ICM11

Variation of Fatigue Threshold of Spring Steel with Pre-stressing

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Abstract

High strength steel grade 51CrV4 in thermo-mechanical treated condition is used as bending parabolic spring of heavy vehicles. Several investigations show that fatigue threshold for very high cycle fatigue depends on inclusion’s size and material hardness. In order to determine allowed size of inclusions in spring’s steel the Murakami’s and Chapetti’s model have been used. The stress loading limit regarding to inclusion size and applied stress has been determine for loading ratio $R=\text{-1}$ in form of $S$-$N$ curves. Experimental results and prediction of $S$-$N$ curve by model for given size of inclusion and $R$ ratio show very good agreement. Pre-stressing and shot-peening causes higher compress stress magnitude and consequently change of loading ratio to more negative value and additionally extended life time of spring.

Keywords: High strength steel, Fatigue threshold, Presetting, Internal cracks, Fatigue, Lifetime;

1. Introduction

High strength steel grade 51CrV4 in thermo-mechanical treated condition is used for parabolic spring of heavy vehicles. Producers of spring steel are faced with keeping constant quality of spring. Usually, production of steel has led to a reduction of the inclusion size in order to improve fatigue strength of steel. Murakami et al showed that the mechanism of fatigue failure starts around the inclusion as “Optical Dark Area” (ODA) as hydrogen embrittlement assisted by fatigue [1,2,3]. Murakami derived the model for the estimation of the threshold $\Delta K_{th}$ as function of $area^{1/2}$.

\begin{equation}
\Delta K_{th} = 3.3 \cdot 10^{-3} (HV + 120) \sqrt[3]{area}^{1/3}
\end{equation}

Where $HV$ is the Vickers hardness, in kgf/mm$^2$, and $area^{1/2}$ is in $\mu$m, giving $\Delta K_{th}$ in MPa$\cdot$m$^{1/2}$. The model works well till the $\Delta K_{th}$ equals the threshold for long cracks, $\Delta K_{thR}$, that depends on microstructure properties of material. It seems that Murakami expression Eq. (1) works well till a value of $area^{1/2}$ of 1 mm for low strength steel, where fatigue threshold equals the one for long crack. The value of $area^{1/2}$ can be connected with 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 of ODA and hardness of high strength material a higher fatigue threshold $\Delta K_{th}$ value can be obtained. Unfortunately, docent of failures of springs steel are caused by large size of inclusion different sizes, from 0.1 until 1.5 mm diameter, where spring survived only few or couple of thousand cycles [4].

However, Chapetti shows that opposite trend for fatigue threshold of long crack appear, as is shown in Fig. 1 [5]. For long cracks the threshold decreases with hardness [6], and becomes independent of crack length for a given $R$ ratio. Chapetti shows that fatigue threshold vs. crack length exhibits bimodal behavior, one for short cracks and one for long cracks. Both models provide fatigue limit $\Delta K_{th}$ as a function of crack length, but with Murakami’s model it is not possible to estimate fatigue life to failure. The aim of paper is estimate fatigue life time, stress loading limit regarding to inclusion size.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$a$</td>
<td>crack length</td>
</tr>
<tr>
<td>$a_i$</td>
<td>initial crack length as size of inclusion</td>
</tr>
<tr>
<td>$a_c$</td>
<td>critical crack length</td>
</tr>
<tr>
<td>$C$</td>
<td>fatigue material constants in Paris range</td>
</tr>
<tr>
<td>$m$</td>
<td>fatigue material constants in Paris range</td>
</tr>
<tr>
<td>$d$</td>
<td>position from the surface of the strongest microstructural barrier</td>
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<tr>
<td>$a_{fn}$</td>
<td>nominal applied stress range</td>
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<tr>
<td>$\Delta K$</td>
<td>applied stress intensity factor range</td>
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<tr>
<td>$\Delta K_C$</td>
<td>extrinsic component of $\Delta K_{th}$</td>
</tr>
<tr>
<td>$\Delta K_{CR}$</td>
<td>extrinsic component of $\Delta K_{thR}$</td>
</tr>
<tr>
<td>$\Delta K_d$</td>
<td>microstructural threshold</td>
</tr>
<tr>
<td>$K_{IC}$</td>
<td>fracture toughness in plane strain for mode I of loading</td>
</tr>
<tr>
<td>$\Delta K_{th}$</td>
<td>fatigue crack propagation threshold</td>
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<tr>
<td>$\Delta K_{th,R}$</td>
<td>fatigue crack propagation threshold for long cracks respect to loading ratio</td>
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<tr>
<td>$R$</td>
<td>stress ratio (minimum stress/maximum stress)</td>
</tr>
<tr>
<td>$R_{p0.2}$</td>
<td>Yield strength [MPa]</td>
</tr>
<tr>
<td>$\sigma_u$</td>
<td>Ultimate tensile strength [MPa]</td>
</tr>
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</table>

