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An abnormally shortened fatigue life of steels caused by anelasticity*

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Some abnormal fatigue life shortenings dependent upon load frequency for several steels are discussed. A possible relation between anelasticity caused by interstitial atoms and the abnormal fatigue life drop is presented. Normally, interstitial atoms are in a position which minimizes the energy around a dislocation, the Snoek ordering sites. We consider the Snoek effect as a typical example of anelasticity, and the possibility on atoms moving from attractive sites to repulsive ones when repeated stresses are applied and discuss a theory to explain the reduction of the fatigue life using Snoek ordered atoms moving out by fatigue stress at the frequency of Snoek effect. Bending fatigue tests were conducted to obtain the relationship between fatigue life and load frequency at two different temperatures (298 K and 333 K) for an iron nitrided steel. A sharp fatigue life drop was observed at a load frequency corresponding to the resonant frequency of the Snoek effect for nitrogen atoms. The frequency was about 3 Hz and 298 K and shifted to a higher frequency – about 6 Hz – at 333 K. Results reveal that the possible explanation to those abnormal phenomena may be anelasticity.

1. Introduction

An abnormal shortening of the fatigue life depending upon the load frequency has been reported on a few occasions. Some of the cases reported are related to nuclear materials, thus it is very important to study its causes because clarifying this problem may help to eliminate unexpected possible fatal failures.

Chopra and Smith [1] found this abnormal effect for an HT-9 (Fe–12 Cr–1 Mo) steel in liquid lithium with a small amount of nitrogen impurities. Their results indicated that the fatigue life (number of cycles to failure) was a strong function of the nitrogen concentration and of the strain rate (also load frequency). The fatigue life of the steel in liquid lithium with 1000 to 1500 p.p.m. of nitrogen was 2 to 10 times lower than that in liquid lithium with 100 to 200 p.p.m. of nitrogen. When the nitrogen concentration was low, the fatigue life became almost independent of the strain rate in the range of their experiment, i.e. 4×10^{-2} to $4 \times 10^{-4}\,\mathrm{sec}^{-1}$. When the nitrogen concentration was higher, however, the fatigue life shortened sharply more than twice as the strain rate lowered. Similar effects were found for 304 and 316 stainless steels with carbon impurities in liquid sodium. The carbon concentration did not affect significantly such static properties as creep or tensile behaviour, but it influenced the fatigue life [1, 2]. The authors believe that these phenomena must not depend upon a static reaction such as corrosion, but upon a dynamic effect during the fatigue experiment such as anelasticity, otherwise it is not easy to explain the strong strain rate dependence (or load frequency dependence) of the fatigue life.

Another similar effect was observed for a stainless steel type 316 with helium by Sonnenberg and coworkers [3, 4]. When the steel contained a small amount of ion bombarded helium, these authors found a sharp decrease of the fatigue life of about two orders of magnitude at load frequencies lower than 3 Hz. This abnormal shortening of the fatigue life was not found for those specimens without helium.

They considered that the cause of this abnormal effect was the transition from intergranular to grain boundary fracture proposed by Trinkaus [5], who found a theoretical transition frequency of the fracture mode. The proposed transition depended on the stress as well as on the frequency. Taking into consideration that their experiments were conducted by bending fatigue tests with thin sheets of 100 μm, which implied a big variation of stress across the specimens, the theory fails to explain such a sharp transition of the fatigue life depending, not on the stress, but on the load frequency. The experiments also showed that the phenomenon was observed only for the specimens irradiated by alpha rays during the fatigue tests, and not in the specimens containing helium but not irradiated by alpha particles. This implies again that this abnormal phenomenon is due to a dynamic effect.

