = -0.0038 \cdot \sigma_u + 15.5 \qquad (5)$$

As a simplification, the Murakami model can be used as a very helpful tool to estimate the first part of the resistance curve (ΔK_{th}) when the material parameters are not available, as it is the usual case for high strength steels for which the material characterization is quite difficult due to its hardness or there exists other limitations like the lack of volume to get the necessary specimens.

Finally, we know that quantitative analysis of fatigue crack growth requires a constitutive relationship of general validity be established between the rate of fatigue crack growth, da/dN, and some function of the range of the applied stress intensity factor, ΔK (crack driving force). Besides, it has to be taken into account threshold for the whole crack length range, including the short crack regime where the fatigue crack propagation threshold is a function of crack length. Among others, the following relationship meets these requirements [16]

$$\frac{da}{dN} = C \cdot (\Delta K - \Delta K_{th})^m \qquad (6)$$

where C and m are Paris range constants obtained from long crack fatigue behaviour and ΔK_{th} is the fatigue crack growth threshold as a function of crack length given by Equation (3). The fatigue crack propagation life from crack initiation up to critical crack length a_c can be then obtained by integrating expression (6). In the case of smooth specimens or spring after shot-peening, the following general expression can be used to estimate the applied driving force as a function of crack length [16]:

$$\Delta K = Y \cdot \Delta\sigma \sqrt{\pi \cdot a} \qquad (7)$$

where Δσ is the stress range nominally applied at the initiation positions. The crack aspect ratio as a function of crack length has to be defined for the combination of component geometry and loading conditions, which allows definition of the value of the parameter Y as a function of crack length.

Results and Discussions

Figure 5 shows schematically the effective fatigue crack driving force as the difference between applied ΔK and the threshold ΔK_{th} obtained by Chapetti's model by applying Equation (3). It is possible to determine the number of cycles to failure regarding different inclusion sizes and different applied fatigue stress magnitudes Δσ, by using simple integration of Eq. (6) with experimentally obtained parameters of Paris fatigue crack propagation range [17]. The following parameters were used: $C = 8 \times 10^{-8}$ and m = 3.25 [17]. It is necessary to mention here that these parameters are not needed to estimate the threshold conditions associated with the fatigue limit of the analyzed configurations, so that the accuracy of the estimation of these parameters are not so important when dealing with threshold configurations. Instead, they become important as the applied stress increases in comparison with the fatigue limit.

Fatigue crack propagation occurs only if applied crack driving force ΔK is higher than threshold ΔK_{th} and if the inclusion size a is higher than the value given by the intersection between the threshold curve ΔK_{th} and the applied crack driving force ΔK. Fatigue crack could then propagate until critical crack length a_c is reached, for which fracture is expected. The value of the critical crack length is determined by fracture toughness of material, $K_{IC} \approx 33$ MPa $m^{1/2}$.

According to expression (5) the threshold for fatigue crack propagation for long cracks for R = -1 is $\Delta K_{thR=-1} = 9.1$ MPa $m^{1/2}$. For smaller stress ratios, only the positive part of the applied component was compared with $\Delta K_{thR=-1}/2$, as it is usually suposed, considering that the compression part of the total applied ΔK does not account for the effective driving force applied to the crack tip [16].

Figure 6 shows the experimental results for both sets of fatigue tests and the estimated fatigue resistance obtained by apply-

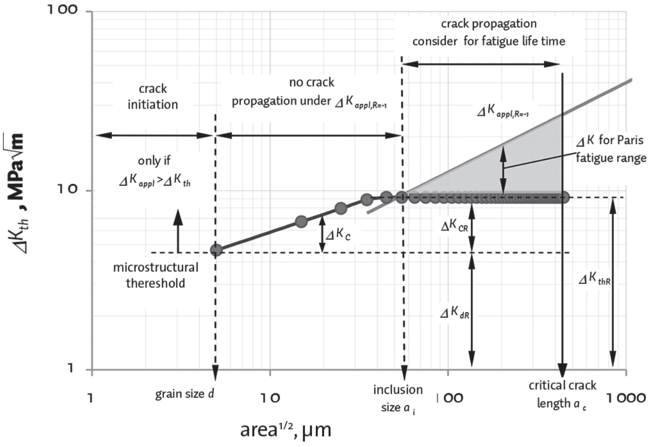

Figure 5. Fatigue threshold as a function of crack length for 51CrV4 and fatigue crack driving force in terms of stress intensity factor range

