LOAD FREQUENCY DEPENDENCE IN FATIGUE LIFE OF NITRIDED STEEL EVALUATED BY FATIGUE TESTS AND INTERNAL FRICTION MEASUREMENTS

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ABSTRACT

The fatigue life vs. frequency in nitrided nitriding steel was studied, and also compared with the behavior of the same steel without nitriding. An abnormally short fatigue life at load frequencies, lower than about 5 Hz in nitrided specimens was encountered.

The internal friction was measured for nitrided nitriding steel fatigue tested at load frequencies of 0.1 and 20 Hz. It revealed less concentration of free nitrogen and more damping on the cold work peak for the sample fatigue tested at load frequency of 0.1 Hz, which is lower than the Snoek Frequency.

This effect may be explained by enhanced nitrogen diffusion due to the Snoek effect.

KEYWORDS

Nitrided Steel; internal friction; load frequency dependence; fatigue; Snoek effect; nitrogen; diffusion.

INTRODUCTION

It is well know that fatigue is one of the most common cause of failure of the machine components. Surface hardening treatment is a conventionally accepted method to improve fatigue endurance in such cases.

Nitriding is one of the usual industrial methods used for surface treatment. Although nitriding is generally accepted to improve fatigue endurance (Sutton, 1936; Bardgett, 1943) the load frequency dependence of nitrided steel for fatigue has not been sufficiently studied (Ishizaki, 1980; 1983).

Considering, for instance, the Snoek effect in a b.c.c. iron, the fatigue endurance of nitrided steel can be easily imagined to depend on the load frequency. The author found an abnormal shortening of fatigue life at low load frequencies. This new phenomenon is presented here.

This abnormal shortening of fatigue life is explained by applying the Snoek effect. The internal friction measurements support the theory presented here.

EXPERIMENTAL PROCEDURE

Common comercial nitriding steel SAE 7140,(Nitralloy steel 135 M) with a chemical composition of C(0.37 ± 0.01), Mn(0.43 ± 0.02), S(<0.2), Cr(1.77 ± 0.09), Mn(0.26 ± 0.05) and Al(1.19 ± 0.02) weight percent, was used in the present work.

The fatigue test pieces were of gauge length 16 mm and diameter 2.5 mm (ASTM A370, 1972), and the surface was polished to 500 grit. These samples were nitrided in a conventional gas nitriding chamber using pure anhydrous ammonia. The conditions of nitriding were 510°C, 3.5 hours of treatment and 30% dissociation rate of the ammonia gas.

The typical results of microhardness tests are shown in Fig.1, for two different nitriding batches to verify the nitrided depth. The reproducibility of nitriding was acceptable. The penetration depth was also verified by Auger electron spectroscopy technique (A.E.S.), measuring the intensity of nitrogen peak on spectra taken across the transverse section area. The results of penetration depth and type of precipitates found by A.E.S. were published elsewhere (Corredor, 1981; Ishizaki, 1982). The typical tensile properties of the steel before and after nitriding are shown in Table 1.

TABLE 1 Tensile Properties before and after Nitriding

	Yield Strength MPa	U.T.S. Mpa	Elongation (%)
As annealed 24h at 525°C	922	981	14
Nitrided	1030	1079	8

Fatigue tests were conducted by a closed-loop hydraulic M.T.S. 810, and Instron 1322. The applied load was alternated sinusoidally between tensile and zero load (R=0). The maximun tensile load was chosen to correspond to 90% and 80% of the ultimate tensile stress respectively. The humidity was less than 70%, and the temperature was 21-22°C.

EXPERIMENTAL RESULTS

Fig. 2 illustrates the fatigue life vs. load frequency in the range of 0.01-60 Hz for annealed steel and for nitrided steel at different stress levels. For the annealed steel tested to the maximun stress of 880 MPa (90% of the ultimate tensile stress), a slight but smooth increase of fatigue life can be observed by increasing the load frequency. This is a normal effect of the frequency reported not only in steels, but also in other alloys (Yokobori, 1976; Rudenko, 1878; Kaplun, 1978; Moody, 1980).

