INFLUENCE OF SHOT PEENING ON THE FATIGUE BEHAVIOR OF A PRECIPITATION HARDENABLE, AUSTENITIC STEEL

E. Hornbogen, M. Thumann and C. Verpoort*

Ruhr-Universität Bochum, Institut für Werkstoffe,
D-4630 Bochum, Federal Republic of Germany
**now at: Rensselaer Polytechnic Institute, Department of Materials Engineering,*
Troy, USA

ABSTRACT

In precipitation hardenable alloys the number of cycles required for crack initiation during fatigue is strongly influenced by the microscopic slip distribution. Inhomogeneous slip causes early initiation at the largest surface steps during dynamic loading. Crack propagation, however, is retarded in this case because of partial reversibility of slip. The microscopic slip distribution can be varied in a wide range by different thermomechanical treatments. If the plastic deformation in the material is distributed homogeneously, crack initiation requires a large number of cycles but cracks propagate quickly.

It was the purpose of this investigation to influence the crack initiation behavior so that the first stage of crack initiation becomes more difficult. To investigate the effect of the slip distribution on the fatigue behavior the untreated condition was compared with a cold rolled (bulk deformation) and a shot peened condition (surface deformation). The optimum of fatigue life was achieved by shot peening leading to an extremely homogeneous slip distribution in the surface.

In addition the fatigue behavior of shot peened specimens at high temperatures was investigated. It was found that a homogeneous slip distribution leads to a significant improvement of fatigue life even at high test temperatures.

KEYWORDS

Crack initiation; reversibility of slip; surface treatments; shot peening.

EFFECT OF THE SLIP DISTRIBUTION ON THE FATIGUE BEHAVIOR

The plastic deformation behavior of alloys may differ microscopically even if the amount of macroscopic plastic deformation is equal. The microscopic plastic deformation can be distributed either homogeneously or inhomogeneously (Williams, Luetjering, 1980). As it is shown in Fig. 1 the same amount of macroscopic plastic strain can lead to either one large slip step or to many smaller ones.

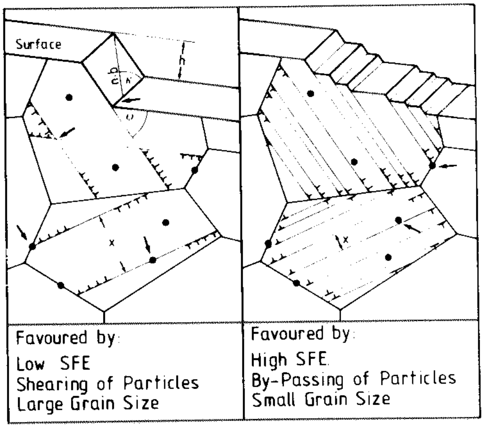

Fig. 1. Homogeneous and inhomogeneous distribution of plastic deformation

The alloy which was investigated here (Fe-26% Ni-15% Cr-2% Ti;A 286) was hardened by γ'-particles like nickel-superalloys. The austenitic matrix demonstrates a planar slip character due to the low stacking fault energy. The slip distribution, homogeneous or inhomogeneous, is further influenced by the different reactions of dislocations with particles, shearing or by-passing. If the γ'-particles are small, they will be cut by the dislocations. Thus weak zones are formed in the material which need a lower shear stress for the subsequent dislocation motion than the undeformed areas. In this way a very inhomogeneous distribution of slip can be produced. With increasing inhomogeneity of slip a decreasing number of cycles is necessary for crack initiation at the high slip steps in the surface. If the γ'-particles are larger than a critical diameter they are by-passed during plastic deformation and a more homogeneous slip distribution is achieved leading to a retardation of crack initiation (Hornbogen, Verpoort, 1981).

The formation of fatigue cracks in the inhomogeneously deforming conditions is shown in Fig. 2. With increasing number of cycles an increase of the average slip step height is observed (Graef, Hornbogen, 1978). The cracks are initiated at the largest steps which can clearly be identified by tapersectionings. The complete fatigue behavior is shown in a S-N-curve for the underaged condition. In addition to final fracture the formation of cracks is also indicated. As mentioned above the formation of cracks occurs at an early stage. The cracks are initiated after about 10 % of total fatigue life. Thus the crack initiation phase is very short and crack propagation controlls the specimen life time. But the cracks are retarded due to the reversibility of slip at the crack tip (Hornbogen, Zum Gahr, 1976).

