FATIGUE AND FRACTURE RETARDATION USING A THERMO-MECHANICAL METHOD

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ABSTRACT

A thermo-mechanical technique has been proposed for the retardation of crack growth, the enhancement of fatigue life and the fracture toughness of components and structures containing stress concentrators. The technique involves the simultaneous application of load and moderate temperature to the critical sites with high stress concentrations. The basic concept of the technique was explained. Experimental investigations on aluminium, steel (including welded) specimens indicated that significant retardation on crack growth and improvement in fatigue life and fracture toughness could be achieved. Further examination of the concept and experimental results indicated that the effectiveness of the technique was a function of the stress state at the critical regions (including the severity of the stress concentration), the yield stress of the materials as a function of temperature, and the remote applied stress.

KEYWORDS

Crack growth retardation, fracture toughness, life enhancement, residual stress.

INTRODUCTION

The importance of residual stresses to the safe operation of a structure and component is well known: They influence both the initiation of cracks in crack-free structures and the growth of pre-existing cracks. The fracture modes which are affected include brittle fracture, stress corrosion cracking, hydrogen cracking and fatigue.

Compressive residual stresses near stress-concentrators or other critical locations are usually desirable and there are various ways of introducing them. One technique involves overloading the structure to produce tensile plastic strains at the stress concentrator: when the load is removed, a compressive stress is generated. For example, plates containing holes can be overloaded by cold expansion (Chandawanich and Sharpe, 1979; Cathey and Grandt, 1980), or gun barrels can be overloaded by auto-frettage (Underwood and Throop, 1979; Clark, 1982), thereby increasing their fatigue lives. For a structure containing an existing crack, if a tensile overload is introduced in the fatigue cycle sequence, crack growth will be retarded or even arrested (Corbly and Packman, 1973; Bathias and Vancon, 1978).

Conversely, tensile residual stresses are undesirable and "stress relief", usually by heat-treatment or some other means, is commonly employed to reduced the magnitude of the tensile residual stress introduced by, for example, welding (Saunders, 1981).

In this paper, a thermo-mechanical technique introducing compressive residual stress at critical locations will be described. The technique involves the simultaneous application of an applied load - but not necessarily an overload - with a moderately high temperature heat-treatment. The basic concept and the results of experimental investigations testing the effectiveness of the techniques will be presented.

THEORETICAL BASIS

The effect of a tensile overload alone, the effect of heat treatment alone, and the effect of an applied load with heat treatment will now be discussed.

The effect of tensile overload alone.

By the application of an overload which results in tensile stresses exceeding the yield stress of a material at the vicinity of a stress concentrator, plastic flow will occur which has the effect of limiting the magnitude of the tensile stress. On subsequent unloading, compressive stress will be created at the immediate vicinity of the stress concentrator. This concept has been used widely, for example cold expansion of holes and auto-frettage of gun barrels. For a structure containing crack, an overload above that of the service load will create a larger compressive zone at the crack tip. These methods have been found to be effective in retarding fatigue crack growth. The magnitude of the overload applied must be such that gross yielding of a component or a structure does not occur.

The conventional stress relief method -- heat treatment without an applied load.

If a structure has regions which are under tensile residual stresses then these stresses may be reduced by heat treatment, which can be applied locally at the critical regions or to the entire structure. The effect of heating is to reduce the yield stress of the material. For a region where there is residual stress above the yield stress at that temperature, plastic flow will be possible resulting in the reduction of the magnitude of the tensile residual stress. This is the normal method of stress relief using heat treatment.

The proposed procedure -- heat treatment with an applied load

Consider a structure under an applied load. The critical regions are those in which the stresses are tensile and of large magnitude. If heating is now applied, the yield stress of the material will be lowered. Provided that the yield stress at the elevated temperature is below that of the tensile stress at the critical regions, the magnitude of the tensile stress will be lowered as explained in the previous section.

If the component is unloaded after it has cooled down to its original temperature, a region of compressive stress will be set up around the critical region. In fact, this method is discriminating: the more critical the region, the larger the magnitude of tensile stress on loading and the larger the magnitude of compressive stress after this heat treatment process and unloading.

The applied load in this treatment is not limited to the magnitude of the service load. It can be an overload. A greater magnitude and extent of compressive residual stress will be expected than a simple overload alone without heating. Thus, greater beneficial effect would be expected from this technique when the same magnitude of overload is applied.

Illustration of the method.

