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EFFECT OF RESIDUAL STRESSES OF SHOT PEENING ON THE FATIGUE BEHAVIOUR OF A HIGH STRENGTH STEEL*

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Abstract—The effects of shot-peening residual stresses on bending fatigue behaviour of welded plate and surface-flawed plate were investigated. The results show that shot peening residual stresses may significantly increase fatigue strength as well as the threshold stress-intensity factor range of a surface-flawed plate. This paper presents a simple analytical method for determining the residual stresses. The calculated values are essentially in agreement with the experimental results.

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INTRODUCTION

Fatigue and stress corrosion failures of metallic materials mostly occur on or near the surface of materials where there are various kinds of defects such as mechanical scratches, welding cracks, forging or casting defects, decarburisation, deficiencies in alloying elements, nonmetallic inclusions, etc., as well as residual stresses caused by cold or hot working. Therefore, improving the surface condition of materials is rather important, especially to products of the aircraft industry.

After shot peening two obvious changes occur on the surface layer: (i) changes in microstructure (subgrain formation, crystal distortion and increasing dislocation density), (ii) compressive residual stresses are induced, both of which could improve the resistance to fatigue and stress corrosion of materials.

It is known that the compressive residual stress within the surface layer can effectively lower the tensile stress level introduced by external loading, so that the life of fatigue nucleation can be raised. However, for materials which have a crack-like surface, the effect of the compressive residual stresses surrounding the tip of the crack is not well knwon [1] and needs to be further clarified.

MATERIALS USED

The testing material is a high strength steel 30CrMnSiNi2A. After heat treatment (isothermo-quench and temper), tensile strength and yield strength are 1660 and 1350 MPa respectively. Specimens are of two kinds: welded plate (Fig. 1a) and precracked plate (Fig. 1b). The maximum bending stress amplitude for preparing the initial surface crack is 1154 MPa at a stress ratio $R = 0{\cdot}1$, and a frequency of 100 Hz. The sizes of the initial surface cracks are in the range $a_0 = 0{\cdot}5$–$0{\cdot}6$ mm, $2C_0 = 1{\cdot}0$–$1{\cdot}2$ mm.

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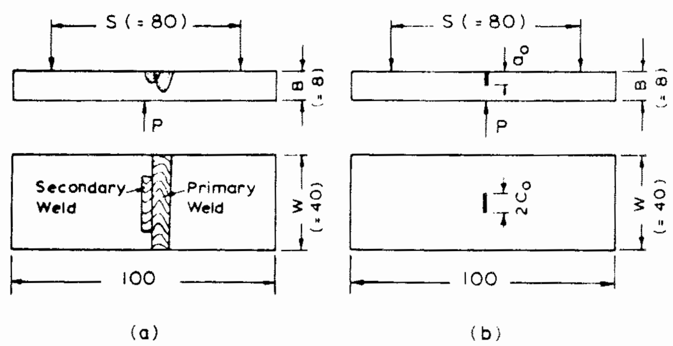

Fig. 1. Three point bending fatigue specimens; all dimensions in mm.

Residual stress distributions in the surface layer are measured by the X-ray diffraction method, and the surface is removed by electropolishing.

ESTIMATION OF THE ENDURANCE LIMIT AND STRESS INTENSITY FACTOR UNDER RESIDUAL STRESS

Estimation of endurance limit

The distribution of residual stresses due to shot peening as well as resultant stresses in the plate are shown in Fig. 2. The surface of the plate has a maximum tensile stress produced by the applied load and a maximum compressive residual stress. But the resultant maximum tensile stress is moved into the subsurface at a distance t from the surface. Under the action of the resultant stress, we suppose that fatigue nucleation is initiated in the subsurface rather than the surface at a distance t [2]. Let the endurance limit of smooth specimens be σ_a, and the endurance limit of specimens having compressive residual stresses by σ_e. As a first order approximation in order to make the stress amplitude at distance t

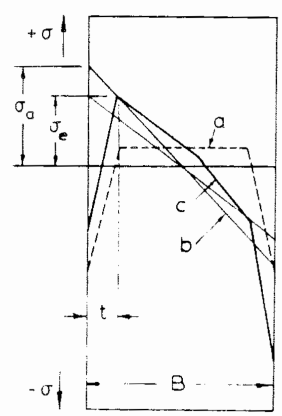

Fig. 2. Schematic distribution of stresses, (a) residual stress, (b) applied alternating bending stress and (c) resultant stresses through the thickness of the plate.