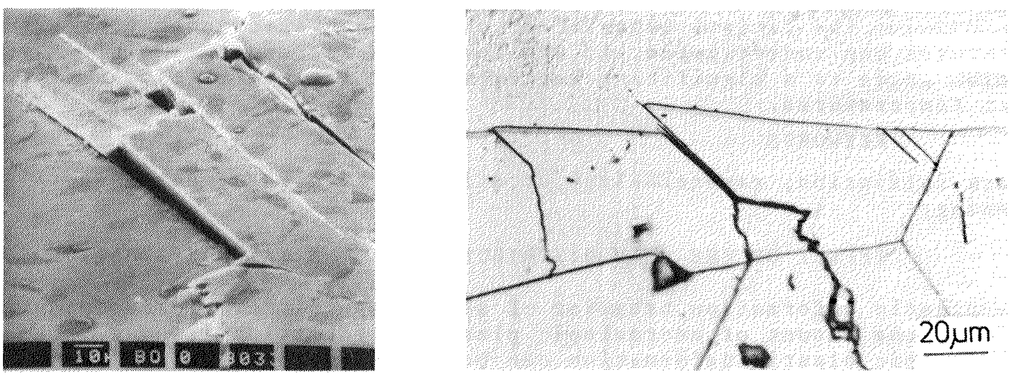

Fig. 2. Fatigue crack initiation at high slip steps, SEM and light-microscopy, tapersectioning.

In order to obtain a homogeneously deforming material and hence an improvement of crack initiation the material was cold rolled. As expected, the number of cycles until crack initiation for these conditions is significantly increased, but the total fatigue life decreases because the subsequent crack propagation rate is increased (Fig. 3).

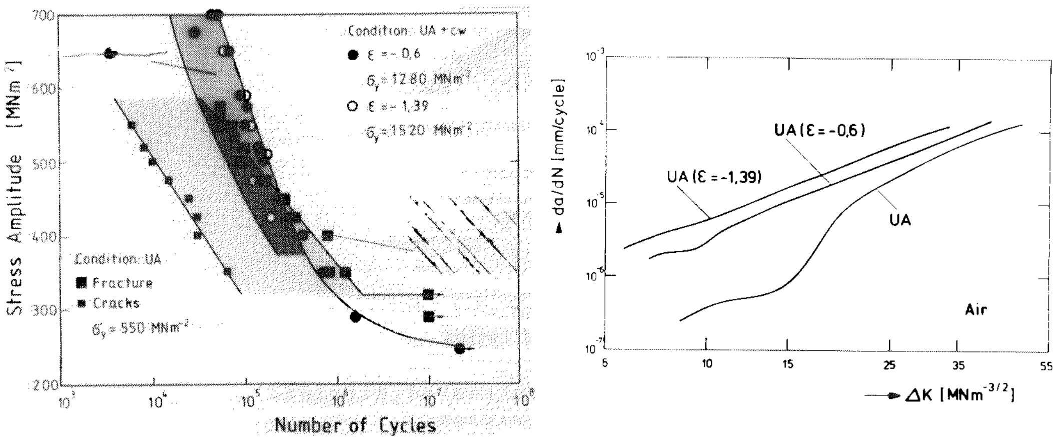

Fig. 3 Crack initiation and crack propagation behavior for an inhomogeneously (UA = underaged) and homogeneously deforming (cold rolled, $\varepsilon = -0{,}6$ and $\varepsilon = -1{,}39$) condition.

EFFECT OF SURFACE TREATMENTS ON THE FATIGUE BEHAVIOR

This investigation indicates that the same microstructural and micromechanical conditions which favor early formation of cracks lead to a low crack propagation rate and vice versa. From these results the conditions for an optimum fatigue life can be determined: to obtain a good crack initiation behavior a homogeneous slip distribution is required; however, an inhomogeneously deforming microstructure is necessary to retard crack propagation. Both points can be combined using a suitable surface treatment (Graef, Verpoort, 1978).

