THE EFFECT OF RESIDUAL STRESSES ON THE FATIGUE FAILURE OF NITRIDED EN 41B STEEL

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INTRODUCTION

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] reported, however, that under direct stressing fatigue, nitriding has little effect upon the fatigue limit - a conclusion also more recently drawn by Tauscher and Buchholz [4].

Recent work at Oxford has been concerned with the precise measurement of the internal stress distribution in nitrided 'Nitralloy'-type EN41B steel, employing the Sachs [5] boring technique. This work forms part of a continuing study of the effects of hard surface layers upon the mechanical properties of metals [e.g.6]. The present study examines the effect of various nitride case depths upon the form of the S - N curve in push-pull fatigue, and attempts to correlate the observations with measurements of internal stress distribution in the nitrided specimens and with the metallography of failure.

MATERIALS AND METHODS

An EN41B steel of UTS 1.02 GPa was selected, and test-pieces of gauge length 6.80 mm and diameter 5.00 mm were prepared. Nitriding was carried out for various selected times at 520°C by a glow-discharge method in a 50/50 N_2/H_2 mixture.

A series of plain specimens and four sets of nitrided specimens were tested in push-pull in a hydraulic closed-loop servo-controlled machine, and the fracture surfaces were examined both by optical and scanning electron microscopy.

The residual stress distribution was obtained by the Sachs [5] drilling technique. Change in strain at the specimen surface was measured using four MicroMeasurements precision strain gauges, connected in two half-bridge Wheatstone bridge circuits. The strain readings were converted to stresses by calculating strain functions from the equations obtained by Weiss [7]. A high order polynomial was fitted to the strain function data and differentiation of these polynomials yielded the required stress profiles.

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By monitoring the specimen temperature using gauge-type sensors, the drilling technique was able to be refined, thus minimizing the stresses introduced by the material removal process. A correction for such damage was made in the computer programme employed to calculate the stresses, and to plot the profiles of axial, tangential and radial stress.

RESULTS AND DISCUSSION

Nitriding

Sets of specimens were nitrided at 520°C for periods of 0.5, 1.0, 2.0 and 24 hr. In order to assess the case-depth obtained in each case, micro-hardness traverses were made upon metallographically prepared sections and the results are shown in Figure 1.

Residual Stress Distributions

The stress analysis results for the 24 hr. nitrided specimens are shown graphically in Figure 2, and Table 1 summarizes the data for all the nitriding times used. The maximum values of axial, tangential and radial stress in the nitrided surface layer (σ_S) and the centre-line stress in the specimen (σ_C) are recorded in this Table.

For all of the nitrided specimens the axial stress was tensile and reasonably constant throughout the core of the material (σ_C) with a steep gradient through the case to a high compressive stress at the surface (σ_S). The tangential stress distribution was of a similar form, whilst the radial stress was almost constant through the core and dropped to zero at the surface. From Table 1 it may be seen that the radial stress is of comparable magnitude to the tangential stress throughout the core of the specimens. This is as would be expected from Timoshenko's analysis [8] of the elastic stress within a solid bar. The state of residual stress in the nitrided specimens may therefore be summarized as follows: the case is in a state of high biaxial stress (in the tangential and axial directions, the radial stress being insignificant); this is balanced by tensile stresses in the core. The state of stress in the core is seen to be triaxial, and its magnitude will of course depend upon the cross-sectional area of the core, i.e. the case depth. For a given specimen size, the core cross-sectional area will decrease with increasing case depth, so that the tensile stress levels will increase. For a given case depth, these stresses would increase as the specimen diameter decreases.

S - N Curves and Fracture Modes

The results obtained are shown in Figure 3. These curves were obtained from tests using between 18 and 42 specimens for each condition of nitriding time. It is seen that significant improvements in the fatigue properties under direct stressing may be obtained in comparison with un-nitrided (i.e. 'plain') specimens, in contrast to the reports in the literature.