Consider the case of a notch in an infinite plate which is loaded in uniaxial tension to some nominal stress, σ. The material is assumed to be elastic perfectly plastic, with a yield stress which decreases with increasing temperature. The yield stress at room temperature is assumed to be σ_y. Figure 1, curve 1 shows the normal elastic stress distribution ahead of the notch at room temperature. If the yield stress is not exceeded at the notch during tensile loading, on unloading at room temperature, no residual stress will be induced at the notch. However, if either the applied stress or the stress concentration factor is high enough, the yield stress will be exceeded at the notch, plastic deformation will occur, and the stresses will be redistributed, curve 2. Upon unloading to zero applied stress a compressive residual stress will remain, curve 3. Curve 3 is found by subtracting the theoretical elastic stress distribution (curve 1) from the elastic-plastic stress distribution (curve 2).

With the proposed thermo-mechanical technique, the material is heated during tensile loading so that the yield stress of the material is reduced to σ_y'. A larger zone of yielded material will be created on loading, curve 4. If the notch is then cooled to restore the room temperature yield stress σ_y, and then unloaded, a compressive stress of greater magnitude will be created, curve 5, Fig. 1. Curve 5 is found by subtracting the theoretical elastic stress distribution (curve 1) from the elastic-plastic stress distribution of the heated material (curve 4).

Comparing curve 3 and curve 5, it can be clearly observed that the magnitude and extent of the compressive stress as defined by curve 5 are larger than that defined by curve 3. Thus, the proposed thermo-mechanical technique has the potential of creating a significant compressive residual stress zone.

If on loading, the stresses do not exceed the yield stress, then on unloading, no residual stresses would be generated. With reference to Fig. 1, this will be the case if the maximum stress defines by curve 1 is less than σ_y for the case with no temperature applied, or less than σ_y' for the case with heating. The larger the stress defined by curve 1, the larger will be the compressive stress on unloading. For the same remote applied stress, the stress at the vicinity of the stress concentrator will be larger the more severe the stress concentration. Thus, the magnitude of the compressive stress generated is clearly a function of the remote applied stress and the severity of the stress concentrator.

In Fig. 1, reversed yield is assumed not to have occurred. With severe stress concentration and high enough remote applied stress, reversed yield could have occurred on unloading. The general observations and conclusions will still be valid. The difference is that a reversed (compressive) plastic zone will exist ahead of the stress concentrator.

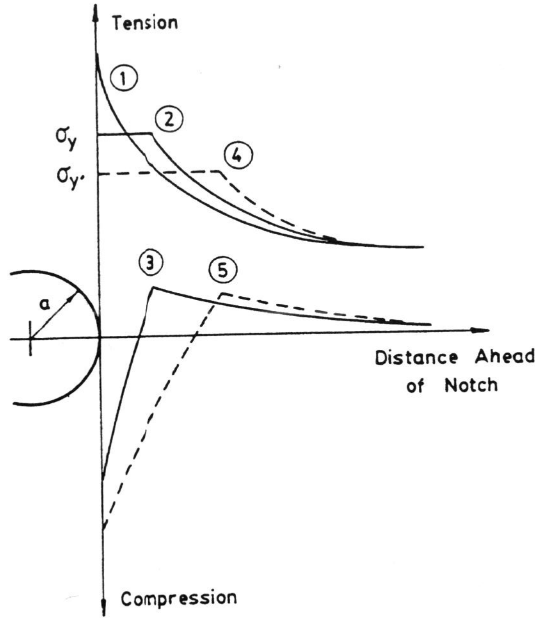

Fig. 1. Theoretical normal stress distribution at a stress concentration of radius, *a*. Curve 1: elastic stress distribution under monotonic tensile loading. Curve 2: elastic-plastic stress distribution. Curve 3: residual stress distribution upon unloading. Curve 4: elastic-plastic stress distribution under tensile loading with heat applied. Curve 5: residual stress distribution after thermo-mechanical treatment.

EXPERIMENTAL INVESTIGATIONS

Experimental investigations were carried out to investigate the effectiveness of the technique in the following areas: (1) fatigue crack growth retardation; (2) fatigue life enhancement from a moderate stress concentrator; (3) fatigue life enhancement for fillet weld; (4) retardation of crack growth rate under static load and (5) improvement of fracture toughness for a cracked specimen. The results will now be presented.

Fatigue Crack Growth Retardation (Lam and Griffiths, 1990; Chen et.al., 1993)

AS1444/X1320H plain carbon-manganese boiler plate steel was used for this investigation. All the test specimens obtained from the plate were annealed for 1.25 hours after machining to relieve the residual stresses due to rolling and machining. The fatigue specimens were of the single-edge-notch type and were 75mm wide and 3mm thick.