Years ago, a similar abnormal load frequency

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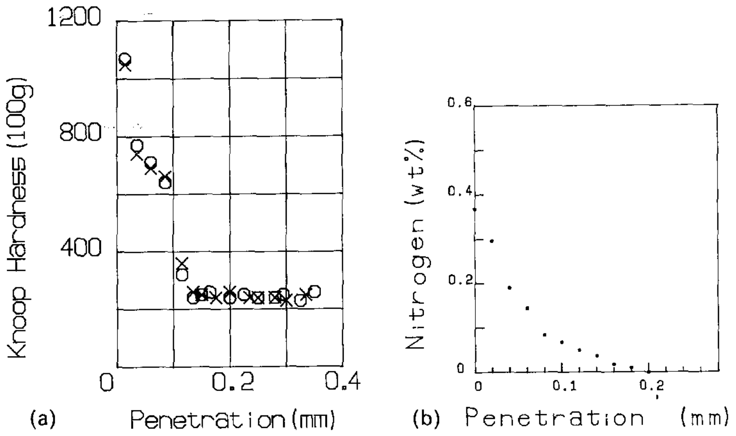

Figure 1 (a) Knoop microhardness plotted against penetration depth for two different nitriding batches. The nitriding condition was reasonably reproducible. (b) Nitrogen concentration on the transverse section of the specimen analysed by AES after calibration by 0.03%N–Fe alloy.

dependence of the fatigue life for a nitrided steel was reported [6–8]. The fatigue life decreased by one or two orders of magnitude around the frequency of the Snoek effect – about 1 to 3 Hz at room temperature. The non-nitrided steel did not exhibit this abnormal effect. This indicated the possible influence of a Snoek jump on the fatigue life. The present work was conducted in order to obtain further experimental evidence showing that anelasticity can cause an abnormal shortening of the fatigue life of a material.

2. Experimental procedure

A common commercial nitriding steel (DIN30CrMoV) with a chemical composition of C(0.313), Cr(2.54), Mo(0.429), Al(0.012), Mn(0.701), Si(0.39) and V(0.134) weight percent was used in this work. The fatigue test pieces were sheets of 2.7 mm thickness bending samples, which were annealed at 1123 K for more than 16 min and then furnace cooled. They were ion nitrided in a 1 : 1 gas mixture of hydrogen and nitrogen at a pressure of 788 Pa and a surface temperature of 783 K.

The typical results of the microhardness tests are shown in Fig. 1a, for two different nitriding batches to verify the penetration depth. The reproducibility of nitriding was acceptable.

The treatment depth was also verified by Auger electron spectroscopy (AES), by measuring the intensity of the nitrogen peaks on the spectra taken across the transverse section area. Results for a similar case of gas nitriding were published elsewhere [9]. The nitrogen concentration was calibrated by the intensities I_N/I_{Fe} for a specimen of a 0.03%N–Fe alloy, this value is linearly extrapolated. The corresponding profile concentration of nitrogen across the specimens is shown in Fig. 1b for the present case. Furthermore, typical tensile properties of the steel before and after nitriding are shown in Table I.

Fatigue tests were conducted using a bending fatigue machine. The applied load was altered sinusoidally ($R = -1$) from 0.5 to 15 Hz. The maximum stress was about 400 MPa. The humidity was less than 50% at 298 K, and a dry nitrogen atmosphere was used at 333 K.

3. Experimental results

For normal cases, such as annealed steel without a nitriding treatment, a slight but smooth increase of the fatigue life (number of cycles to failure) may be expected by increasing the load frequency [6–8]. This is a normal effect of the load frequency reported not only in steels, but also in other metals and alloys [10–13].

For a nitrided steel, moreover, the fatigue behaviour is greatly dependent upon the load frequency, as can be observed in Fig. 2, which shows the fatigue life plotted against load frequency in the range of 0.5 to 15 Hz for a nitrided steel at different temperatures. One can observe an inverse effect, i.e. a decreasing function of the fatigue life with respect to the load frequency between 0.6 and 3 Hz at the temperature of 298 K (Fig. 2a), with a sharp minimum life at around 3 Hz. On the other hand, the minimum shifted to a load frequency between 4 and 8 Hz at 333 K (Fig. 2b) [14].