For nitrided steel, moreover, the fatigue behavior is greatly dependent up-

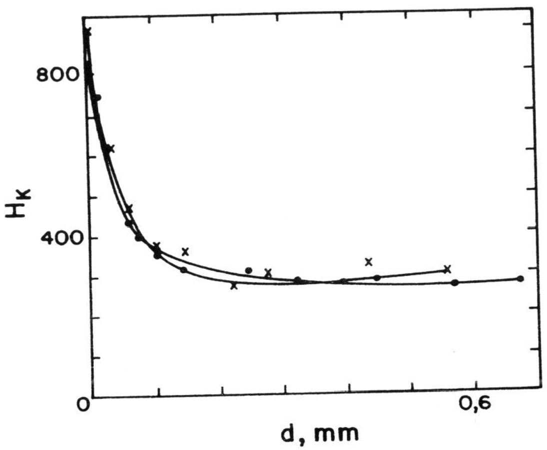

Fig. 1. Knoop microhardness (0.1 kg), Hk vs. penetration depth, d: for two different nitriding batches.

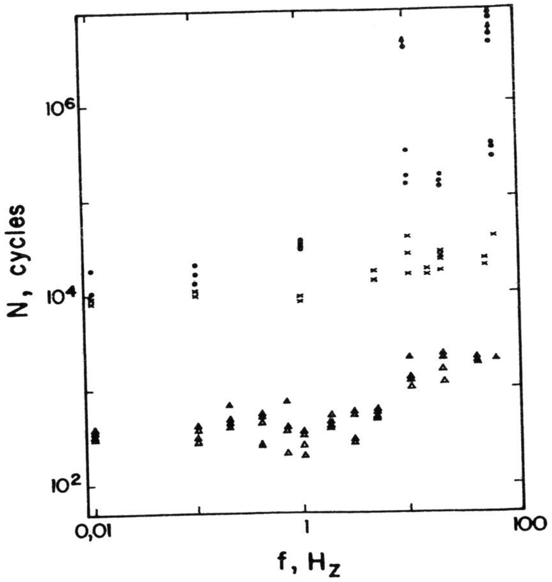

Fig. 2. Fatigue life, N vs load frequency, f.
Annealed steel, 880 MPa (×),
Nitrided steel, 865 MPa (●),
Nitrided steel, 970 MPa (▵),
and unbroken samples (↕).

on the load frequency, as can be observed in Fig.2, for the two stress levels of 970 MPa and 865 MPa corresponding to 90% and 80% of the ultimate tensile strength, respectively. In all cases the stress applied was below the yield point of each steel. Fatigue lives are abnormally short at a load frequency of less than 5 Hz, and the difference of the fatigue life is about two and one orders of magnitude for the stress of 865 MPa and 970 MPa, respectively. At the frequencies of 0.01 and 0.1 Hz, the fatigue lives of nitrided steel for the maximun stress of 865 MPa are of the same order as those for annealed steel for the stress 880 MPa. Although the stress levels are slightly different, this implies that the nitriding treatment does not improve the fatigue behaviour at low frequencies for the stress levels investigated. At higher frequencies, however, the increase of fatigue life due to nitriding is evident.

An internal friction study was also made (Pink, 1983) for a similar steel (DIN 34CrAlMo5) after being fatigue tested for 10.000 cycles at load frequencies 0.1 Hz and 20 Hz. The maximun stress was 80% of the ultimate tensile stress, and fatigue tests were done between tensile and zero load (R=0). Fig.3 shows the results of this study. The nitrogen Snoek peak for load frequency of 0.1 Hz exhibits lower damping than that of 20 Hz. The cold work peak, on the other hand, demonstrates higher damping for the specimen of 0.1 Hz than 20 Hz. This implies that at low load frequencies samples hardened more effectively than at high load frequencies. One also has to note the shift of the nitrogen Snoek peak to higher temperature due to the solute elements such as aluminium and chromiunm.

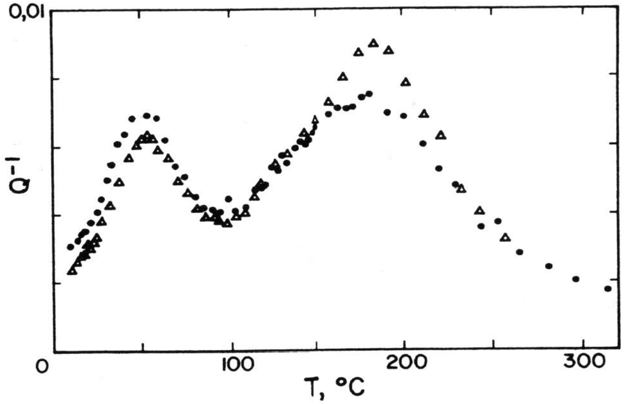

Fig. 3. Damping, Q^{-1} vs. temperature, T: for nitrided steel fatigued to 10,000 cycles (R=0) at 0.1 Hz (△) and 20 Hz (●).

