Effect of Surface Residual Stresses on the Fretting Fatigue of a 4130 Steel


ABSTRACT: Fretting fatigue is defined as the fatigue of a material caused by the presence of a rubbing contact with a relative displacement of less than 100 micrometres. The presence of fretting results in a lowering of the fatigue life of the material. The relative displacement, also known as the slip amplitude, has a considerable effect on the life of the specimens that were investigated. Different surface microstructures were studied in order to investigate the effect of slip amplitude on the fatigue life. These treatments, namely carburization and decarburization, also induced surface residual stresses which were instrumental in causing the changes that were observed in the fatigue life.

Effects of residual stress on fretting fatigue were studied using three kinds of heat-treated specimens of a medium carbon steel. Two sets of experimental specimens were respectively decarburized and carburized to induce residual stresses on the surface. A set of control specimens of tempered martensite was used to compare results. All three structures showed a minimum in life versus the slip amplitude; the carburized specimens exhibited longer lives in general and the opposite was true for the decarburized specimens. In all cases, transverse cracks initiated on the surface, at the interface between the contacting and free surfaces, and propagated inwards, perpendicular to the loading axis. An attempt is made to explain the observed phenomena using residual stress arguments.

KEY WORDS: residual stresses, carburizing, decarburizing, fretting, fatigue, debris, slip, normal load, cyclic stress, fatigue cracks, martensitic

It is well known that residual stresses are present in many components. These stresses may be intentional or unintentional, depending on the thermal and mechanical history of the component. It is generally acknowledged, however, that compressive surface residual stresses aid in prolonging the fatigue life of components by reducing the surface tensile stress felt by the components [1].

Thermo-chemical treatments such as shot peening, hammer peening, etc., have been widely used in order to induce compressive residual stresses on and below the surface.

In many of the above situations, fatigue is accompanied by a form of cyclic wear known as fretting. A general fretting situation comprises two contacting
surfaces having a relative oscillatory motion of small amplitudes, usually less than 100 micrometres [2]. The ensuing wear itself is capable of resulting in an undesirable loss of material from the surface in the form of metallic or oxidized debris. However, the main deleterious effect of fretting on fatigue is a reduction in the fatigue life of the component, resulting from an increased number of surface cracks initiated by fretting [3-5]. The latter phenomenon, termed fretting fatigue, is observed in a wide range of engineering applications and in a variety of metals. Although the fretting fatigue life in general has been observed to be lower than the fatigue life under the same loading conditions, the analysis of the situation is complicated by the fact that the extent to which the life is reduced depends on several variables such as normal load and degree of relative motion [6,7]. This study emphasizes not only the effect of surface residual stresses on fretting fatigue, but the effect of a few other important variables as well.

**Fretting Fatigue**

A fretting fatigue situation consists of a component under loading in contact with one or more surfaces. The contact surfaces impose a load normal to the instantaneous load on the surface of the component. The normal load causes a tangential load on the surface of the component, the extent of which is dependent on the nature of the interface between the two surfaces. The relative motion between the two surfaces is termed slip. The magnitude of slip is referred to as the slip amplitude and is dependent on several factors, including the modulus of the respective materials, the cyclic stress, and the normal stress. The resistance to slip is often represented by a coefficient of friction, which is the tangential force divided by the normal force.

The effects of various fretting parameters on fatigue life have been reported by several investigators. Waterhouse [6] reported a general decline in fatigue life under fretting conditions. The fretting fatigue limit increased with an increase in compressive mean stress and declined with an increase in tensile mean stress. When normal stress was increased, the fretting fatigue life was observed to decline until it saturated at some level beyond which no further degradation in life occurred [6,7]. Nishioka and Hirakawa [8-10] studied the effect of slip amplitude at a constant normal load and observed that the stress required to initiate fatigue cracks lessened with an increase in slip amplitude. Waterhouse [6] reported an increase in fretting fatigue strength with a decrease in slip amplitude. Plate-like debris indicating surface delamination has been revealed by surface damage studies [11-13]. Spherical wear particles were also observed in some cases [3,14].

In fretting, the time required to initiate a fatigue crack was observed to decline when compared with tests performed in the absence of fretting. An equation developed by Nishioka and Hirakawa [8] for the initiation of fretting fatigue cracks in flat fatigue specimens fretted by cylindrical pads is

\[ \sigma_{f_{\text{init}}} = \sigma_{\text{init}} - 2\mu P_0 \left[ 1 - \exp\left( -s/k \right) \right] \]

where \( \sigma_{f_{\text{init}}} \) is the alternating stress necessary to initiate fretting fatigue cracks, \( \sigma_{\text{init}} \) is the alternating stress necessary to initiate cracks in the absence of fretting, \( \mu \) is the coefficient of friction, \( P_0 \) is the peak Hertzian normal stress, \( s \) is the relative slip, and \( k \) is a constant depending on the material and the surface condition.

