SURFACE CRACKING OF QUENCHED AND TEMPERED STEEL BY SHEAR INSTABILITY, EFFECT ON FATIGUE CRACK INITIATION

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Shear instability cracking in AISI 4340 steel has been studied. A test bar with hole and pin has been used to create a multiaxial stress state resembling that of a lug and pin joint. Fatigue testing has been carried out to study the effect of shear instability cracking on fatigue initiation.

BACKGROUND AND EARLY WORK

A serious helicopter accident in the North Sea was found to be caused by fatigue failure of a main rotor spindle lug, leading to the loss of a blade.

The spindle material was AISI 4340 steel quenched and tempered to a hardness of 380 HV.

During a subsequent metallurgical investigation, (Wold and Nøkleby (1)) it was observed that the fatigue fracture had started from a local area in the lug about 10 mm long, containing several small fatigue cracks. Later a similar crack pattern was found in four unbroken spindles from two other aircraft. In all cases the fatigue cracks were observed after relatively short accumulated flying times.

The spindle material is of a type which may be prone to surface cracking by plastic shear instability (Tanaka and Spretnak (2), Chakrabarti and Spretnak (3)). This is a phenomenon which can occur in steels which exhibit a low strain hardening coefficient. In such materials, where the uniaxial stress-strain curve approaches that of an ideal elastic-plastic material, flow can be localized in narrow bands along directions of pure shear strain. Due to insufficient strain hardening, flow is not transmitted to the adjacent material and cracks can form by a ductile type failure in the narrow bands, at low magnitudes of nominal strain. Shear instability has been treated by several investigators, notably Spretnak and co-workers (3),(4),(5).

It was considered possible that the premature fatigue initiation, and the unusually high number of fatigue cracks in a small area, might have been

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prompted by peak stresses known to have occurred occasionally, through the formation of shear instability microcracks.

In the present work the behaviour of AISI 4340 steel during deformation, and also the effect of shear instability cracks on fatigue initiation, have been studied.

DEFORMATION EXPERIMENTS WITH A MULTIAXIAL STATE OF STRESS

The chemical composition and mechanical properties of the material used for these experiments are given in Tables 1 and 2.

TABLE 1 - Chemical composition of forged bar material.

% C	% Si	% Mn	% P	% S	% Ni	% Cr	% Mo
0.43	0.21	0.82	0.003	0.005	1.77	0.87	0.25

TABLE 2 - Mechanical properties of forged bar material.

Yield strength 0.2 % offset N/mm^2	UTS N/mm^2	Elongation (5xd) %	Reduction of area %	Vickers hardness HV10
1124	1193	13.6	57	376

Both regarding chemical composition and mechanical properties this material is closely similar to the spindle material.

Initial experiments with three-point bending did not produce microcracks by shear instability.

In the area of the spindle lugs where cracks have repeatedly been observed, however, the stress state is multiaxial, due to the contact stresses between the pin and the lug, which come in addition to the tension in the lug. It was therefore considered that the state of stress could be an essential variable in the initial formation of microcracks and some experiments were carried out to check this possibility.

To this end a special kind of tensile test specimen was devised. This test bar was made from forged 25 mmØ round bars of AISI 4340 aircraft quality and is shown in Fig. 1. The test bar has a square portion which contains a cylindrical hole into which a hardened steel pin was shrink fitted. As an axial tensile load is applied to the test bar the hole will tend to become oval and the contact stresses against the surface of the pin will increase as the load on the test bar increases, thus creating a multiaxial state of stress resembling that of a lug and pin joint.

The first of these test bars was pulled to a permanent nominal strain of 0.8 % measured on a 40 mm gauge length. The deformation in the local regions of minimum cross section is of course higher but is difficult to define since it will depend on the degree of localisation of the measurements. Throughout this paper the strain values for this particular test bar refer to a fixed arbitrary gauge length of 40 mm.

After deloading the test bar was split in two so that the areas of maximum contact stresses (3 and 9 o'clock positions in the hole) were made accessible for examination in a scanning electron microscope (SEM).

In the SEM it was immediately observed that in a zone corresponding to 10-15° of arc symmetric about the 3 and 9 o'clock positions, and there only, the straining had produced a considerable number of microcracks in the surface. The cracks are generally parallel to the axis of the cylindric hole. These microcracks are shear instability cracks. An example is shown in Fig. 2.

Further testing with the same type of test bar showed that the pattern of observations described above is quite reproducible in this material. The number and depth of shear instability cracks were found to be strongly dependent on the amount of strain. A critical strain of about 0.4 % was necessary for these cracks to form. At a nominal strain of 0.6 % the cracks were found by metallography to be about 25 μm deep.

An experiment has also been done to study the effect of altering the strain hardening exponent on the tendency to shear instability cracking. For the forged bar material used for the above experiment a strain hardening exponent of $n = 0.030$ was measured. After annealing this material for 90 min. at 660 °C the UTS dropped to 900 N/mm² and the hardness to 285 HV. At the same time the strain hardening exponent was increased to 0.044. This heat treated material showed no tendency to shear instability cracking when strained 0.7 % using the test bar with hole and pin.