To obtain the optimum fatigue life the specimens were exposed to several surface treatments: mechanical treatments, diffusion treatments, and surface coatings. The consequence of all these treatments were always compared with the untreated condition. However, new crack initiation processes underneath the surface can result in little improvement (nitriding) or even deterioration (hard coatings) of the fatigue properties. Only shot peening produced a beneficial effect on the microscopic slip distribution in the surface and as a consequence the optimum of fatigue life for this type of alloy was reached by shot peening.

In Fig. 4 the effects of nitriding and shot peening on the fatigue life are shown. The duration of exposure to the beam was varied between 2 and 18 min. In addition the ball velocity and the Almen-intensity was varied. All fatigue tests were carried out under rotating bending. The results indicate that the fatigue life of the specimens increases with increasing time of exposure. Measurements of microhardness indicate an increasing thickness of the work hardened layer with increasing time of shot peening. Under the optimum shot peening conditions the endurance limit of the underaged condition increases from $\sigma_a = 300\ MNm^{-2}$ to $\sigma_a = 500\ MNm^{-2}$.

In addition to the high dislocation density residual stresses are introduced in the surface by shot peening as shown in Fig. 5.

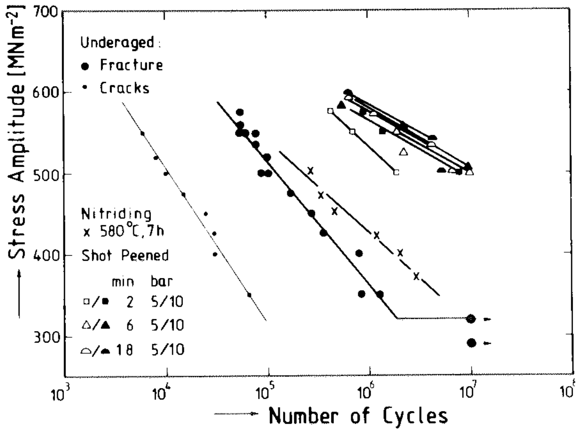

Fig. 4. S-N-curve for the untreated,nitrided and shot peened condition.

To investigate the mechanisms of shot peening the number of cycles until crack initiation for the shot peened condition were determined and compared with the untreated condition. After shot peening the' number of cracks in the surface was much lower than in the untreated condition. It was found that many more cycles are required for the formation of cracks than in the untreated condition (Fig. 6), but after shot peening crack initiation is found after about 20 % of total fatigue life. The tapersections indicate that the slip bands pile up underneath the shot peened surface zone. The dislocations in the slip bands have to interact with the sessile dislocations in the deformed zone so that no sharp slip steps can be formed. This effect leads to a very homogeneously deforming surface zone and therefore to a retardation of crack initiation. If,however, a crack is initiated it grows slowly due to the compressive residual stresses in the surface zone (Leverant, Langer, Yuen, Hopkins, 1979). In addition, the subsequent crack propagation in the matrix material is retarded due to the reversibility of slip at the crack tip. Therefore it is indicated that the shot peening treatment is the optimum surface treatment for inhomogeneously deforming conditions,because this measure, leading to a retardation of crack initiation, has an additional beneficial effect on the propagation rate of cracks in the surface zone.

EFFECT OF SHOT PEENING ON THE HIGH-TEMPERATURE-FATIGUE

It will be shown that the introduction of a homogeneously deforming surface layer by shot peening has also a favourable effect on the fatigue life if the tests are carried out at high temperatures. Relevant to the interpretation of the microstrucural changes in the shot peened zone are investigations on recrystallization behavior of precipitation hardenable alloys. These investigations have shown that in such alloys recrystallization occurs only in an intermediate range of amounts of deformation (Hornbogen, 1977). At very high amounts recrystallization is inhibited due to the nucleation effect which certain dislocation arrangements have on incoherent phases (η-particles). All mi-

