The Effect of Nitride Case - Hardening upon Fatigue Fracture in Torsion and in Push - Pull of an EN41B Steel

J. W. Martin, Oxford University Department of Metallurgy, UK
and C. V. B. Gowda
Waterloo University Department of Civil Engineering, Canada

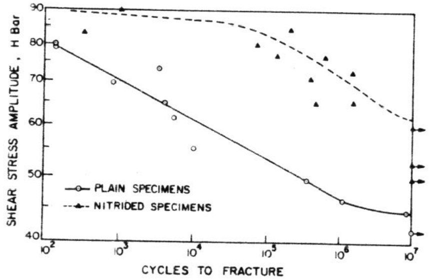
It has been known since the early work of Hengstenberg and Mailänder[1] that nitriding leads to an increase in the rotating bending fatigue limit of steel. Sutton[2] and Bardgett[3] have furthermore shown that under direct stressing fatigue, nitriding has little effect upon the fatigue limit. The object of the present work was to compare the effect of nitriding upon the form of the S - N curves in torsion and in push-pull of a nitriding steel, and to identify the mode of failure in each stress condition by fractographic study.

Materials and Methods

An EN41B steel (wt% composition: 0.42C, 0.38Si, 0.013S, 0.015P, 0.57Mn, 0.19Ni, 1.56Cr, 0.17Mo, 1.01Al), quenched and tempered to a UTS of 93.02 hbar, was selected and direct-stress specimens (gauge length 6.8mm, diameter 4.7mm) and torsion specimens (gauge length 6.2mm, diameter 3.9mm) were prepared. Nitriding was carried out at 520°C by a glow-discharge method in a 50/50 N_2/H_2 mixture for 18 hr, producing a case of depth 0.45mm. A series of plain and nitrided specimens were tested at a frequency of 1420 cycles/min in push-pull in a Dowty hydraulic closed-loop servo-controlled machine, and in torsion in an Avery dynamic testing machine. The fracture surfaces were examined in a scanning electron microscope.

Results and Discussion

Figs.1(a) and (b) show the S - N curves obtained in torsion and push-pull respectively, and it is seen that nitriding enhances the fatigue limit in torsion by $\sim$45%, whereas in push-pull it has little effect at high stresses but reduces the fatigue limit by $\sim$12%. The mechanisms can be understood from a study of the fracture surfaces obtained from low and high-stress tests, bearing in mind the state of internal stress of the nitrided specimens which, in agreement with Linhart[4], has been shown by a Sachs method to consist of a biaxial (i.e. axial and tangential) compressive stress in the case (with negligible radial stress) counter-balanced by low tensile stresses in the core.



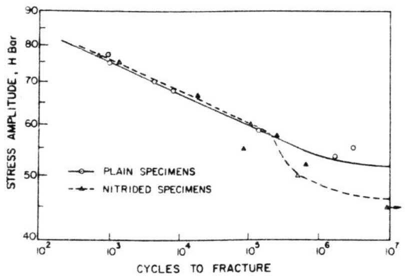


Fig.1 (a) Torsion test (b) Push-pull test

Torsion. (a) Nucleation: Fig.2, from a long-life specimen, shows clearly a fracture nucleus located beneath the case. Surface nucleation is suppressed by the compressive stresses present, and a sub-surface inclusion has nucleated failure. At the radius corresponding to this nucleus the stress amplitude is lower than the surface stress on an un-nitrided specimen tested identically, so that an increased life is to be expected. Fig.3, from a short-life specimen, shows that at high stresses multiple cracks are formed on 45° planes.
(b) Propagation. All un-nitrided specimens showed a plane of fracture at 90° to the axis, some showing occasional 45° ledges (fig.4). The fracture path of the nitrided specimens was apparently parallel to the plane of maximum normal stress: in the long-life specimens the residual stresses due to the case have the effect of changing this plane from 45° to 30-35° to the axis (fig.4). A change in the plane of rotating - bending fatigue fracture in the presence of residual stresses has been previously reported[5]. It is seen (fig.3), however, that at short lives the high level of applied stress swamps the effect of the residual stresses, so that the fracture plane is 45°. Fig.1(a) suggests that as the value of the applied stress approaches the UTS, the effect of the case disappears quite sharply, and, by extrapolation, the two curves appear to coincide at about this stress, as might be expected.