2. Material properties, pre-stressing and shot-peening of leaf spring

Spring steel is delivered to spring producer in hot rolled condition as ferrite-perlite microstructure, where average grain size $d=10 \mu m$ and average hardness 430 HV (42±2 HRc). Tensile mechanical properties of steel as delivered condition are $R_{p0.2}=1050$ MPa and ultimate tensile strength $\sigma_u=1270$ MPa. Spring producer perform hot rolling, hot bending, eye making and heat treatment. The goal of heat treatment is achieve fine microstructure of tempered martensite with average grain size $d=5 \mu m$ and average hardness 590 HV (52±2 HRc). Tensile mechanical properties of steel as delivered condition are $R_{p0.2}=1580$ MPa and ultimate tensile strength $\sigma_u=1670$ MPa. Inclusions are usually sulphides (MnS), alumino-silicates and TiN. The size of inclusions vary between 35 $\mu m$ to 500 $\mu m$. Springs after heat treatment are subjected to prestressing by cold reverse bending. Figure 2 shows an usual prestressing applied to a truck springs. 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 compress residual stresses will act to protect the spring against its tensile service loads. The residual stress patterns are shown in the figure 1 and also indicate the result of shot-peening the upper surface after presetting. Properly shot-peening springs can have their fatigue strengths increased to the point that they will fail by yielding instead of failing by fatigue [7]. The two treatments are additive on the upper surface in this case, affording greater protection against tensile stresses in fatigue. Note that if the spring were reversely loaded in service up to yielding, the beneficial compressive stress could be relieved compromising the fatigue life of the spring. The magnitude of residual stresses after pre-stressing and shot-peening could be close to $-0.9 \cdot R_{p0.2}$. Compress residual stresses have effect only on fatigue stress ratio $R$. If the spring is...
subjected to $\Delta \sigma_a = 1300$ MPa, the residual stress reduces loading ratio to more than $R = -5$. Since, the experiments show that results for $R = -1$ are more conservative than results for lower $R$ (negative) ratios, $R = -1$ can be considered in the proposed model.

Fig. 1. Fatigue threshold as a function of $area^{1/2}$ parameter for 51CrV4 steels: with hardness $430 \, HV$ as delivered and with hardness $590 \, HV$ in Quenched and Tempered condition

Fig. 2. Residual stresses profile from prestressing and shot-peening a leaf spring [8]
3. Estimation of fatigue crack propagation life

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 Fig. 3. The initial crack length is given by the position of the strongest microstructural barrier if the material were free of cracks or crack like flaws. This intrinsic resistance is considered to be microstructural threshold for crack propagation as [5]:

$$\Delta K_{dR} = Y \cdot \Delta \sigma_{eR} \sqrt{\pi \cdot d}$$  \hspace{1cm} (2)

where $Y$ is the geometrical correction factor. In most cases the nucleated microstructurally short surface cracks are considered semicircular, and the value of $Y$ would then 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 steel in as delivered condition $d=10 \mu m$, and Q+T conditions $d=5 \mu m$.

The pure fatigue crack propagation threshold $\Delta K_{th,R-1}$ is equal to the lower value of equations [6]:

$$\Delta K_{th,R-1} = 4 \cdot 10^{-3} (HV + 120) \cdot a^{1/3}$$ \hspace{1cm} (3)

$$\Delta K_{th,R-1} = -0.0038 \cdot \sigma_u + 15.5$$ \hspace{1cm} (4)

Where the pure fatigue crack propagation threshold $\Delta K_{th}$ as function of crack length, and $\Delta K_{th,R-1}$ (a constant value for given tensile strength or hardness) are in MPa·m$^{1/2}$, the crack length $a$ in mm, the Vicker’s hardness $HV$ in kgf/mm$^2$ and the ultimate tensile strength $\sigma_u$ in MPa. 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, $\Delta K$ (crack driving force). Besides, it has to take into account the 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 [9]

$$\frac{da}{dN} = C \cdot (\Delta K_{appl} - \Delta K_{th,R-1})^m$$ \hspace{1cm} (5)

where $C$ and $m$ are Paris range constants obtained from long crack fatigue behavior and $\Delta K_{th,R-1}$ is the crack growth threshold as lower value of Eq. (3) and (4). The fatigue crack propagation life from crack initiation up to critical crack length $a_c$ can be obtained by integrating expression (5) and using expression (4) for the threshold of the material ($\Delta K_{th,R-1}$). In the case of smooth specimens or spring after shot-peening, the stress can be considered constant for any crack length, equal to the nominal applied stress $\Delta \sigma_n$. The following general expression can be used to estimate the applied driving force as a function of crack length [5]:

$$\Delta K_{appl} = Y \cdot \Delta \sigma_n \sqrt{\pi \cdot a}$$ \hspace{1cm} (6)