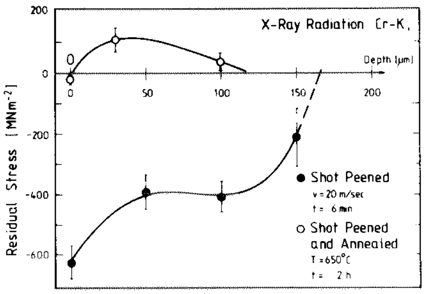

Fig. 5. Residual stresses in the surface

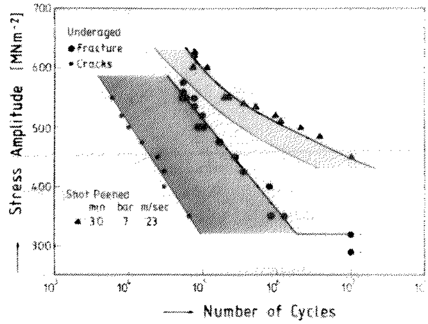

Fig. 6. Crack initiation for the untreated and shot peened condition

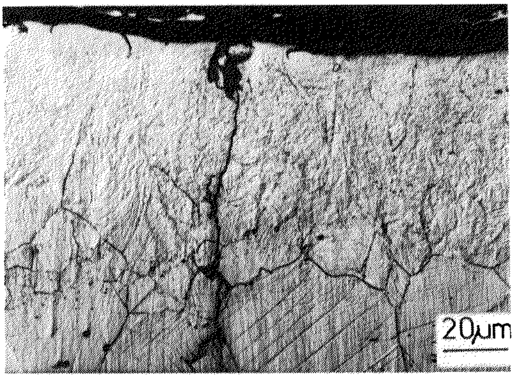

Fig. 7. Tapersection of a shot peened specimen after fatigue

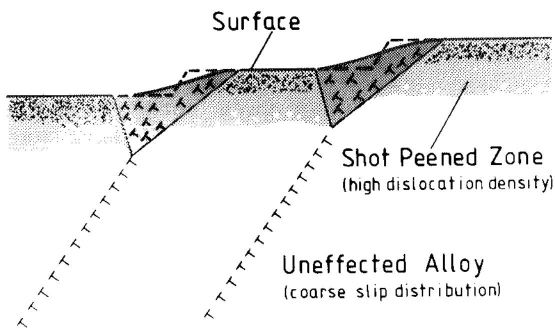

Fig. 8. Effect of shot peening on the slip distribution in the surface

crostructures shown in Fig. 9 should occur in a shot peened surface if the maxium amount of deformation is sufficiently high to produce the range-III-microstructure. This microstructure is characterized by the fact that recrystallization is inhibited and therefore the microstructure consists of a dispersion of coherent particles and a dense network of subgrain boundaries. This microstructure is sufficient to disperse strain localization and therefore the alloy is protected up to rather high temperatures against transcrystalline crack initiation. It is well known that, with increasing temperature, an increasing tendency for intercrystalline crack initiation is to be expected (Gleiter, Hornbogen, Baero, 1968). When grain boundaries and their environment were investigated in the shot peened zone it was found that a similar beneficial effect of the surface treatment applies to grain boundaries. Grain boundaries are highly curved and pinned by precipitates in the shot peened zone and as a consequence grain boundary sliding is highly reduced.

Thus it can be concluded that there are two possibilities for improving fatigue life at high temperatures by shot peening:

1. If the type-III-microstructure is preserved at the surface.

2. If a recrystallization (type-II-microstructure) occurs leading to a fine grain size respectively small slip length in the surface.

Both types can be introduced by adjusting the shot peening parameters.

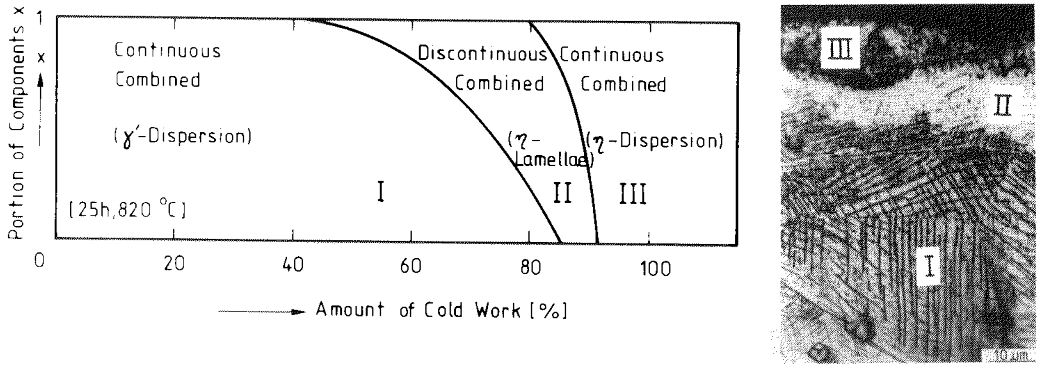

Fig. 9. Types of microstructures obtained by heat treatment after different amounts of deformation. Microstructure I, II, III occuring in a shot peened surface, as shown by tapersectioning of a fatigued specimen.

