FRETTING FATIGUE OF STEELS WITH DIFFERENT STRENGTH

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Abstract

The investigation of fretting influence on fatigue properties of steel parts with different strength. Instrumentation of fretting fatigue testing at fluctuating tension stress, with low values of sliding. Results of fretting fatigue testing on steels for railway wheel sets - axles, on carbon steel EA1N, and on the heat treated Cr-Mo low alloy steel EA4T, with strength values 578; 676; 736 and 1050 MPa were obtained. Comparison of the fatigue properties and fatigue limits in steel parts without influence of fretting, and with fretting. Analysis of surface fretting damage with wear and seizing up to the initiation of first fretting cracks occurring in the damaged places; development of fatigue fracture. Microstructure changes on the surface resulting from cyclic plastic deformation owing variable friction by fretting. Micro-hardness changes in the thin surface layer on carbon steel and on heat treated steel. Discussion of the influence of fretting on the fatigue properties of investigated steels with different strength. Increased unfavourable fretting influence at the higher strength values of steel and increased fatigue notch reduction factor \( \beta_k \). Low influence of fretting in carbon steel with the low strength values and low value of factor \( \beta_k \). Insignificant influence of the strength increase on the fatigue strength of parts at fretting under the given conditions.

Keywords: fatigue, fretting, damage, steels

1. INTRODUCTION

Fatigue damage affected by friction is an often occurred phenomenon in industry. It originates e.g. in the dovetail roots of blades of steam turbine - and turbo- compressor-rotors, in groove and tongue joints, or in press joints of shafts subjected to alternating stress. In railway wheel sets this damage often determines the lifetime of axles in the area of press fitted hubs of wheels and the lifetime of the whole sets, as well. Our results of fatigue tests carried out on large cylindrical specimens with pressed hubs of various strength Rm (550-1000 MPa) suggest [1,2] that alloy steels heat treated to a higher strength does not necessary show a more pronounced increase of fatigue strength and lifetime in comparison with carbon steel with a lower strength. The present work aimed at obtaining the data on the effect of strength and chemical composition on fatigue strength of various axle steels under simplified conditions of fretting application.

Strength and contents of alloying elements belong to the factors that can affect the fatigue strength with fretting application. According to Lindley [3] the published works are mostly consistent in result that unfavourable effect of fretting is far more remarkable in high strength steel parts than in lower strength steels. This implies that the fatigue strength in both cases approach each other. However, this conclusion is not supported by results of Tanaka et al. [4] obtained on two spring steels with markedly different strength (1677 and 718 MPa). Fretting fatigue limits determined in their work were substantially different (325 MPa in the first case, 130 MPa in the second case) while the values of fatigue fretting notch coefficient \( \beta_k aC \) were almost the same, \( \beta_k aC = 1.92 \) in the first case and 1.96 in the second case.

G. Husheng et al. [5] have drawn the attention to the important effect of the slip amplitude on fatigue strength in this conditions. Their results show that the values of fretting fatigue limit of steels with the strength 1568 MPa, 1058 MPa and 715 MPa differ considerably when the slip amplitude is 10 \( \mu \)m, but they are close to each other at slip amplitude 49 \( \mu \)m.
2. MATERIALS, SPECIMENS AND EXPERIMENTAL METHODS

Our programme was realized on two types of steels corresponding with the EN 13126 Standard, that are commonly used in the production of railway wheel axles. Chemical composition and basic mechanical properties of materials tested are given in Table 1 and 2, respectively. Flat specimens (see Fig.1) have been sampled from heat treated bulky axles, from the area between the outer diameter and the axle center. The fatigue testing took place on the resonance fatigue machine PHT Schenck Ltd. with a fluctuating value of load cycle (R~0).

