Influence of Residual Stresses on Crack Growth

H. Berns and L. Weber

Ruhr-Universität
Bochum
West Germany

ABSTRACT

The investigations are carried out using as rolled unmachined and unnotched specimens. The specimens are surface treated by shot-peening, shot-peening under prestress and nitriding to get compressive residual stresses in the surface layer. The loading was done under four-point bending. During fatigue the crack start and growth was followed up until fracture by means of an ultrasonic testing device using surface waves. The residual stress distribution after surface treatment is measured and compared to that after fatigue loading until fracture. The influence of residual stress level and distribution on fatigue crack growth and fatigue life is shown. The correlation between crack growth, residual stress distribution and its modification is explained by a fracture mechanics model.

INTRODUCTION

Cyclic stresses are usually highest at the surface. Therefore the surface condition is a most important aspect for a lot of applications in regard to the fatigue life. The possibility to prolong the fatigue life by inducing compressive residual stresses in the surface layer to compensate for tensile loading stresses is known and has been used since a long time.

The aim of the present investigation was to add information concerning the interaction between fatigue crack growth and compressive residual surface stresses. The specimens chosen were as rolled, quenched and tempered and subsequently surface treated flat samples. To induce compressive residual stresses shot-peening and nitriding were chosen. By means of ultrasonic surface waves it was possible to observe and register on-line the crack initiation and growth during the cyclic four-point-bending-loading of the specimens. The tests were done within the low cycle fatigue range. The residual stress distribution after surface treatment and their arrangement due to the cyclic loading will be discussed.
SURFACE CONDITION AND FATIGUE

FATIGUE BEHAVIOUR

To understand the proceedings during fatigue first the essential fatigue behaviour of materials under cyclic loading has to be known. The reactions of a material loaded under a cyclic stress amplitude may be generally divided into four stages /1/:

The crack-free stage I causes a specific dislocation pattern. Subsequently micro cracks are formed at the surface due to the formation of slip bands (Stage II). If the crack reaches a certain size (Stage III) the macro crack propagation begins. One may speak about a macro crack if the crack propagation is controlled by normal stresses. The crack will grow until the crack length reaches a critical value i.e. the material fracture toughness. Failure is induced at the onset of the last stage IV.

RESIDUAL STRESSES

The formation and characteristics of residual stresses have to be defined before discussing the processes inducing them /2-4/. Independent of the applied processes residual stresses are always induced when inhomogeneous plastic deformations occur sectionally over a macro region in a material. These stresses may be induced for example by cold working, by temperature changes which are accompanied by volume changes or by a local precipitation hardening. The influence of residual stresses on the fatigue behaviour may be described mainly as follows /2/:

- Residual stresses influence the fatigue strength like mean stresses. Therefore negative residual stresses raise while positive residual stresses diminish the fatigue life.
- The extent of the effect depends on the material strength. In high strength material residual stresses influence the fatigue strength more than in softer materials where the hardening effects prevails at the surface.
- The amount and depth distribution are essential for the fatigue strength.

PROCESSES FOR SURFACE TREATMENT

The processes for surface treatment may be divided into three main groups:
1. Mechanical treatment (shot-peening, rolling)
2. Thermal treatment (flame-/induction-hardening)
3. Thermochemical treatment (nitriding)

These methods mostly induce compressive residual stresses in the uppermost surface layer. The present work deals with shot-peening. Nitriding is considered for comparison. For flame-hardening see /6/.
SHOT-PEENING

There are a lot of publications dealing with shot-peening \(^{7-10}\). The effects produced by shot-peening may be described as follows: (1) surface pitting due to the impact of the shot; (2) work-hardening of a thin surface layer and (3) the formation of bi-directional compressive stresses in the surface layer with compressive residual stresses improves the fatigue life because the applied tensile loads are diminished. The effective stress equals the sum of the positive loading stress and the negative residual stresses. It must be considered, though, that the surface hardening and the residual stress distribution substantially depend on the state of the base material i.e. principally on the strength.

Shot-peening under prestress induce a higher level of compressive stresses \(^{11-13}\) as more plastic deformation is induced. Under unstressed condition the impact of shot-peening has to surmount a large amount of elastic deformation while due to the prestressing the distance to the yield strength is diminished and therefore the peening will be more effective.