FATIGUE TESTING

A limited amount of fatigue testing has been carried out to investigate effects of shear instability cracks on fatigue initiation, and, in particular, to see if this effect could lead to initiation of numerous fatigue cracks in a local area.

All fatigue testing has been done with test bars of the type shown in Fig. 1 and at a mean stress of 245 N/mm².

The first set of test bars was run without prestrain using constant amplitude loading and R-values in the range 0.1-0.3. The results are presented by the curve in Fig. 3.

The fracture surfaces were examined in a SEM and it was found that in all cases fatigue initiation had taken place in local fretting attacks. An example is shown in Fig. 4. The number of initiation points in this series did not exceed three. The fatigue limit at $20 \cdot 10^6$ cycles was found to be close to a stress amplitude, σ_a, of 120 N/mm².

In the following series two test bars (points A and B in Fig. 3) were given nominal prestrains of 0.3 and 0.6 %, respectively, and then fatigue tested at $\sigma_a = 122$ N/mm². 0.3 % strain is too low to cause shear instability cracking in the present test bar, while 0.6 % is known to exceed the critical value so that shear instability cracks are present. This was later confirmed by SEM work. Both of these test bars, however, survived without developing fatigue cracks in the region of the hole.

In the third series test bars were prestrained varying amounts and fatigued by what is mainly constant amplitude loading but including one stop-restart cycle, going down to zero load each 10^4 cycles. This type of loading in principle corresponds to a "ground-air-ground" (GAG) cycle of an aircraft, the one cycle going down to zero load corresponding to a landing.

In this series the following observations were made:

- Two test bars with subcritical prestrain (no shear instability cracks present) did not develop fatigue cracks in the region of the hole. They failed, however, by fatigue cracks in the threaded ends of the test bars (points E and F in Fig. 3).

- Two test bars (points C and D in Fig. 3) where the prestraining had caused formation of shear instability cracks exhibited fatigue lives below $0.3 \cdot 10^6$cycles (30 GAG cycles).

- In the latter specimens multiple fatigue crack initiation had taken place, and always in connection with shear instability microcracks. This is illustrated in Figs. 5 and 6 which show a typical part of the initiation area in the 3 o'clock region of the hole in test bar D.

SUMMARY AND DISCUSSION

Experiments with deformation of 4340 steel have demonstrated that this material under certain conditions of moderate macroscopic plastic deformation, may develop surface microcracks by plastic shear instability. Whether or not such cracking will occur is mainly dependent on the following variables:

- The strain hardening exponent of the material
- The stress state during deformation
- The amount of deformation.

The interplay between these variables is complicated and makes it difficult to predict on beforehand whether or not shear instability cracks will occur under a certain set of conditions.

From the point of view of avoiding this cracking phenomenon it appears that controlling the strain hardening exponent of the material is the easiest. Under the conditions of the present experiments it was shown that increasing the strain hardening exponent from a value of 0.030 to 0.044 removed the tendency to shear instability cracking.

The effect of shear instability cracks on fatigue initiation depends on the loading spectrum during fatigueing. In the present experiments shear instability microcracks were non-propagating in the constant amplitude testing. This is most likely due to the presence of a residual compressive stress field created by the prestraining cycle.

When a stop-restart cycle (GAG cycle spectrum) was introduced rapid multiple fatigue initiation took place from shear instability cracks, leading to a substantial reduction of fatigue life.

The effect of the stop-restart cycle is presumably to provide stress amplitudes sufficiently high for the shear instability microcracks to break through the layer of compressive stresses, whereafter propagation is taken over by the large number of smaller load cycles.

In connection with the fatigue cracking of spindle lugs the above results seem to be able to explain most of the observations, in particular the premature initiation and the presence of many fatigue cracks in a local area.

REFERENCES

1. Wold,G, and Nøkleby,J.O., 1980, "Conditions for formation of surface cracks in a quenched and tempered steel. Effect of shot peening and state of stress". VERITAS Report No 80-1027.

2. Tanaka,K., and Spretnak,J.W., 1973, "Analysis of plastic instability in pure shear in high strength AISI 4340 steel". Met.Trans., vol 4, pp 443-454.

3. Chakrabarti,A.K., and Spretnak,J.W., 1975, "Instability of plastic flow in the directions of pure shear. II Experimental". Met.Trans. A, vol 6A pp 737-747.

4. Spretnak,J.W., 1968, "Plastic instability in some ultra-high strength steels". Proc. internat. conf. on strength of materials. Japan Inst. Metals, vol 9, pp 305-311.

5. Russo,V.J., Chakrabarti,A.K., and Spretnak,J.W., 1977, "The role of pure shear strain on the site of crack initiation in notches". Met.Trans.A, vol 8A, pp 729-740.