Table 1. Chemical compositions of steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>Al</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA1N</td>
<td>0.39</td>
<td>0.34</td>
<td>0.79</td>
<td>0.091</td>
<td>0.027</td>
<td>0.017</td>
<td>0.017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EA4T, EA4T-V</td>
<td>0.33</td>
<td>0.35</td>
<td>0.77</td>
<td>0.92</td>
<td>0.21</td>
<td>0.079</td>
<td>0.053</td>
<td>0.013</td>
<td>0.017</td>
</tr>
<tr>
<td>EA4T-A</td>
<td>0.287</td>
<td>0.27</td>
<td>0.75</td>
<td>1.14</td>
<td>0.2</td>
<td>0.146</td>
<td>0.03</td>
<td>0.014</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>$R_{eh}$ ($R_{p,0.2}$) [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>HV 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA1N</td>
<td>379.3</td>
<td>578.3</td>
<td>164</td>
</tr>
<tr>
<td>EA4T</td>
<td>484</td>
<td>676</td>
<td>199</td>
</tr>
<tr>
<td>EA4T-A</td>
<td>572.5</td>
<td>736.4</td>
<td>229</td>
</tr>
<tr>
<td>EA4T-V</td>
<td>798</td>
<td>1049</td>
<td>331</td>
</tr>
</tbody>
</table>

Vibration friction tests proceeded with the help of the jig developed to this purpose (Fig.2). Two opposite bridges with pads were pressed over to the specimen. Their flat contact surfaces have width 3 mm. The adherence pressure was made by a screw. The force effect was evaluated by means of tensometric measurements on the connecting linkages, Fig.2. Calibration of the force effect has been carried out on a tensile-strength testing machine by loading of the jig over a pin in the axis of the screw. The adherence bridges were made of the heat treated EA4T-A steel, the hardness of which was 225 HV 30. The specific pressure used for the testing was determined from the adherence pressure applied on one pad and from the contact surface of width 3 mm. The pressure $p = 21.7$ MPa was chosen for our tests.

Fig. 1 Test specimen

Fig. 2 Jig for testing with fretting
The slip amplitude in the area of contact of pad and specimen during the testing \( (s_1) \) is given substantially by the deformation of the specimen between the bearing surfaces of pads with length \( \ell \) during the fatigue testing i.e. \( s_1 = \Delta \sigma / 2E \ell \), where \( \Delta \sigma = 2 \sigma_a \) is the value of peak-to-peak amplitude during the cyclic loading and \( E \) is elastic modulus. Calculation value of the slip amplitude on the fatigue limit in our tests was \( s_1 = (13-17) \mu m \). The deformation of the bridge with pads arising from the frictional force is very small and it could be neglected in the first approximation.

The fatigue tests with fretting have been carried out at the frequency of approximately 33 Hz, to \( 10^7 \) cycles, or to fracture. They took place without the usage of lubricants.

3. RESULTS OBTAINED

The results of fatigue tests are given in Tables 1, 2 and in Fig. 3; 4; 5 and 6. The fatigue diagrams and values of fatigue limits of samples without application of fretting show the expected dependence on the material strength. Comparison of fretting fatigue limits EA1N and EA4T specimens with different strength is on Fig. 7.

Fatigue strength of specimen of EA1N carbon steel with the lowest strength, characterized by the upper cycle stress is \( \sigma_{h,c} = 320 \) MPa.

The values of fatigue strength of EA4T low alloy steel, described by upper cycle stress \( (\sigma_{h,c}) \) are as follows:

- 440 MPa for EA4T steel with the strength 676 MPa
- 480 MPa for EA4T-A steel with the strength 736,4 MPa
- 610 MPa for steel EA4T-V with the strength 1049 MPa.
The fatigue limit under the influence of fretting for the specimens made of the EA1N steel with lowest strength (for $10^7$ cycles) was 260 MPa. In the case of low alloy EA4T steels, we found the values $\sigma_{hC} = 290$ MPa for EA4T steel with lower strength, $\sigma_{hC} = 260$ MPa for EA4T-A steel with the medium strength and $\sigma_{hC} = 230$ MPa for EA4T-V steel with the highest strength. The lowest value was obtained for the steel with the highest strength see Fig. 7.