Fig. 2 shows the dependency of tensile strength and yield stress on temperature for this material. Baseline fatigue test result at room temperature indicated that for R=0.02, the crack growth rate data can be represented by:

$$da/dN = 3.1 \times 10^{-9} (\Delta K)^3 \qquad 14<\Delta K<95 \qquad (1)$$

where the units are mm/cycle and MPa $m^{1/2}$.

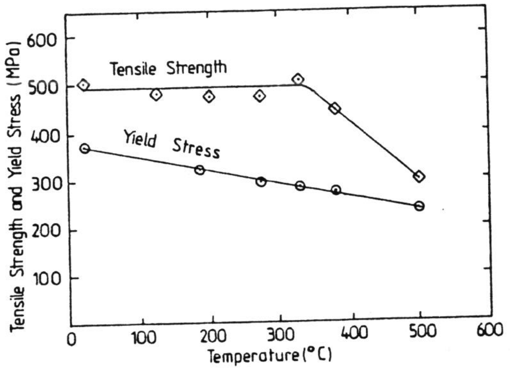

Fig. 2. Tensile strength and yield stress versus temperature.

Spot heating was applied to the specimens with two cylindrical copper blocks of 30mm diameter each. They were heated by electrical resistance wires and pressed against the specimens with a contact pressure of 8.3MPa for 1.5 min. The arrangement was such that at the end of the heating, a temperature of 300° C was achieved at the crack tip region.

All fatigue tests were carried out under constant stress intensity factors with R =0.02. Fig. 3 shows the effect of spot heating alone (with no applied load). Fig.4 shows the effect of application of an overload with two different overload ratios Ω. (Ω is defined as the ratio of overload to the maximum load at steady state). Fig. 5 shows the effect of spot heating with a single overload equal to the maximum load at steady state (Ω=1). Fig 6 shows the effect of spot heating with a single overload with Ω= 1.25.

It can be observed that spot heating with an overload for the conditions tested was far more effective in the retardation of fatigue crack growth than either spot heating alone or overload alone. Indeed, for both Ω=1 and 1.25, the crack was arrested when spot heating was applied with an overload. In order to start the crack growing again, the maximum applied load had to be increased. A comparison of Figs 5 and 6 indicated that with higher overload (Ω=1.25), the technique was more effective.

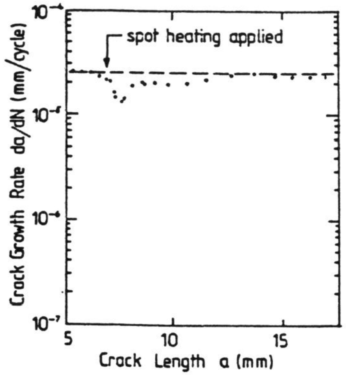

Fig. 3. Effect of spot heating alone on crack growth. (- -) indicates the crack growth rates predicted based on constant amplitude loading [eq. (1)].

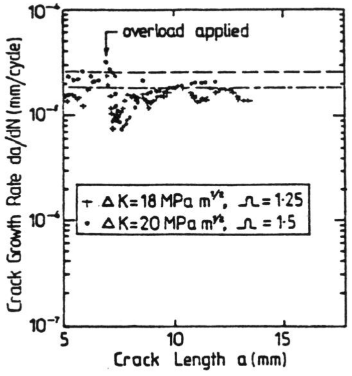

Fig. 4. Effect of single overload alone on crack growth. (-.-) and (- -) indicate the growth rates predicted based on constant amplitude loading [eq. (1)] for ΔK = 18 MPa $m^{1/2}$ and ΔK =20 MPa $m^{1/2}$ respectively.

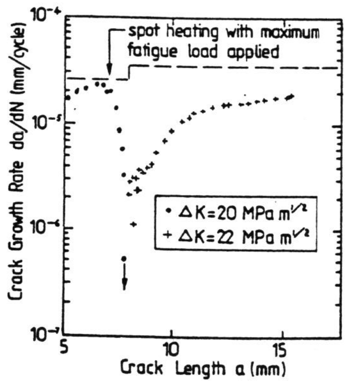

Fig. 5. Effect of spot heating with maximum fatigue load (Ω = 1) on crack growth.
(- -) indicates the growth rates predicted based on constant amplitude loading (eq. (1)].
(↓) indicates crack arrest occurred for a given ΔK.