Although Eq 1 was developed for a specific geometry, it is not unreasonable to assume that an equation of the same general form would apply to other geometries. Also, since compressive surface residual stresses reduce the apparent tensile stresses on the surface and delay crack initiation, the same mechanism might be expected to operate in the case of fretting fatigue. Hence, according to Eq 1, any treatment that causes an increased fatigue life will also increase the life under fretting fatigue.

**Experimental Procedure**

A 4130 steel was chosen because of the ease of controlling residual stresses by thermo-chemical as well as mechanical means. It is worth noting that the thermo-chemical treatments alter the surface hardness and the surface microstructure in addition to inducing surface residual stresses, whereas the mechanical treatments such as shot peening may be used to induce compressive surface residual stresses without much change in surface hardness. Some of the relevant information on the steel used in the investigation are shown in Table 1.

Specimens were cut out of a sheet 0.254 cm thick with the longitudinal axis along the rolling direction. The dimensions of the specimen are shown in Fig. 1.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Chemical composition of the 4130 steel (weight percent).</th>
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<tbody>
<tr>
<td>C</td>
<td>Mn</td>
</tr>
<tr>
<td>0.3</td>
<td>0.44</td>
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</table>

All dimensions in cm

![FIG. 1 — Dimensions of specimen.](image-url)

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Carburization and decarburization were chosen as surface treatments for inducing surface residual stresses. The heat-treatment details are shown in Table 2.

Specimens were polished with 600 grit paper after heat-treatment and cleaned with acetone in an ultrasonic cleaner before testing. It is worth mentioning that the X-ray strain measurements were made after the final polishing.

The testing was done in a 130-MN Instron dynamic loading machine. Tension-tension mode was used and the tests were conducted at a tensile stress of 400 MPa. The minimum tensile stress was maintained at a small positive value of 22 MPa. A sinusoidal waveform was used for the tests.

A drawing of the fretting fatigue apparatus is shown in Fig. 2. The apparatus was designed to allow independent control of the fretting variables while maintaining rigidity and ease of handling. Since the cyclic load was applied by means of two martensitic (65 R$_s$) cylindrical pads of 4130 steel with a curved tip radius 1.58 cm to avoid edge effects. Two sets of spring washers were used to apply a precise normal load on the specimen. The whole assembly was then bolted rigidly to the stationary grip of the testing machine. Since the cyclic load was applied by the bottom grip, it is evident that the cyclic displacement increases as the distance from the top (stationary) grip increases. Thus, for a given normal load, slip can be controlled by changing the position of the pads on the gage length of the specimen. It was also observed that the slip amplitude decreased linearly as the normal load increased, and this fact was used to vary the slip amplitude in the experiments.

The slip amplitude was measured both by direct and indirect methods. The direct method used was as follows: A 2500 mesh transmission electron microscope grid (10 microns between lines) was attached to one of the nonfretting sides of the specimen, between the two fretting pads. A paper marker was attached to one of the fretting pads, so as to point at the grid. Once the experiment started, the relative motion between the marker and the grid was "frozen" by using a variable frequency strobe light, and the displacement was measured through a microscope by counting the number of lines on the grid that the marker traversed. In the indirect method, strain gages were mounted on the posts of the fretting fatigue apparatus to measure the strain in the posts. The output of the strain gages was displayed on an oscilloscope screen. The peak-to-peak measurement of this strain waveform was found proportional to the actual slip amplitude, as measured by the direct method. Thus the slip amplitude could be measured indirectly to a reasonable degree of accuracy.

Results

Specimens were tested at various levels of slip amplitude until failure occurred by specimen separation, and their fatigue lives were plotted against the slip amplitude. The slip amplitude was observed to remain fairly constant throughout the experiment. However, to avoid discrepancies, slip amplitudes at regular intervals were noted and time-averaged to obtain a single value of the slip amplitude for the entire life of each specimen. Since the slip amplitude was found to vary inversely with the normal load, the plot in Fig. 3 also indirectly represents the variation of fretting fatigue life with normal load. The lines drawn through the points highlight the trends observed in the experiments.