The influence of fretting on the fatigue properties can be expressed as fatigue strength reduction factor obtained from the stress amplitudes on the fatigue limit $\sigma_{aC}$ (Table 3.)

Table 3. Fatigue strength of specimens with/without fretting. Fatigue strength reduction factor $\beta_{k_{aC}}$

<table>
<thead>
<tr>
<th>Steel</th>
<th>Fatigue strength [MPa] (R~0)</th>
<th>Fatigue strength reduction factor $\beta_{k_{aC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic material</td>
<td>with fretting</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{hC}$</td>
<td>$\sigma_{aC}$</td>
<td>$\sigma_{hC}$</td>
</tr>
<tr>
<td>EA1N</td>
<td>320</td>
<td>155,7</td>
</tr>
<tr>
<td>EA4T</td>
<td>440</td>
<td>213,5</td>
</tr>
<tr>
<td>EA4T-A</td>
<td>480</td>
<td>233,45</td>
</tr>
<tr>
<td>EA4T-V</td>
<td>610</td>
<td>273,5</td>
</tr>
</tbody>
</table>

$\beta_{k_{aC}} = \frac{\sigma_{aC}}{\sigma_{aC}}$ of basic material / $\sigma_{aC}$ of material with fretting

To obtain a more evidential comparison of the fatigue properties of the above mentioned steels with application of fretting, additional fatigue tests at the same stress level $\sigma_{hC} = 320$ MPa were carried out on four specimens of each steel. Our results are shown in Table 4.

The results in Table 4 show some differences in the mean lifetime values of investigated steels. On the other hand, the lifetime show a remarkable scatter and thus the differences do not seem to be significant, the only exception being the lowest value of EA4T-V steel with the highest strength. In principle this result confirms that for the given steels with different strengths the mean values of fretting fatigue life-time during the chosen cyclic loading are not substantially different. The smaller lifetime values have been found only on the steel specimens with the highest strength and the highest notch effect of fretting.

Table 4. Comparison of fatigue limits with application of fretting ($\sigma_{hC} = 320$ MPa)

<table>
<thead>
<tr>
<th>Steel</th>
<th>Rm [MPa]</th>
<th>Fatigue life [cycles]</th>
<th>Mean value of fatigue life [cycles]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA1N</td>
<td>578</td>
<td>379476 ; 5591412 ; 5918499 ; 8471599</td>
<td>3176637</td>
</tr>
<tr>
<td>EA4T</td>
<td>676</td>
<td>691867 ; 672127 ; 1899334 ; 5396813</td>
<td>2165035</td>
</tr>
<tr>
<td>EA4T-A</td>
<td>736,4</td>
<td>514974 ; 1466661 ; 1543192 ; 10000250</td>
<td>3381769</td>
</tr>
<tr>
<td>EA4T-V</td>
<td>1049</td>
<td>783501 ; 884978 ; 1272661 ; 684918</td>
<td>906514</td>
</tr>
</tbody>
</table>
The insignificant effect of the material strength on the level of fretting fatigue limit is well characterised in Fig. 7 where the results of the fatigue testing are summarized.

4. FRETTING DAMAGE AND DISCUSSION OF RESULTS

The first phase of the friction damage in the course of cyclic friction where the fretting originates is a frictional wear, Fig. 8. The products arising from contact leads, together with the increasing number of cycles, to the initiation of coarsening and local seizing - see Fig. 8. In the course of testing the intensity of seizing as well as the related coarsening increase [7]. In the first phase of the process the areas with a local seizing do not form a continuous zone, but just separate spots. These spots gradually grow and join together. Inner relief coarsening was often observed inside these areas, see Fig. 9. Cyclic overcoming of peaks of this coarsening during the surface contact together with the effect of slip leads to repeated plastic deformation in the surface layer and to the changes in the material structure. Coarsening in the contact area causes the increase of friction coefficient and friction force and leads thus to the increase of variable stress tension component in the surface layer. The slip on coarsened surface is also showed itself as moderate increase.