where $\Delta \sigma_n$ is the nominal applied stress range. 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. In case of small embedment crack, where the crack is only few inclusion size, we are considering shape function by $Y = 0.65$. 
Figure 3 shows fatigue crack driving force as difference between applied force $\Delta K_{\text{appl}}$ and threshold $\Delta K_{\text{th,R}}$ obtained by Chapetti’s model by applying Eq.(4). It is possible to determine the number of cycles to failure regarding to different inclusion size and different applied fatigue stress magnitude $\Delta \sigma_n$, by using simple integration of Eq. (5) with experimentally obtained parameters of Paris fatigue crack propagation range ($C=8\times10^{-8}$ and $m=3.25$). Fatigue crack propagation occur only if applied crack driving force $\Delta K_{\text{appl}}$ is higher than threshold $\Delta K_{\text{th,R}}$ and if inclusion size (as $\text{area}^{1/2}$ in Fig. 3) is higher than value in intersection between threshold limit curve $\Delta K_{\text{th,R}}$ and applied crack driving force line. Fatigue crack is going to propagate until critical crack length $a_c$. The value of critical crack length is determined by fracture toughness of material $K_{\text{IC}}=33.19$ MPa·m$^{1/2}$. Figure 4 shows fatigue crack driving force curves vs. initial crack area for constant applied stress $\Delta \sigma_n$.

**Fig. 3.** Fatigue threshold as a function of $\text{area}^{1/2}$ parameter for 51CrV4 and fatigue crack driving force as difference between applied force and threshold

**Fig. 4.** Fatigue threshold as a function of $\text{area}^{1/2}$ parameter for both conditions of steel 51CrV4

**Fig. 5.** Prediction of fatigue failure in form of $S-N$ curve by using fracture mechanic approach and considering different size of inclusions in Q+T steel
Figure 4 shows that as delivered steel (softer) switch to constant threshold value $K_{th,R}=-1=10.769$ MPa·m$^{1/2}$ at larger size of inclusion $a_i=120$ μm than quenched and tempered (Q+T) steel, with size of inclusion $a_i=35$ μm and with constant threshold value $K_{th,R}=-1=9.154$ MPa·m$^{1/2}$. Figure 5 shows results in form of $S$-$N$ curves obtained by using proposed model for both conditions of 51CrV4 steel. Figure 5 shows that Q+T steel can be subjected to higher fatigue stress amplitude ($\Delta\sigma=1300$ MPa) then steel in as delivered condition ($\Delta\sigma=900$ MPa) for same number of cycles to failure. Steel in Q+T condition shows higher fatigue resistance with smallest inclusions size $a_i=0.035$ mm. For same Q+T steel the $S$-$N$ analysis has been performed for two different size of inclusion 0.25 and 0.5 mm. Fatigue four point bending tests are performed by cracktronic Romul, with loading ratio $R=-1$ and publish in ref.[10]. For testing four bending specimens without pre-stressing and shot-peening was used, made from the same material and same inclusions size of $a_i=0.5$ mm. Experimental results and prediction of $S$-$N$ curve for same size of inclusion and $R=-1$ shows very good agreement. Additional tests were conducted by spring producer on a leaf spring made from same steel with same inclusion size $a_i=0.5$ mm [11]. As it was mentioned the residual stresses on the surface should be at least $\sigma_{RS}=-1100$ MPa. Tests were performed on six specimens. All six springs after pre-stressing and shot-peening were subjected the same loading regime (720±630 MPa), therefore, an applied stress amplitude $\Delta\sigma_n=1260$ MPa and effective ratio $R=-6.8$. All leaf springs failed between 83535 and 194117 number of cycles as shown in Fig. 5. The experimental results on specimen without residual stresses lie in the same range of cycles, but for an applied stress amplitude $\Delta\sigma_n=400$ MPa and ratio $R=-1$. Therefore, difference between thus two groups of experimental results is consequence of different $R$ ratio, caused by residual stresses!

4. Conclusions

Chapetti's model has been used for determination of a threshold $\Delta K_{th}$ from short crack of grain size until critical crack length from one or few millimeters corresponding to applied maximum stress $\Delta\sigma_n/(1-R)$. Life time of spring material subjected to applied stress amplitude $\Delta\sigma_n$ from microstructural threshold up to critical crack length of high strength steel has been determine, by combining fracture mechanics parameters $K_{IC}$, fatigue propagation Paris range parameters $C$ and $m$, and considering inclusion size $a_i$ as crack initiation area. Results are presented in form of $S$-$N$ curves. Model shows very good agreement with experimentally obtained fatigue results for spring steel in Q+T condition with same inclusion size. The pre-stressing and shot-peening increase magnitude of compression residual stresses on the surface of leaf spring. Residual stresses change loading ratio to more negative value (e.g. $R=-6.8$) and additionally extended life time of spring subjected to higher stress amplitude.

5. References