NITRIDING

The stress pattern and fatigue behaviour of nitrided materials is discussed in a number of papers \(^{14-17}\). A nitrided part consists of a homogeneous base material with a steep hardness gradient at the surface and a simultaneous formation of a compressive residual stress zone. It is not sufficiently cleared which of these two effects has the greatest influence on the fatigue behaviour. Due to the hardness profile a marked difference in fracture toughness is induced which leads to characteristic crack growth in the surface layer and in the base materials.

EXPERIMENTALS

The investigation is carried out using the as rolled steel 50 CrV 4 with the chemical composition given in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>0.55</td>
</tr>
</tbody>
</table>

The preliminary heat treatment and the resulting mechanical properties of the base material is shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2 Heat treatment and mechanical properties of the base material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardening: 860°C / 20 min / oil quench</td>
</tr>
<tr>
<td>Tempering: 496°C / 2 h / air cool</td>
</tr>
<tr>
<td>( R_m = 1500 \text{ MPa} ) ( R_{p0,2} = 1435 \text{ MPa} )</td>
</tr>
</tbody>
</table>
This heat treatment was followed by one of the surface treatments listed in Table 3.

**Table 3 Surface conditions**

<table>
<thead>
<tr>
<th>Treatment No.</th>
<th>Surface treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>none, unmachined</td>
</tr>
<tr>
<td>2</td>
<td>as 1 and shot peened (Almen intensity $A = 0.59$)</td>
</tr>
<tr>
<td>3</td>
<td>as 1 and shot peened under a prestress of 0.75 times the yield strength ($A = 0.52$)</td>
</tr>
<tr>
<td>4</td>
<td>as 1 and gas nitrided (500°C/84 h/ammonia atmosphere)</td>
</tr>
</tbody>
</table>

To study the fatigue behaviour a special testing set-up was used which is described in more detail in an earlier work /17/. Figure 1 shows the specimens with a size of 400 x 100 x 15 mm.

![Figure 1 Testing set-up](image)

Five ultrasonic TR-probes were attached over the width of the specimen. They are fastened on a PMMA-wedge to generate ultrasonic surface waves. By means of this arrangement individual cracks are registered within the measuring area of 100 x 100 mm. Their propagation is followed up by the rising of the echo height which was correlated to the size of the crack. Therefore the size of a fatigue crack and its location is known at all stages of a fatigue test. The ultrasonic signals are processed by a computer which also controls the closed-loop hydraulic testing machine. The ultrasonic testing device provides the detection of cracks with a depth of about 0.1-0.2 mm. The resolution was found to be 0.9 %/mm² where % means the ultrasonic signal height and mm² the area of the fatigue crack.
RESULTS

EFFECTS OF THE SURFACE TREATMENTS

Figure 2 shows the micro-hardness (load: 5 N) profiles of the nitrided and shot-peened conditions.

![Figure 2 Micro-hardness profile (Designation see Table 3)](image)

The nitrided sample shows a hard surface with a maximum value of about 820 HV. With growing depth below surface the hardness decreases and reaches the value of the base material at about 0.7 mm. The shot peened condition shows no hardness increase. A hardness decrease is to be observed which is caused by a decarburization of the uppermost surface layer.

The results of the residual stress measurements (in direction of the bending axis) of the surface treated specimens are shown in Figure 3.

The untreated base condition 1 was assumed to have no internal stresses. By shot-peening compressive residual stresses are induced with a surface value of about -550 MPa and a maximum value of about 690 MPa at a depth of 0.2 mm below surface. By shot-peening under prestress, the complete level of compressive residual stresses is increased: The surface value to 720 MPa, the maximum value to near 1000 MPa and depth is raised. The nitride condition shows values similar to the shot-peening. Only the effective depth is increased.
EFFECTS OF THE FATIGUE LOADING

Stage I
The crack-free stage I is determined by a cyclic softening. A dislocation cell structure is formed and first plastic deformation may be observed by the formation of glide traces at the surface /18/.

Stage II
As the ultrasonic testing device detects cracks with a crack depth greater than 0.1-0.2 mm no information about the fatigue behaviour of micro-cracks can be given. The reason is the un-machined surface which limits the resolution capability. In polished samples of comparable strength levels the crack start was always observed at nonmetallic inclusions /18/.