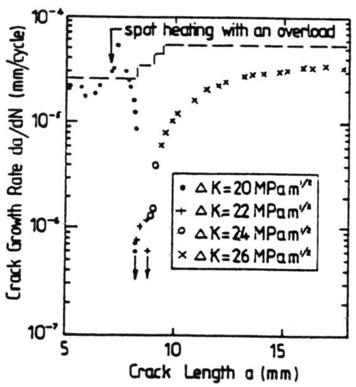

Fig. 6. Effect of spot heating with an overload (Ω = 1.25) on crack growth. (- -) indicates the crack growth rates predicted based on constant amplitude loading [eq. (1)]. (↓) indicates crack arrest occurred for a given ΔK.

From Figs 5 and 6, the crack was not arrested immediately after the application of spot heating with an applied load. The crack growth rates decreased over a distance before it was arrested. This retardation phenomenon was similar to that of a single overload alone (McMillan and Hertzberg, 1968; Corbly and Packman, 1973; Bathias and Vancon, 1978; Ranganathan et. al. 1979) . It was known that with multiple overloads, more retardation of crack growth will occur. Thus, one would expect that spot heating with multiple overloads would provide more retardation to crack growth also.

Fatigue Life Enhancement for a Stress Concentrator (Cole and Lam, 1991)

The previous section demonstrated that fatigue crack growth can be retarded using the proposed thermo-mechanical technique. A crack is an infinite stress concentrator. Thus, it was of interest to investigate the effect of the technique for a stress concentrator which is much less severe than a crack.

The stress concentrator chosen was a circular hole in a steel plate. The properties of the steel plate, although not exactly the same, were similar to that described in the previous section and will not be repeated here. The fatigue specimens were 6mm in thickness and waisted to a width of 25mm in the test section. A hole of 3mm in diameter was drilled at the centreline of the specimen. It was calculated that the theoretical elastic stress concentration of the hole was 2.69. (Based on the nominal stress across the ligament at the plane of the hole).

For heating, similar set-up was used as in the previous section. However, for this case, rectangular copper block was employed to provide uniform heating across the whole specimen width. The temperature was maintained for 3 minutes.

All fatigue tests were conducted at pulsating tension at 142Hz in a resonant machine. For the thermo-mechanical technique, the chosen temperature was 375 ° C and the overload ratio Ω =1 was used (ie. no overload). At each stress level, at least three data points were obtained.

Fig. 7. shows the comparison of fatigue lives of specimens with and without the application of the thermo-mechanical technique. From the figure, it appears that the technique was most effective at low stress level and provided little improvement in fatigue life at high stress level.

At high level of remote applied stress, the thermo-mechanical technique might establish a compressive stress zone around the stress concentrator. However, the subsequent application of the high level of remote applied stress caused significant net plastic deformation resulting in redistribution of the residual stress at the edge of the hole. This redistribution of residual stress would reduce the effectiveness of the technique. As an example, for a remote applied stress of 320MPa, the ligament nominal stress at the plane of the hole would be approximately 364MPa, which was about 93% of the yield stress (390MPa.) at room temperature. Thus, it can be expected that significant net section plastic deformation would occur at this level of applied stress resulting in redistribution of residual stress.

Fatigue Life Enhancement for a Welded Component (Lam and Cole, 1993)

There has been debate as to whether the fatigue life of welds is mostly dependent upon crack initiation (Lawrence et. al., 1978; Itoh, 1987), or may be described using fracture mechanics and fatigue crack growth methodologies (Maddox, 1970; Zettlemoyer and Fisher, 1977). It is well known that the introduction of compressive residual stress by peening (Faulkner and

Bellow, 1975; and Knight, 1978) and prior overloading (Gurney, 1963 and Harrison, 1965) improve the fatigue performance of welds.

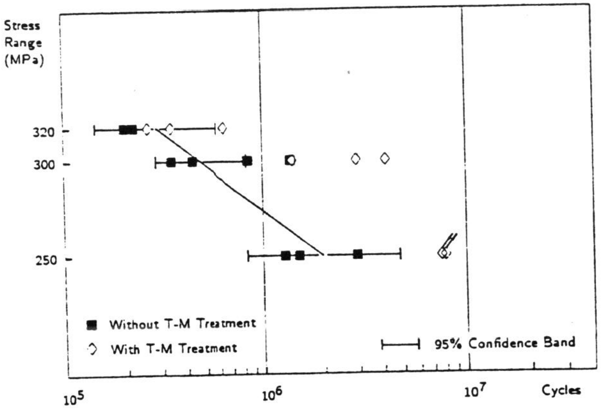

Fig. 7. S-N curve of specimens with holes. Regression line and confidence bands apply to untreated specimens. Arrows on data points indicate run outs.