With the increase number of cycles, first cracks developed in some of these areas of seizing, Fig. 10. Cracks occur both inside these areas, Fig. 11, and at their boundaries, Fig. 12. They often originate in several places of the contact surface. Propagation of these cracks often deviates from the direction perpendicular to the action of the cyclical force. Fatigue failure originates at some of these cracks, Fig. 13. However, no crack propagation was observed on some other cracks even after $10^7$ cycles. These cracks had a character of retarded cracks and their propagation can occur in the course of following substantial prolongation of the test, as it has been described by Kondo, Y. et al. [6].

Plastic deformation of the thin surface layer in the area of seizing and crack formation in the specimen of EA4T-A steel with a higher strength is apparent in Fig. 14, Fig. 15. Micro-hardness measurements showed a higher hardness in this thin layer- see Fig. 16.

It can be expected that the repeated low-cycle deformation of this layer leads quickly to the formation of first cracks. These processes occurring in a thin surface layer apparently lead also to the mutual approaching of strength and fatigue values of the investigated steels in these places. It could explain not too different values of fatigue limit of steels with a different strength and structure owing to fretting – Table 3. Increased values of fatigue notch coefficient $\beta_{k,a}$ observed in steels with a higher strength are subsequently just a result of this process.

Complexity of deformation conditions with fretting can cause a higher scatter of fatigue lifetime as shown by the results of repetitive tests carried out at the same stress level Table 4.
Fig. 9 Areas with seizing. EA4T-A steel specimens

Fig. 10 Origin of small fretting cracks EA4T-A steel specimen

Fig. 11 Origin of fretting cracks within areas with frictional wear and seizing. EA4T-A steel specimen

Fig. 12 Fretting crack on the boundary of area with frictional wear and seizing. EA4T-A steel specimen
Fatigue properties under the conditions of fretting at repeated stress have been studied on the EA1N and EA4T steels with the strength of 578.3 MPa, 676 MPa, 736.4 MPa and 1049 MPa used for the axles of railway vehicles. A simple test jig with the bridge pressure elements with pads has been used in the course of testing. The tests took place under the specific pressure 21.7 MPa. The calculation value of the slip amplitude on the fatigue limit was ca (13-17) µm.

- In the fatigue tests of specimens without fretting, the effect of higher strength has shown itself in a regular manner, i.e. higher fatigue limit corresponded to higher strength. $\sigma_C = 320$ MPa at the EA1N carbon steel, 440 MPa in the heat-treated EA4T steel with a lower strength, 480 MPa in the same
EA4T-A steel with higher strength (736 MPa) and 610 MPa in the EA4T-V steel with strength 1049 MPa.

- In the tests of specimens with fretting the specified values of fatigue limit were not too different from each other, i.e. \(\Delta h_C = 260\) MPa in the EA1N steel, 290 MPa in the EA4T steel with a strength 676 MPa, 260 MPa in the EA4T-A steel with a strength 736 MPa and 230 MPa in the EA4T-V steel with the highest strength 1049 MPa.
- With respect to the natural scatter of results, the observed differences in fatigue limits are not significant.
- The influence of fretting at the EA1N steel with a small strength was insignificant, namely in the area of fatigue limit to 107 cycles.
- According to these results the damage effect of fretting is more pronounced in steels with a higher strength. This corresponds also to the values of fatigue notch coefficient at the fatigue limit in the investigated steels \(\beta_k = 1.27; 1.52; 1.89; 2.52\).
- The fatigue tests with fretting performed on four specimens of each steel at one stress level, showed a higher scatter of testing results. However, the difference in mean lifetime is not too significant, see Table 4, except the steel with the highest strength and with the highest notch effect of fretting, where the mean lifetime value was substantially lower.
- According to the micro-fractographic analysis, the plastic deformation in the contact areas after formation of coarsening and local seizing in a thin surface layer was observed. Before occurrence of failure in the contact areas during the repeated cyclic process, these effects lead to the structural changes and to the approaching of strength and fatigue properties of steels with a different strength. The strength of steel has practically no significant influence on the fatigue limit under the condition of fretting.

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