Stage III
The fatigue behaviour of macro-cracks in respect to the surface treatment is shown in Figure 4. As the specimens were loaded under four-point-bending several individual cracks appear until fracture within the area of maximal bending stress. Figure 4 shows the growth of the leading crack.
The fatigue crack behaviour at different loading stress levels is shown. After crack start and some micro-crack growth the macro-crack appears at \( N_1 \), the number of the cycles to macro-crack initiation corresponding to a crack depth of 0.1 to 0.2 mm. After registration, the crack will not grow steadily in a shot peened surface but remain at a certain depth until at \( N_2 \) further stable crack growth to fracture \( N_f \) sets in. The crack delay rises with decreasing loading stress and by shot-peening under prestress.

The fatigue crack behaviour of the nitrided version is quite different. At crack initiation time an unstable crack growth is observed which is stopped and followed up by a stable crack growth until fracture. The fast initial crack growth occurs across the nitrided layer while the base material slows down the crack propagation velocity.

**Stage IV**

Figure 5 shows the Wöhler diagrams for all surface conditions. The test were interrupted when the specimens reach number of cycles of greater then \( 5 \times 10^5 \) as the investigations were restricted to the short time fatigue resistance.

In comparison with the untreated condition (1), the fatigue life is increased by shot-peening (2). The period to crack initiation is prolonged even more by shot-peening under prestress (3). This condition shows the greatest fatigue life. At comparable stress levels the nitrided version (4) reveals a short fatigue life. At the highest stress level crack initiation was observed.
after the first cycle. At a stress level of 920 MPa and below no crack initiation was observed.

![Graph showing cycles to failure and crack initiation](image)

**Figure 5** Cycles to crack initiation and to failure in respect to the surface treatment (Designation see Table 3, $P$; statistical probability)

After fatigue loading the residual stress distribution was measured. Figure 6 shows the values compared to those before loading.

![Graph showing influence of fatigue loading on residual stress distribution](image)

**Figure 6** Influence of fatigue loading on the residual stress distribution (maximum cyclic bending stresses: 2 - 1040 MPa; 3 - 1280 MPa; 4 - 1026 MPa)
The shot-peening under prestress (4) shows a uniform compressive stress decay. The stress maximum drifts in surface direction in contrast to the shot-peened condition (2) where the residual stress maximum has vanished. The surface treatment shows the greatest decrease in compressive residual stresses although a lower bending stress was applied.

Although the nitrided version (4) displays a distribution similar to the shot-peened condition (2), a slight decrease of the compressive residual stresses is observed up to 0.3 mm below surface. With a growing depth the compressive stresses increase.

DISCUSSION

The crack growth is obviously influenced by a compressive residual stress distribution in the surface layer. The effect may be divided into three sections.

a) Firstly the compressive stresses act like a mean stress. Therefore the effective stress may be considered as the sum of the loading and the residual stresses as shown in Figure 7.

![Figure 7 Stress distribution as a function of loading and residual stresses (Designation see Table 3)](image)

The course of effective stress is pointed out for the conditions (3) and (4). This effect is essential for stage I of fatigue as the period to crack initiation will be prolonged for condition (2) and (3) which can be seen in Table 4 where absolute values for cycles to crack initiation \( N_I \) and to failure \( N_f \) are listed. The values are calculated for a stress level of 1580 MPa.
Table 4 Comparison of cycles to crack initiation $N_i$ and to fracture $N_f$ in respect to the surface treatment at a stress level of 1580 MPa

<table>
<thead>
<tr>
<th>Surface Treatment</th>
<th>(1) as rolled</th>
<th>(2) shot-peened</th>
<th>(3) shot peened under prestress</th>
<th>(4) nitrided</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_i$</td>
<td>5500</td>
<td>18300</td>
<td>34500</td>
<td>1</td>
</tr>
<tr>
<td>$N_f$</td>
<td>9200</td>
<td>30800</td>
<td>72900</td>
<td>120</td>
</tr>
<tr>
<td>$N_i-N_f$</td>
<td>3700</td>
<td>12500</td>
<td>38400</td>
<td>119</td>
</tr>
</tbody>
</table>

In contrary, the nitrided condition (4) shows crack initiation after the first cycle. This effect is to be explained by the extreme hardening of the nitrided surface layer. By rising the hardness of a material the fracture toughness will decrease drastically. The effective stress is diminished not enough to lead to an uncritical fracture toughness value. Therefore unstable crack growth is activated at once. As the base material shows quite a lower hardness the fracture toughness increases and therefore the unstable crack can be stopped. In /17/ similar experience are described.

b) Stage II and III are also influenced. The compressive residual stress profile increases with growing depth below surface. Therefore the effective stress at the crack-tip will decrease. This correlates with the observed delay of the crack growth. This delay will increase by raising the compressive stress maximum below surface and by spreading of the residual stress profile so to be seen by shot-peening under prestress. In the nitrided condition (4) the increase of the fracture toughness in the base material leads to the stop.

c) The influence of fatigue loading on the stability of residual stresses has to be taken into consideration (Figure 7). The compressive residual stress profile is not stable but decreases by the time. Therefore, the crack delay may not be considered as a lasting crack stop for the effective stress as the crack-tip rises due to the decay of the residual stresses.