TABLE 1 Effect of shot peening at different temperatues

Cycles to Rupture at Different Temperatures

$\sigma_a/\sigma_y = 0.9$	20 [°C]	650 [°C]	840 [°C]
electrolytically polished	8.5×10^4	4.5×10^4	33×10^4
shot peened	1000×10^4	130×10^4	2600×10^4
$f = \frac{N_f\,[sp]}{N_f\,[ep]}$	120	30	80

In TABLE 1 the results of shot peening at room temperature, at 650 °C (no residual stress, no recrystallization) and at 840 °C (no residual stress, recrystallization) are shown. At the temperature of 650 °C all compressive residual stresses are resolved (see Fig. 5) but no recrystallization occurs. The beneficial effect of shot peening can be attributed to the work hardened surface layer. At the temperature of 840 °C the recrstallization leads to a very fine grain size so that a pronounced increase of fatigue life even at this high temperature can be found.

In the untreated condition cracks are initiated at steps at grain boundaries as shown by tapersections (Fig. 10). The shot peening treatment produces a fine grain size layer in the surface. No grain boundary cracks can be found. Many cracks are initiated now underneath the homogeneously deforming surface zone so that cracks propagate under va-

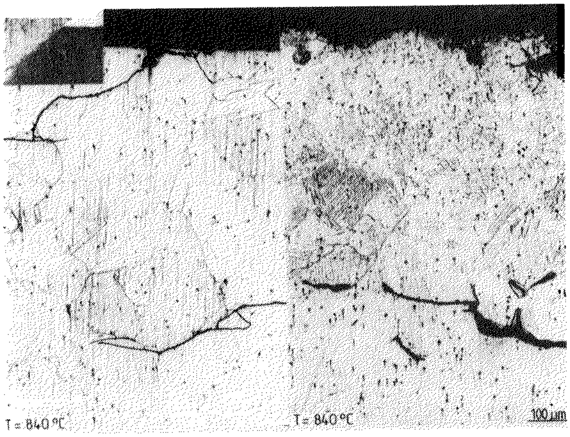

Fig. 10. Tapersections of fatigued specimens at high temperature, left: untreated, right: shot peened.

cuum conditions. The shot peening conditions as well as the upper limit of the temperature and service times have to be controlled carefully to obtain beneficial effects from this method during application at elevated temperatures.

ACKNOWLEDGEMENT

This work was supported by BBC Aktiengesellschaft BROWN, BOVERI & CIE., Baden, Switzerland. We would like to thank Dr. Stuecheli, BBC Zentrallabor, Baden, Dipl.-Ing. von Armin and Dr. K. Schneider, BBC Mannheim and Dipl.-Ing. Peters, Friedr. Krupp Huettenwerke, Bochum, for their help with some experiments. The material was provided of the Thyssen Edelstahlwerke AG, Krefeld; Friedr. Krupp Huettenwerke, Bochum; Boehler AG, Duesseldorf and BBC Mannheim.

One of the authors, C. Verpoort, would like to thank the Alexander von Humboldt-Stiftung for providing him with the Feodor-Lynen-scholarship.

REFERENCES

Gleiter, H., E. Hornbogen and G. Baero (1968). Acta Met. 16, 1053.

Graef, M. and E. Hornbogen (1978). Scripta Met. 12, 147.

Graef, M. and C. Verpoort (1978). 5th Intern. Conf. on the Strength of Metals and Alloys ICSMA 5, Aachen, West-Germany, Vol. II, 1207.

Hornbogen, E. and C. Verpoort (1981). 5th Intern. Conf. on Fracture ICF 5, Cannes, France.

Hornbogen, E. and K.-H. Zum Gahr (1976). Acta Met. 24, 581.

Hornbogen, E. (1977). Jour. Mat. Sc. 12, 1565.

Leverant, G. R., B. S. Langer, A. Yuen, S.W. Hopkins (1979). Met. Trans. 10 A, 250.

Williams, J. C. and G. Luetjering (1980). 4th Intern. Conf. on Titanium, Kyoto, Japan.