Let us consider in turn the curves in Figure 3 in order of increasing nitriding time. A comparison of curves D and E shows that a 0.5 hr. nitriding treatment has negligible effect on fatigue life at high stresses but a small improvement in properties is apparent at stresses close to the fatigue limit. The fracture modes observed in the specimens of curve D were in accordance with previous reports in the literature, namely under stresses leading to short lives cracking of the case took place early in the test leading to the propagation of a fatigue crack from the surface. At stresses corresponding to long lives fracture was observed to occur by the nucleation of a crack within the core of the test-piece. Figure 4 illustrates this effect (in a specimen from curve C of Figure 3): a non-metallic inclusion in the core has acted as a nucleation site for the fatigue crack. This effect has been reported in rotating bending fatigue of nitrided specimens by Wellinger and Gimmel [9]. The increase in fatigue limit under these conditions is normally accounted for in terms of the suppression of surface fatigue crack nuclei by the presence of residual compressive stresses in this region arising from the nitriding treatment.

Curve C, obtained from specimens nitrided for 1 hr show a considerable improvement in properties in comparison with those treated for 0.5 hr (curve D). From Table 1 it is clear that magnitude of the surface compressive stresses is significantly higher in specimens C than D, so that the maximum tensile stress experienced by the surface layer during fatigue testing will be smaller than in D, and hence the fatigue limit is effectively raised in this material. At the same time, a 1-hour nitriding treatment still gives a relatively shallow case depth (Figure 1) and thus a relatively large core diameter. The residual tensile stress in the core are therefore not increased over the values observed in specimens D to give rise to deleterious effects.

The two hours nitriding treatment (curve B) is seen, however, to have a much smaller effect on the fatigue limit of the material than the one-hour treatment (curve C), when comparison is made in Figure 3 with E, the un-nitrided material. Furthermore, as the applied fatigue stress rises it is seen that lives *shorter* than those encountered in plain specimens are observed. This effect is considered to arise in the following way: although high compressive surface stresses are developed on nitriding (Table 1) for 2 hr, the increased case depth associated with this treatment (Figure 1) leads to a smaller core diameter and thus to an increased core stress (Table 1) which corresponds, as already discussed, to a state of triaxial tension.

These relatively high tensile stresses can, when superposed on the applied stress lead to the promotion of fatigue crack nucleation at non-metallic inclusions present in the specimens. Relatively prolific nucleation of cracks within the core of the specimen were metallographically observed throughout the gauge length of the specimens. At final failure of the test-piece these interlink to produce a characteristic 'moonscape' type of fracture surface, as seen in Figure 5.

Finally, after a 24-hour nitriding treatment, these thicker cased specimens showed an S - N curve (A) exhibiting three regions corresponding to differing failure modes. At stresses near the fatigue limit, failure was by subsurface crack nucleation. A fatigue limit lower than that in series C was observed since the 24-hour heat-treatment gives rise to higher core stresses (Table 1), because of the smaller core diameter. At very short lives (up to 10^3 cycles), case cracking appeared to dominate the fracture process, and Figure 6 illustrates the type of fracture surface obtained, which clearly involves the propagation of the surface-nucleated crack. Finally, at intermediate stresses, the fracture process observed appeared to undergo a transition between the two extreme processes discussed and this is seen to be associated with an inflection in the S - N curve itself, an effect which was not detectable when the thinner cases were tested. A similar effect has been reported in a carburized steel by Landgraf and Richman [10].

CONCLUSIONS

1) It is seen that nitriding always gives rise to an increase in the fatigue limit in push-pull of an EN41B steel.
2) With increasing fatigue stress, the relative magnitudes of the *case depth* and the *core diameter* appear to influence the mode of failure.
3) Under conditions of moderately high applied fatigue stresses in the presence of high triaxial tensile core stresses, multiple subsurface fatigue crack nucleation takes place which may (e.g. curve B) lead to a decrease in fatigue life in comparison with plain specimens. The non-metallic inclusions in the steel clearly play a vital role in this process and a high sensitivity to the cleanliness of the steel is expected under these circumstances.
4) At very high fatigue stresses, nitride case cracking occurs. This leads to a reduction in fatigue life due to the propagation of fatigue cracks into the core from these surface cracks.