4. Discussion

An application of stress to body-centred cubic metals favours the occupation by interstitial atoms of those octahedral sites for which the distortion coincided with the overall strain. When a stress in the opposite direction applies the interstitial atoms jump back to their original sites. This phenomenon is called the Snoek effect. The reasonant frequency at which interstitial nitrogen atoms jump in alpha-iron (hereafter referred to as the Snoek frequency) has been reported by various investigators at room temperature. Nowick, Fast and Verrijp [15], and Evans and Douthwaite [16] reported 3 Hz; moreover, Rosinger [17], Powders and Doyle [18], and Schoeck [19] reported a frequency of ~ 1 Hz.

Interstitial atoms may be located at the lowest energy sites around a dislocation stress field [20]. This is sometimes called Snoek ordering. The attractive force on dislocations generated by the Snoek ordering

TABLE I Tensile properties before and after nitriding

	Yield strength (MPa)	Ultime tensile strength (MPa)	Elongation (%)	Hardness RC
As-annealed	270	470	40	12
Nitrided	380	510	25	19

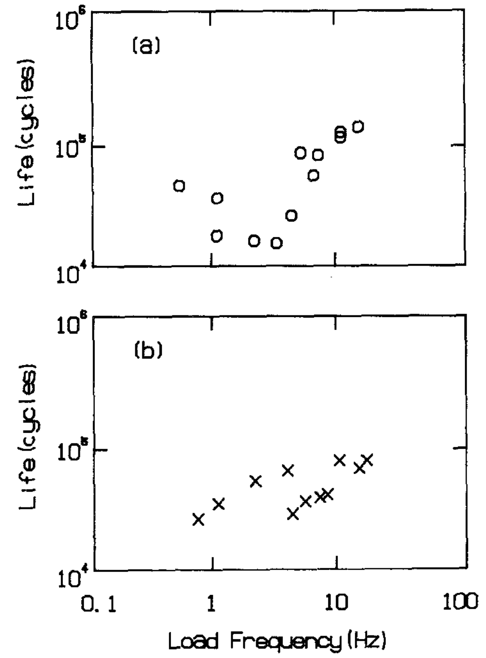

Figure 2 Fatigue life plotted against load frequency at (a) 298 K and (b) 333 K. The sharp drops of fatigue life are an order of magnitude around 3 Hz and a factor of two or three around 6 Hz for (a) and (b) respectively.

is one of the mechanisms of hardening. This also explains the hardening mechanisms by screw dislocation by interstitial atoms which exhibit, mainly, hydrostatic stresses around them.

If an alternative force of Snoek frequency is applied to a bcc metal which is hardened by interstitial atoms in Snoek ordering sites, the resonant frequency of the applied stress may remove those interstitial atoms from Snoek ordering sites to the adjacent octahedral positions. The new sites may not have an attractive force on dislocations but a repulsive force. This transition is quite possible between two adjacent octahedral positions as indicated by Williamson *et al.* [21]. This implies the dislocations are ready to move, i.e. softening occurs. This results in an abnormal weakening of the metal.

That N atoms jump to other sites means that the forces between N atoms and dislocations change from attractive to repulsive and that the dislocations locked by N atoms extend at the same time. This is repeated and the dislocations run from the high to the low N concentration side. Therefore fatigue life drops at the Snoek point. On the other hand, an applied load with higher frequency has practically no effect on the nitrogen atoms. The nitrogen atoms jump most effectively at the resonant (i.e. Snoek) frequency. The Snoek frequency depends strongly on temperature, and so does the fatigue life.

Previously the relation of internal friction and tensile to zero load ($R = 0$) fatigue tests were discussed elsewhere [8]. The present work shows even sharper effects on the abnormal shortening of the fatigue life. This may be due to the fact that the present work was conducted under bending conditions, and the effects of nitriding on the surface of specimens are stronger than under normal tensile or compression conditions.