ing the approach described in the previous section. It should be noted that for each inclusion size a different residual stress value was assumed, according to the residual stress distribution. Bending tests are performed as is shown in Figure 2b by applied stress amplitude 1250 MPa (R = 0.1) at room temperature and frequency 0.5 Hz. Test is stopped when spring failed.

In the case of the set of fatigue test carried out by rotating bending of specimens without residual stresses, the estimated results show a great agreement and show that an initial crack length of 0.35 mm can explain conservatively all results.

On the other hand, in the case of the set of fatigue tests carried out by bending at R = 0.1 on the springs at their final conditions, the estimated results show clearly how important the compressive residual stresses on the definition of the fatigue strength of these springs are. Besides, the procedure allow to analyze the different combinations of initial crack lengths and residual stress levels, the results show how much the fatigue resistance can be changed by varying that configuration. The fatigue resistance estimated for an initial crack length equal to 0.35 mm, also explains conservatively all results observed for the springs.

Estimated results in Figure 6 also show that the improvement of the steel quality, decreasing the inclusion size from 0.25 mm to 0.15 mm, could improve the fatigue resistance in only 4 %. This is due to the nature of the residual stresses induced by shot-peening. The maximum residual stresses of about -1100 MPa or even more is observed for all procedures used in reference [14], but for a given shot-peening procedure the residual stress can be of the same level for a depth of about 0.15 mm.

Results show clearly that the approach allows ways to analyze the different improvements that can improve the fatigue resistance of the springs. The analysis and the conclusions documented in reference [14], mentioned in section 2.2., lose sustenance when trying to apply those conclusions to the results of Figure 6. Residual stresses and inclusion size should be considered in an integrated way taking into consideration that the fatigue resistance is a result of the combination of the applied driving force and the resistance for fatigue crack propagation, both as a function of crack length, mainly when the fatigue initiation process is almost eliminated for the existence of the inclusions that act as initiators.

Finally, it is necessary to mention that the approach used for the analysis can be applied only for high cycle fatigue and short crack propagation, for which linear elastic fracture mechanics can be used. Results for springs are clearly near the low cycle fatigue regime, so that results cannot be related directly. However, due to the high strength of the analyzed steels, the fatigue resistance curve (S-N) has very small slope and so no great difference can be observed in fatigue strength as a function of fatigue life. This is mainly a result of the nature of the configuration that defines the fatigue process. Fatigue crack initiation process is almost eliminated by the relatively great inclusions that act as initiators so that the fatigue resistance is mainly associated with a threshold configuration for fatigue crack propagation.