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Table 1 Residual Stress Distributions

Nitriding Time (hr)	Specimen Series	Stresses in MPa					
		Axial		Tangential		Radial	
		σ_c	σ_s	σ_c	σ_s	σ_c	σ_s
24	A	200	-1000	100	-1100	90	0
2	B	150	-1000	70	-950	50	0
1	C	80	-600	30	-680	30	0
0.5	D	40	-220	20	-250	25	0

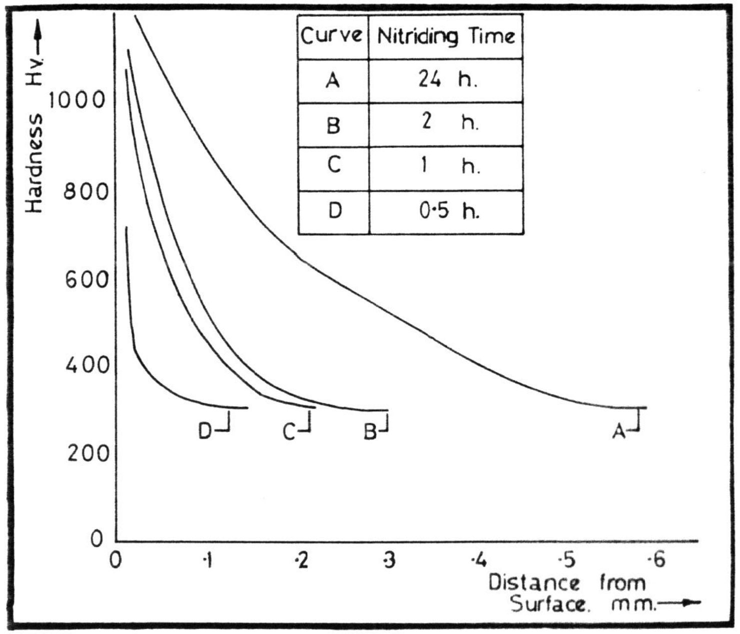

Figure 1 Microhardness traverses on specimens subject to nitriding at 520°C for the stated times, to illustrate the case depths obtained