Fig.2. Nitrided torsion specimen fractured at ± 65 hbar

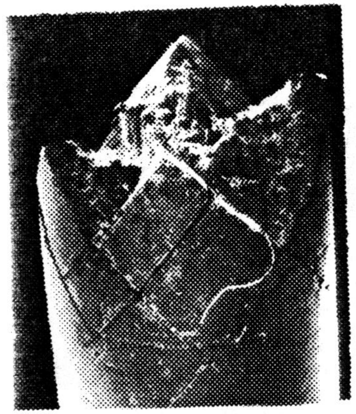


Fig.3 Nitrided torsion specimen fractured at ± 83.4 hbar

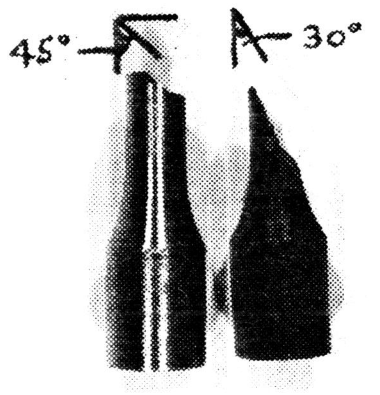


Fig.4 Torsional fatigue fractures in (L)plain and (R) nitrided specimens

Fig.5 Nitrided push-pull specimen fractured at ± 66.5 hbar

Push-Pull. Since the applied stress amplitude is uniform over the specimen cross-section, the effect of super-posing residual stresses by nitriding, which are highly compressive in the case and mildly tensile in the core, will again be to suppress fatigue crack nucleation at the specimen surface, since the effective tensile stress there will be small. Within the interior of the specimen, however, there will be no reduction of effective stress, so that fatigue crack nucleation in association with non-metallic inclusions is to be

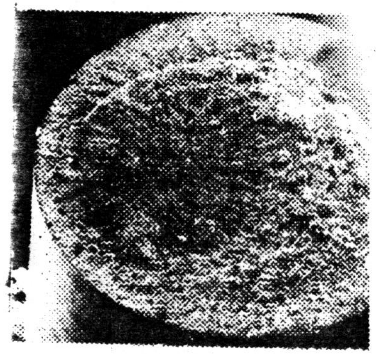


Fig.6. Nitrided push-pull specimen fractured at ± 50hbar

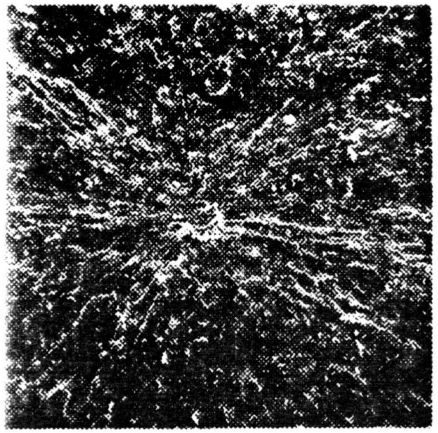


Fig.7. Fracture nucleus of specimen in fig.6.

expected[3]. Fig. 5 illustrates the type of fracture surface observed on highly-stressed specimens, with short fatigue lives. Prolific subsurface nucleation has taken place, always in association with an inclusion, and these have extended to form penny-shaped voids which have finally propagated rapidly to fracture. Under these conditions of stress, no change in fatigue life is observed in comparison with the un-nitrided material.

Fig.6 shows the fracture surface of a long-life specimen (± 50 hbar), and in this experiment only a single crack nucleus was observed in the form of a shiny circle which again was seen at higher magnification (fig.7) to have been associated with an inclusion. When the applied stresses are low, the magnitude of the residual tensile stresses in the core will no longer be negligible in comparison with the applied stress, and it is suggested that fatigue crack nucleation takes place in association with an inclusion lying in the region of maximum residual tensile stress. It is concluded therefore that the amount by which the fatigue limit is reduced by the nitriding treatment is comparable with the magnitude of the maximum residual tensile stress existing within the core of the test-pieces.

Conclusions

It has been shown that the biaxial compressive stress introduced by nitriding effectively suppresses Stage II fatigue cracking in both torsion and push-pull.

At low stresses, a sub-surface crack nucleus develops at a non-metallic inclusion, probably in the region of maximum residual tensile stress. Whereas in torsion this region experiences a reduced stress and therefore a longer life than an un-nitrided specimen, in push-pull this is not the case and a reduced fatigue limit is observed. At high stresses many more sub-surface nuclei form, so that the fracture surface, in both torsion and push-pull, corresponds to the interlinking of several cracks.

It is suggested that only in the absence of non-metallic inclusions could nitriding lead to an enhancement of fatigue life under conditions of direct stressing.

References

1. O. Hengstenberg and R. Mailänder. Z.d.V.d.I. 1930 77 1126
2. H. Sutton. Metal Treatment 1936 2 89
3. W.E. Bardgett. ibid. 1943 10 87
4. V. Linhart. Proc.Int.Conf.(Warsaw) "Fatigue Resistance of Materials and Metal Structural Parts" ed. A. Buch, 1964: Oxford (Pergamon Press) p.199.
5. H. Bühler and H. Buchholtz. Stahl und Eisen 1933 53 1330

Acknowledgements

The authors wish to thank Mr L. Quong for assistance with the experimental work and Mr J.L. Phillips for many useful discussions.