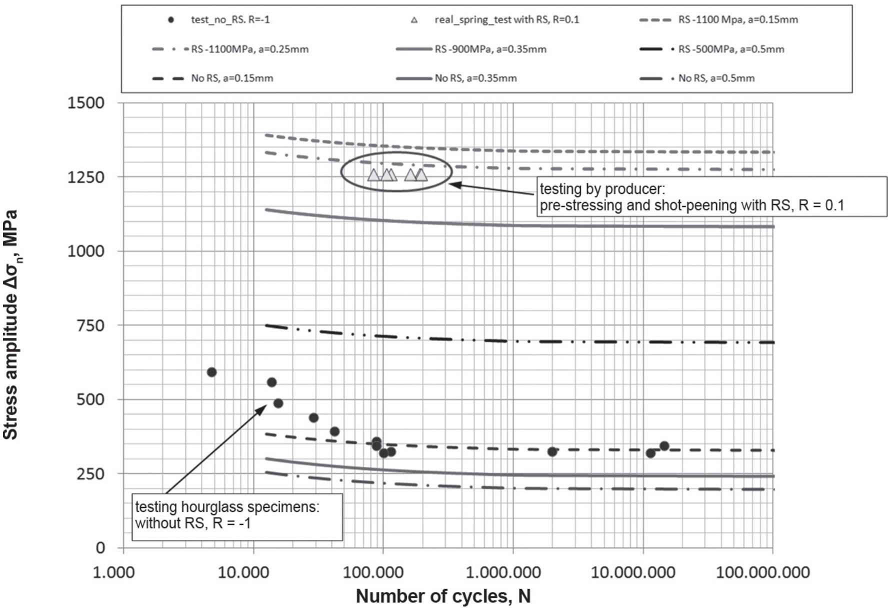

Figure 6. Prediction of fatigue failure in form of S-N curve by using fracture mechanical approach and considering different sizes of inclusions at residual stress levels, experimental results are also shown

Conclusions

The aim of this work was to improve the knowledge about the influence of the residual stresses and the inclusion size on fatigue resistance of parabolic steel springs. The analysis was carried out by using a fracture mechanic approach and dealing with the resistance curve concept, quantifying the applied driving force and the resistance for different configurations of residual stresses and inclusion sizes. Murakami's and Chapetti's models and concepts were used to estimate the fatigue threshold of several configurations including different residual stress levels and inclusion sizes.

Two groups of experimental results were obtained from representative specimens made from steel with hardness of 590 HV under quenched and tempered condition without residual stresses. First group of tests are performed on hourglass specimens at room temperature using a four-axis cantilever type rotary bending fatigue machine (R = -1). The second group of specimens was a set of six single leaves of springs for tracks, tested by bending with applied stress amplitude of 1250 MPa (R = 0.1).

In case of the set of fatigue tests carried out by rotating bending of specimens without residual stresses, the estimated results showed a great agreement and an initial crack length of 0.5 mm can conservatively explain all results. On the other hand, in the case of the set of fatigue tests carried out by bending at R = 0.1 on the springs at their final conditions, the estimated results show clearly the influence of the compressive residual stresses on the definition of their fatigue strength. Results also showed that the procedure allow us to analyze the different combinations of initial crack length and residual stress levels, and how much the fatigue resistance can be changed by varying that configuration. For this set of tests, the fatigue resistance estimated for an initial crack length equal to 0.35 mm, explain conservatively all results observed for the springs.

The analysis and the results showed that the steel quality, decreasing the inclusion size to 0.15 mm, could improve the fatigue resistance about 20 % if the residual stress level could be kept at approx. -1100 MPa.

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Abstract

Effekt der Eigenspannungen und Einschlussgröße auf die Dauerschwingfestigkeit von parabolischen Stahlfedern. Der Effekt der Einschlussgröße und der Eigenspannungen auf die Ermüdungslebensdauer unter hohen Lastwechseln des Federstahls 51CrV4 wurde mittels Ermüdungsprüfung experimentell bestimmt. Da Federn mit deutlichen Oberflächendefekten oder Einschlüssen an der Oberfläche von der Montage ausgeschlossen sind, werden die Eigenspannungsprofile in Oberflächennähe für die Ermüdungsrissbildung und das Versagen relevant. Die Untersuchungen zeigen, dass der Schwellwert für die Ermüdung bei hoher Lastwechselzahl neben den Eigenspannungen von der Einschlussgröße und der Werkstoffhärte abhängt. Um die zulässige Größe von Einschlüssen im Federstahl und den Einfluss der Eigenspannungen zu bestimmen, wurden die Modelle und Konzepte von Murakami und Chapetti verwendet. Die Beanspruchungsgrenze bezüglich auf Einschlussgröße und der angelegten Spannung wurde für das Beanspruchungsverhältnis R = -1 und 0,1 an Proben mit und ohne Eigenspannungen bestimmt.

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