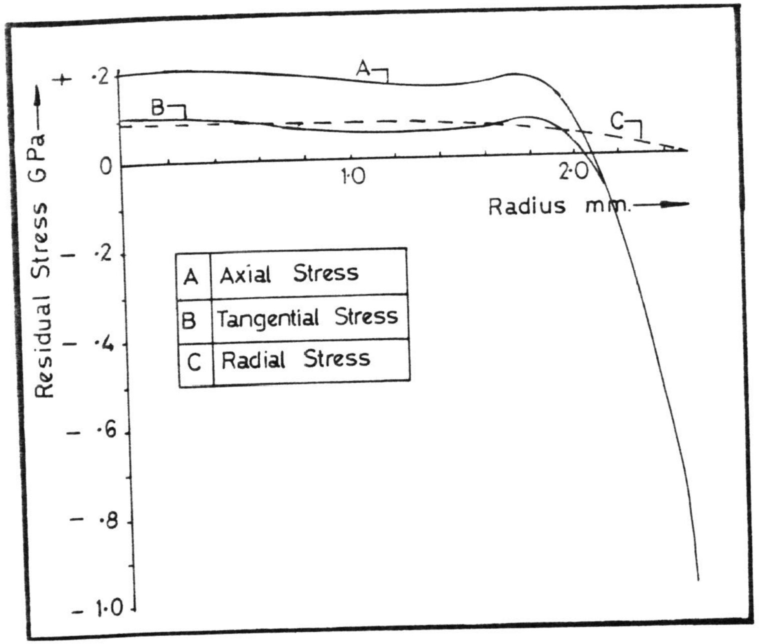

Figure 2 Residual stress distribution in test-piece nitrided 24 hr at 520°C

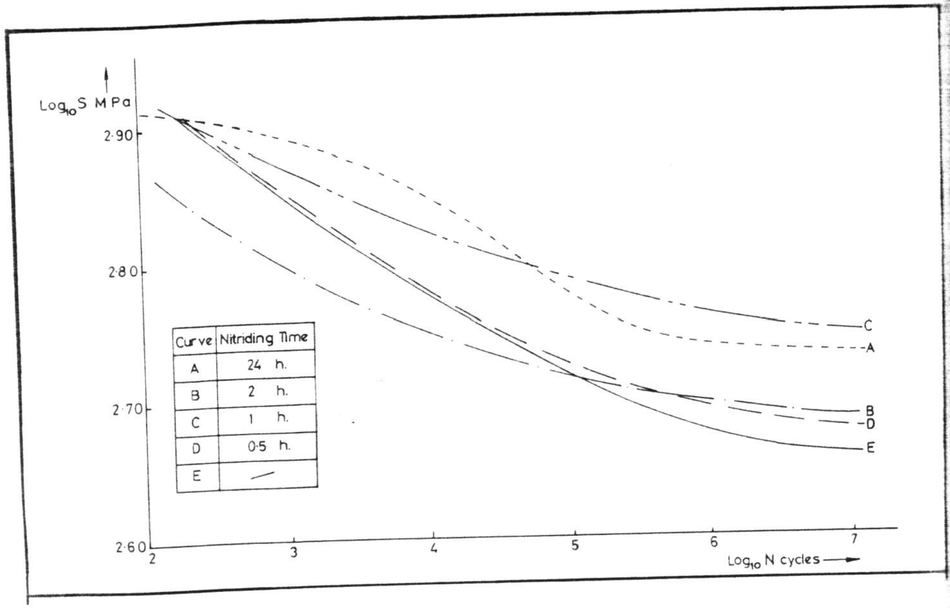

Figure 3 Log. S - N curves for nitrided specimens (A - D) and plain specimens (E)

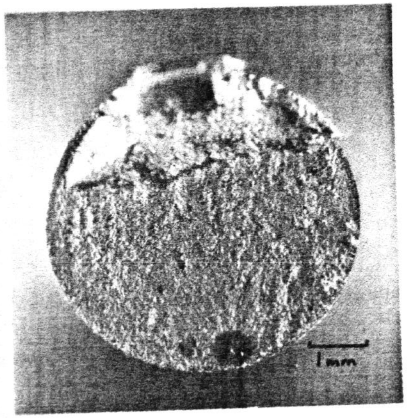

Figure 4 Specimen nitrided 1 hr, fractured after 318104 cycles at 589 MPa

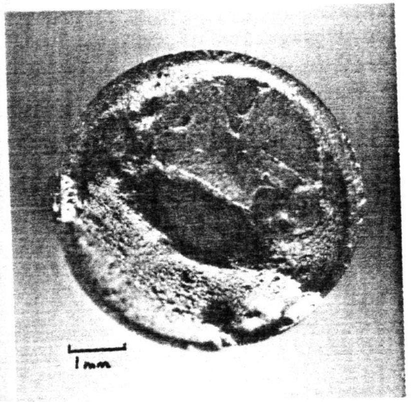

Figure 5 Specimen nitrided 2 hr, fractured after 32685 cycles at 544 MPa

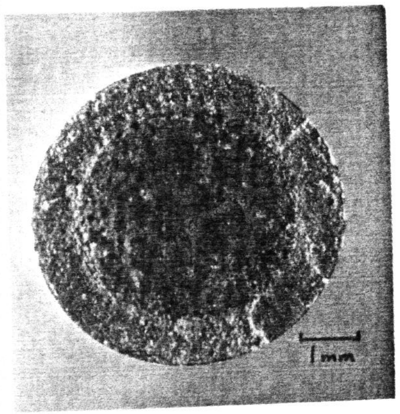

Figure 6 Specimen nitrided 24 hr, fractured after 120 cycles at 815 MPa