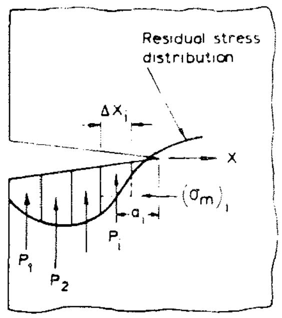

Fig. 3. Schematic of concentrated force distribution at crack surfaces.

reach the required level, the external applied stress amplitude must be raised such that

$$\sigma_a = \frac{B}{B-2t}\,\sigma_e. \tag{1}$$

Thus if the depth of the compressive residual stresses and the endurance limit of smooth specimens are known, the endurance limit of specimens having compressive residual stresses can be calculated from equation (1).

It is important to point out that the residual stresses can be relaxed during fatigue. It has been shown that if the applied alternating stress is near the endurance limit, the relaxation of residual stress is very small [3]. In such cases the relaxation of residual stresses could be neglected when estimating the endurance limit.

Estimation of stress intensity factors due to residual stresses

The residual stress distribution around a crack is shown in Fig. 3. We suppose that these stresses act on the crack surfaces as concentrated forces $P_1, P_2, P_3, \ldots, P_n$. Obviously, each concentrated force is:

$$P_i = (\sigma_m)_i \Delta\chi_i. \tag{2}$$

The meaning of $(\sigma_m)_i$ and $\Delta\chi_i$ are shown in Fig. 3. These concentrated forces are acting at a distance a_i from the crack tip. For the half-infinite plate the stress intensity factor due to a concentrated force is typically given by

$$\frac{2P_i}{\sqrt{\pi a_i}} \quad \text{(negative)}$$

and the stress intensity factor for all concentrated forces is the summation of these terms.

The stress intensity factor of a surface crack in an infinite plate under tensile bending is given by [4]

$$M\,\frac{1{\cdot}1\sigma_B\sqrt{\pi a_0}}{\sqrt{Q}} \quad \text{(positive)}$$

where Q is a surface crack shape parameter, M is the stress intensity magnification factor for a semi-elliptical surface crack, and σ_B is the maximum bending stress on the surface.

According to the linear super-position principle, the effective stress intensity factor is the summation of the above negative and positive terms which illustrates the fact that the stress intensity factor at a crack tip can be reduced by a compressive stress field produced by residual stress, so that the ability to resist crack propagation would be increased.

RESULTS AND DISCUSSION

The residual stress distribution after shot peening is shown in Fig. 4. The depth of compressive residual stress is about 0·6 mm. The change of half peak breadth of the X-ray diffraction plane (310) of shot peened specimens are less than 0·3 mm depth. Hence it may be suggested that after shot peening no appreciable change of microstructure occurs ahead of the crack tip of pre-cracked specimens.

The *S–N* curves of three point bending fatigue are shown in Fig. 5. The endurance limit is increased from 490 to 605 MPa by shot peening. The calculated endurance limit of shot peened specimens according to equation (1) is 577 MPa, which is close to the predicted value.

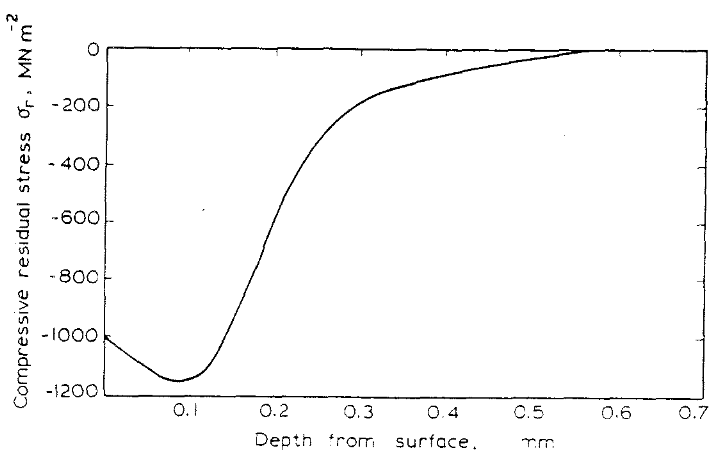

Fig. 4. Residual stress distribution near the surface of a specimen.