DISCUSSION

The nitrided case contains nitrogen as precipitates, as well as in solid solution whose concentration is close to that of saturation. The solubility limit of nitrogen in alpha-iron is about 0.1% (Agren, 1979), which implies about 10^{26} nitrogen atoms in solution per 1 m^3 of steel at this concentration. The number of possible trap sites of dislocations for the solute nitrogen atoms is estimated for a dislocation density of 10^{10} m^{-2} ($10^{6} cm^{-2}$, annealed) to $10^{15} m^{-2}$ (10^{11} cm^{-2}, cold-worked) as follows: it is important to consider that the stress field created by nitrogen is not hydrostatic which is clearly understood if we consider that the stress field of the Snoek effect is not isotropic. Therefore, solute nitrogen atoms lock not only edge dislocations but also screw dislocations (Wriedt, 1965; Shoeck, 1964; Cochardt, 1955). Dividing the dislocation length by the magnitude of the Burgers vector, the number of trap sites using the mechanism of dislocation core atmosphere is 10^{20} - 10^{25} m^{-3} (10^{14} - 10^{19} cm^{-3}), which coincides with an experimental value of just under 10^{20} m^{-3} for annealed iron and a little over 10^{23} m^{-3} for heavily deformed iron trapping hydrogen atoms (Kumick, 1980). Even if we consider the trap sites by dislocation elastic field (Cottrell atmosphere), the number of trap sites will be an order of magnitude higher than that for dislocation core (Hirth, 1980). Petarra and Beshers (1967) estimated nitrogen trap sites for iron by internal friction measurements, and concluded 4.75 nitrogen atoms per atomic length of dislocation. Therefore the maximun possible trap sites are 10^{21} - 10^{26} m^{-3}. Hence there are always enough solute nitrogen atoms in the nitrided case to interact with dislocations.

On the other hand, the application of an unidirectional stress to b.c.c. metals favours the occupation by interstitial atoms of those octahedral sites for which the distortion coincided with the overall strain. This phenomenon is the Snoek effect, and is particularly strong for carbon and nitrogen interstitial solid solution atoms in alpha-iron. The frequency at which interstitial nitrogen atoms jump in alpha-iron at ambient temperature (hereafter referred to as the Snoek frequency) has been reported by various investigators. Among them Polder (1945), Nowick, Fast and Verrijp (1959), Evans and Douthwaite (1973) reported 3 Hz; moreover, Rosinger (1975), Powers and Doyle (1959), Smallman (1963) and Schoeck (1963) reported the frequency of ∿1 Hz.

Any cyclic load at a frequency lower than the Snoek frequency, forces solute nitrogen atoms to jump. In the case of normal Snoek effect, the nitrogen atoms jump back to the original position with the next cycle of the load. But if there is a concentration gradient of nitrogen or a chemical potential gradient due to a stress field of defects, the nitrogen atoms jump forward to result in an effective diffusion. On the other hand an applied load with higher frequency has practically no effect on nitrogen atoms. Hence each cycle of load at frequencies below the Snoek frequency has more permanent effects on the nitrided steel than at frequencies above the Snoek frequency.

The results of internal friction measurements also indicate the same phenomenon at the high load frequency of 20 Hz; more free nitrogen and less damping on the cold work peak were observed. On the other hand, at the low frequency of 0.1 Hz, the opposite phenomenon was observed. Hence the discontinuous change of the fatigue endurance is expected between the fatigue life at frequencies above the Snoek frequency and frequencies below the Snoek frequency.

A low frequency cycle load may cause an enhanced diffusion on nitrogen atoms to form a dislocation cell structure faster than a high frequency cyclic load. This enhanced diffusion of nitrogen atoms results in the abnormal lower fatigue life at a lower frequency load than the Snoek frequency.

CONCLUSIONS

Nitrided steel was fatigue tested (R=0) at different frequencies between 0.01 and 60 Hz, and examined by internal friction after fatigue testing at frequencies 0.1 and 20 Hz. One may conclude the following:

1. At frequencies lower than about 5 Hz, the fatigue life of nitrided steel

is greatly decreased with respect to fatigue life at frequencies higher than 5 Hz.

2. The shortened fatigue life at low frequencies may be due to enhanced nitrogen diffusion caused by the Snoek effect.

3. The internal friction measurements reveal lower concentration of free nitrogen and more damping of the cold work peak for the sample fatigue tested at the low load frequency of 0.1 Hz.

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