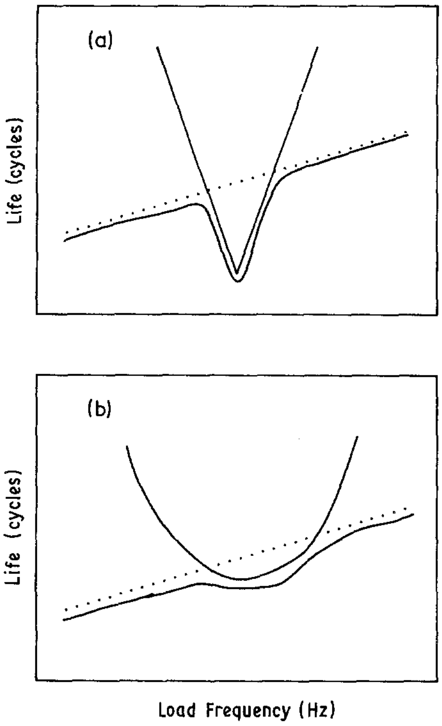

Figure 3 (a) Schematic representation of the effect of load frequency on the fatigue life. The dotted line shows a normal case of smooth change of fatigue life plotted against load frequency. V indicates an abnormal shortened fatigue life around the Snoek frequency. Addition of both of them, gives the solid line. (b) If the abnormal shortening of fatigue life is less sharp, the fatigue life may shortened in U-shape, and the resulting fatigue life looks like a step instead of sharp V as in (a).

If an abnormal shortening of the fatigue life is caused at load frequency around a peak frequency of an internal friction, a schematic graph of fatigue life plotted against load frequency may be drawn as shown in Fig. 3. The dotted line shows the normal case of smooth change of fatigue life plotted against load frequency curve. The V line in Fig. 3a indicates the effect of abnormal shortening around the Shoek frequency. The solid line can be obtained by adding them together. If the abnormal shortening is less sharp, the drop may be represented by U-shape as in Fig. 3b instead of a V-shape.

The experimental conditions may be one of the causes of the difference in the sharpness of the drop. Bending tests have sharper shortening than simple tensile–compression tests, because bending tests have a higher stress concentration on the sample surface.

Alloying elements may be another reason why there is a difference of sharpness of the fatigue life drop. Nitriding steels may have chromium, aluminium, vanadium, manganese and so on as alloying elements in order to enhance the hardening effect or to reduce the nitriding time. These elements have a tendency to broaden or shift the Snoek peak. For example, iron alone has a nitrogen Snoek peak at 295 K and at 1 Hz. When aluminium is added to iron, a second peak appears at 327 K [22]. Iron may have an additional peak at 323 K, 348 K, 360 K and 305 K with chromium, molybdenum, vanadium, and manganese respectively [23]. The second peak can be identified as another peak or just a broadening of the original one by overlapping them, depending upon the concentration of the third element. Hence pure iron must have a sharper Snoek peak than alloyed steels. There is a possibility of observing a sharp V-shaped drop of the fatigue life, even if a tensile–compression fatigue test is conducted for nitrided pure iron instead of an alloyed steel.

On the other hand the change of the fatigue life at 333 K is not as sharp as that at 298 K. The drop is an order of magnitude at 298 K. However, the difference is about a factor of two or three at 333 K, as shown in Fig. 2. The sharp drop also changes from a load frequency of 3 Hz to about 6 Hz. This can be explained by lowering the dotted smooth line of Fig. 3a to have a small difference of fatigue life from the V. This lowering of the life is due to a normal effect of higher temperatures. Of course the Snoek frequency also shifted to a higher value at the higher temperature.

5. Conclusions

A series of abnormal shortenings of the fatigue life depending upon the load frequency – probably caused by interstitial atoms – can be explained by the anelasticity of materials due to interstitial atoms, which may also pertain to an internal friction peak. Ion-nitrided steel exhibited a very sharp drop of the fatigue life around 3 Hz at room temperature. The results suggest a relation between an abnormal fatigue life and the Snoek effect.

Taking into consideration alpha particles, carbon as well as nitrogen in liquid lithium or sodium, the abnormal fatigue phenomena discussed here are very important for nuclear materials.

The anelastic mechanism proposed here forecasts unexpected accidents of nuclear materials and the results also imply that those interstitial impurities have less effect on creep.

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