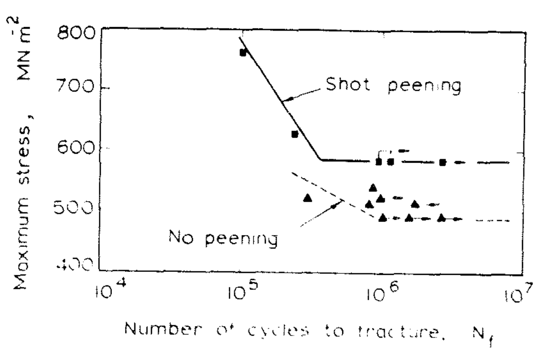

Fig. 5. *S–N* curves for three-point bending fatigue of welding plate (R = 0·1).

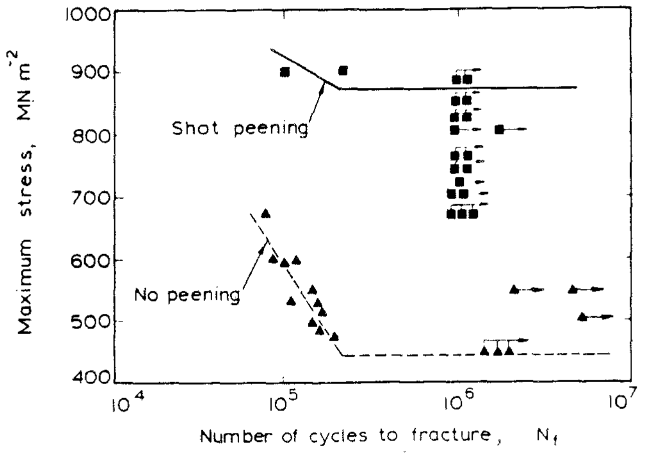

Fig. 6. *S–N* curves for three-point bending fatigue of surface-crack specimen ($R = 0{\cdot}1$).

The *S–N* curves of surface-cracked specimens are shown in Fig. 6. Endurance limit ($N = 10^6$ cycles) of the two kinds of specimens are 440 and 900 MPa respectively. The threshold stress intensity factor range obtained from the endurance limits are

$$\Delta K_{th} = 10{\cdot}9\ \mathrm{MN\ m^{-\frac{3}{2}}}\ \text{(without shot peening);}$$
$$\Delta K_{th} = 22{\cdot}5\ \mathrm{MN\ m^{-\frac{3}{2}}}\ \text{(after peening).}$$

Therefore ΔK_{th} of specimens can be increased by $11{\cdot}6\ \mathrm{MN\ m^{-\frac{3}{2}}}$.

According to the distribution of compressive residual stresses (Fig. 4) the increase in the threshold stress intensity factor range is, for ($a_0 = 0{\cdot}55$ mm),

$$10{\cdot}3\ \mathrm{MN\ m^{-\frac{3}{2}}}.$$

The calculated result is essentially in agreement with the experiment result.

Other test results obtained in our laboratory from compact tension specimens of this material have shown that compressive residual stresses caused by shot peening could also raise the value of ΔK_{th} from 4·85 to 6·56 $\mathrm{MN\ m^{-\frac{3}{2}}}$.

CONCLUSIONS

(1) When the depth of microstructural changes is smaller than crack length, the compressive residual stresses from shot peening is a major factor in improving the endurance limit and threshold stress intensity factor of high strength steel.

(2) An equation for estimating the endurance limit as well as the stress intensity factor produced by residual stress has been proposed. The calculated values are essentially in agreement with experimental results.

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