It can be seen that although the maximum alternating stress was well below the fatigue limit, most of the specimens failed under 10$^6$ cycles.

The trend lines show a minimum in their fatigue lives. The minimum for the carburized specimens, which have the least compressive surface residual stress, occurs at a lower slip amplitude than the other two. In short, the minimum occurs at a higher level of slip amplitude with a higher compressive surface residual stress.

All three minima appear to occur around the same number of cycles-to-failure.

Figure 4 shows a schematic drawing of the cracks that were found on the fretted specimen and the one which propagated to failure. Cracks that led to failure in all the specimens were found to initiate below the fretting pads. Cracks, both parallel and transverse, were found under the fretting region but did not propagate to failure.

Oxide debris were observed at slip amplitudes of greater than 50 microns, regardless of surface treatment.
slip amplitude has the most pronounced effect on the fatigue life. The trend observed in the change in fatigue life with the slip amplitude can be attributed to two competing phenomena. According to Sproles and Duquette [14] the wear mechanism in fretting fatigue involves creation of subsurface cracks in the initial stages, parallel to the specimen surface. These cracks eventually connect with transverse cracks and surface delamination occurs. The delaminated debris are oxidized in a favorable environment. However, at very low slip amplitudes no debris were observed, leading the authors to conclude that the relative motion was too small to create enough subsurface cracks or transverse cracks. Thus it can be inferred that initiation of fatigue cracks under fretting increases with increasing slip amplitude and the fatigue life can be expected to diminish. By the same argument, at higher slip amplitudes, a large amount of wear and debris removal can be expected and the fatal cracks can be expected to be shortened or eliminated by wear. This crack elimination or stunting through material removal has a favorable effect on the fatigue life and increases as the slip amplitude increases. A hypothesis based on the above argument is proposed in the following paragraph.

Figure 5 schematically demonstrates the difference in trends between a carburized and a decarburized specimen. The figure has been divided into two regions. In Region I, the carburized specimens have shorter lives than the decarburized specimens and vice versa in Region II. In Region I, the surface of the carburized material provides easy subsurface crack initiation owing to its low plasticity and low energy absorption capacity. The wear rate at this point is not high enough, however, to remove the cracks. The lower compressive residual stresses allow the fatal crack to open up sooner than in the decarburized material. A decarburized material in the same region will deform plastically before any of the cracks can actually initiate. The depth of deformation, however, is higher owing to high ductility of the surface material. In Region II, the carburized material tends to delaminate, thus wearing away any candidate for a fatal crack. Subsurface cracks coalesce and join the transverse cracks to form platelets which eventually get removed from the fretting region. The lower compressive residual stress permits more transverse cracks to open up and aids in wearing away cracks that might eventually be fatal. In a decarburized material, at high slip amplitudes, the surface work hardens to a greater depth and although material removal is higher, the cracks are too deep to be worn out and failure results when one of the cracks reaches critical length.

The difference in hardness shown in Fig. 3 has not been taken into account in the discussion above. Further work needs to be done to separate the effects of residual surface stresses from the effects of surface hardness variation, and tests intended to isolate the effects are being prepared.

Readers may note that in Table 3 the surface residual stress for the carburized material is less compressive than for the other two, which is contrary to common belief. This can be explained, however, by the following argument: Surface residual stresses due to cooling are compressive in nature [15] regardless of the surface treatment. However, martensitic transformation results in a tensile stress on the surface and the net effect of both cooling and martensitic transformation...

Discussion

It is evident from the results shown that the presence of fretting in fatigue has a deleterious effect. Of all the measurable variables, the relative movement or the...
Conclusion

Effects of residual stresses on fretting fatigue are complex. Thermo-chemical treatments used in this study further complicate the problem by introducing surface hardness as an additional variable. The isolation of surface stress as a variable (for example, by using shot-peened specimens) will shed better light on the problem and a study is currently under way. Here an explanation of the observed phenomena using combined residual stress and surface plasticity arguments has been presented. One of the important observations was that all the treatments examined showed a lowering in fatigue lives in the presence of fretting, and an explanation is offered which takes into account the different surface treatments and stress states.

References


results in less compressive net surface stress for the carburized specimen than for the other two conditions.

Readers may also note that the graph in Fig. 3 shows trend lines drawn from individual data points. Because of the high amount of scatter at this stress level, the trends need to be confirmed with further experimentation. Similar trends for a quench and tempered 4130 steel have been observed by Gaul [3] after considerable amount of experimentation. Work is currently under way to confirm the above trends with statistical analysis.