These conclusions may be also viewed under the aspect of fracture mechanics shown in Figure 8 in a schematic way. Each material has a characteristic threshold value of crack growth $\Delta K_o$ for fatigue loading. Beneath this value no crack growth is encountered.

The loading stress induces the highest values of $\Delta K$. With growing crack length $\Delta K$ is increased exponentially. The surface treatments diminish $\Delta K$ at the surface by means of the compressive stresses and will lead to a further decrease due to the residual stress distribution. Therefore a crack may propagate after being formed at the surface and grow until $\Delta K$ descends below the threshold value $\Delta K_o$. Crack growth is again activated when the residual stresses decay by fatigue loading and the stress intensity range ascends above $\Delta K_o$. 
A special attention is given to the fracture appearance in respect to the surface treatment as shown in Figure 9.

Shot-peening and nitriding lead to quite different fracture modes. In the shot-peened surface layers the fatigue crack is always formed at the surface due to the high testing loads. The further crack front was observed to be semi-elliptical until the critical crack length was reached.
In the nitrided layer cracks also start at the surface. But in contrast to the peened conditions, at first an unstable crack growth across the nitrided layer is observed. This rapid crack formation takes place all over the width of the specimen. A stable crack growth follows in the base material until fracture.

As the loading is done under four-point-bending the maximum stress acts over a large specimen region. Therefore a number of cracks is formed with one being the critical. Figure 10 shows a crack formation at the surface.

Figure 10 shows crack I with a crack length of about 0.88 mm having surmounted the residual stress field. This crack may lead to the failure of the specimen. The origin of this crack lays at the surface where two small cracks were formed which join together beneath the surface. Crack II and III are stopped at a crack length of about 0.2 mm within the compressive residual stress layer and are momentarily not able to propagate. Figure 10b shows the crack appearance at the surface.

CONCLUSIONS

It is shown how residual stresses influence crack growth in shot-peened and nitrided specimens. The crack detection and the pursuit of their extension was enabled by means of an ultrasonic testing device using surface waves.

The investigations lead to the following conclusions:
- Shot-peening and nitriding lead to similar compressive residual stress distribution. The absolute values of the compressive residual stresses will further increase by shot-peening under prestress. In contrast to the peening, nitriding causes
a steep hardness gradient at the surface which leads to a drastic decrease of fracture toughness within the surface layer.

- The crack-free stage I of fatigue is influenced by compressive residual stresses. They act like mean stresses and therefore reduce the effective stresses.

- Compressive residual stresses also influence crack growth (Stage II and III). Due to the residual stress distribution the effective stress intensity $\Delta K$ is decreased and may descend below the threshold value $\Delta K_0$. Therefore the propagation of a short macro-crack may be stopped.

- Fatigue loading leads to a rearrangement of the residual stress distribution. The absolute compressive residual stresses are diminished and the residual stress maximum is displaced in surface direction.

- Due to the decay of the residual stresses the effective stress intensity $\Delta K$ increases and leads to further crack growth until fracture.

- Shot-peening increases the fatigue life due to the compressive residual stresses which prolong the time to crack initiation and delay the crack growth. Nitriding may show a similar effect at lower bending stress levels. But the surface hardness causes also a decrease of the fracture toughness within the surface layer. This leads to early unstable crack growth at high bending stress levels and therefore to a decrease in the fatigue life.

- The fatigue appearance depends on the surface treatment. The nitrided condition shows a rapid unstable crack growth all over the width of the specimen within the nitried layer which is followed by stable crack growth until fracture within the base material. The shot-peened conditions show a semi-elliptically crack front.

REFERENCES


15. Harig, H., Ermüdungsverhalten nitrierter und nitrocarburierter Stähle, AWT-Seminar, Berlin, April 1985
17. Spies, H.J.; Pusch, G.; Brock, K., Bruchmechanische Bewertung der Zähigkeit des Stahles 30 CrMoV 9, Neue Hütte, 30 (1985) 3, 100