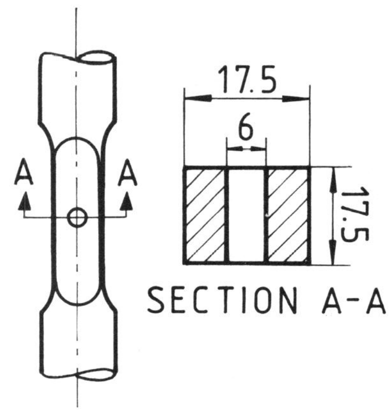

Figure 1 Test bar used for straining and fatigue testing. During testing a hardened pin is shrink fitted into the cylindrical hole.

Figure 2 Shear instability cracks in 3 o'clock position of hole, formed at a nominal strain of 0.8 %.

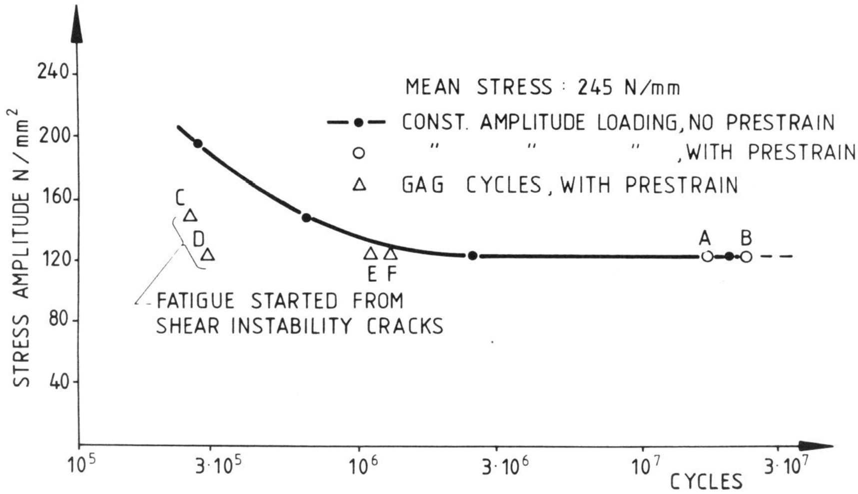

Figure 3 Results of fatigue testing using test bar in Figure 1.

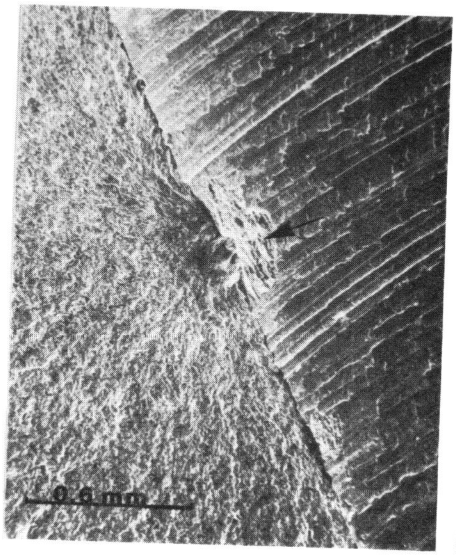

Figure 4 Fatigue initiation from fretting attack (arrowed). No pre-strain.

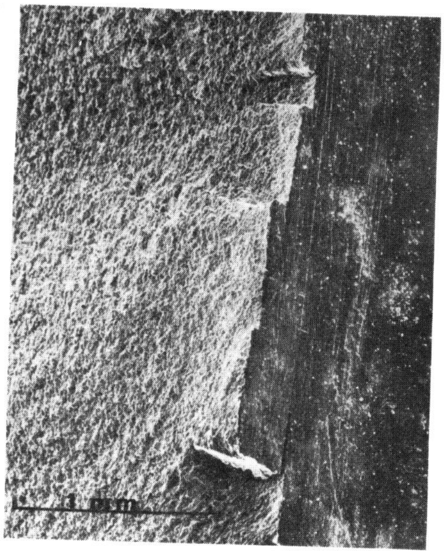

Figure 5 Multiple fatigue initiation from shear instability cracks. 0.6 % prestrain and GAG cycle loading.

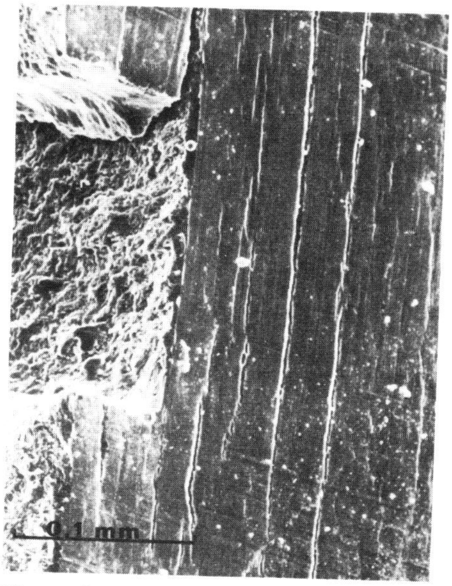

Figure 6 Detail from Figure 5 showing numerous microcracks near fracture.