As discussed in the previous section, for both fatigue crack growth and crack initiation from a stress concentrator, the thermo-mechanical technique was found to be effective in fatigue life enhancement. Thus, the technique should be effective in fatigue life enhancement of welded components.

Butt welded specimens made from 6mm thick C-Mn steel plates conforming to Australian Standard AS1548-1988 grade-460R were used in this investigation. The yield stress and ultimate tensile strength were 409MPa and 526MPa respectively. The effects of temperature on ultimate tensile strength and yield stress were similar as described in the previous section and the details will not be repeated.

Butt welds were chosen because they represent the simplest form of welded joint. Their fatigue behaviour was found to be determined largely by the stress concentration at the toe of the weld. To minimise variability in the weld a fully automated process employing flux cored wire and CO_2 shielding gas was used. The joint was a double-welded single V butt joint with a bevel angle of 60°, a root face of 3mm and a root gap of 0mm. Two 130mm wide steel plates were welded together. Fatigue specimens were cut from the plate with a waisted down tested section of 25mm and with the butt weld at the centreline of the test section.

All fatigue tests were conducted at pulsating tension at 142Hz in a resonant machine and the total number of cycles to final failure was recorded. For the thermo-mechanical technique, the heating technique used was similar to that described in previous section. The chosen temperature was 375 ° C and the overload ratio $\Omega=1$ was used (ie. no overload). At each stress level, at least three data points were obtained.

Fig. 8. shows the comparison of fatigue lives of specimens with and without the application of the thermo-mechanical technique. From the figure, the effectiveness of the thermo-mechanical technique was similar to that for the specimens containing a hole, ie. it appears that the technique was most effective at low stress level and provided little improvement in fatigue life at high stress level. The explanations for this behaviour are similar to that described in the previous section.

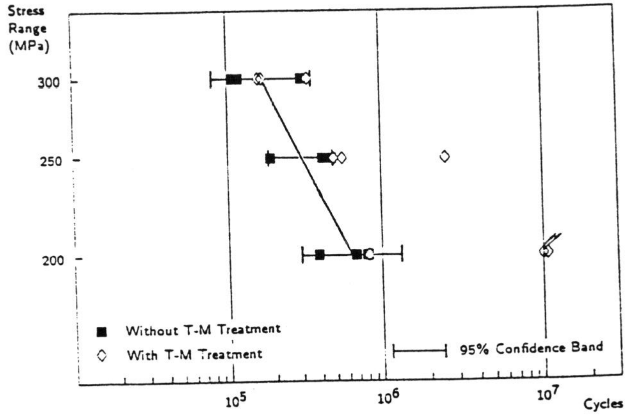

Fig. 8. S-N curve of butt welded specimens. Regression line and confidence bands apply to untreated specimens. Arrows on data points indicate run outs.

Improvement of fracture toughness (Lam and Ibrahim, 1994)

Aluminium alloy 6351-T6 used in the manufacture of gas cylinders was the subject of the present study. It was demonstrated that this alloy was susceptible to crack growth from defects under a static load (Stark and Ibrahim, 1992). This study has a particular significance as the safety margin for the operation of gas cylinders would be increased with an increase in K_{IC}. Owing to geometrical limitation of gas cylinders, standard compact tension specimen could not be obtained for valid K_{IC} testing. Thus, small cylindrical specimens (Ibrahim and Stark, 1990) were used for toughness testing, see Fig. 9.

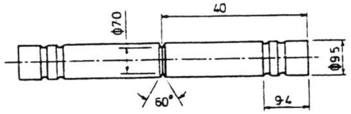

Fig. 9. Small circumferentially-cracked cylindircal specimen. All dimensions in mm.

The yield stress and ultimate tensile strength of Al6351-T6 as a function of temperature are tabulated in Table 1. The fracture toughness at room temperature without any preload was determined from three specimens and found to be 31 ± 1 MPa$\sqrt{m}$.

Table 1. Yield and ultimate strengths of A1-6531-T6 as a function of temperature

Temp. °C	25	70	100	130
σ_y, Mpa	291	280	272	262
σ_{uts}, Mpa	338	338	315	297

For the application of thermo-mechanical method, a range of preload stress intensity factors and temperatures were applied. The whole heating and cooling cycles took approximately thirty to forty-five minutes. The results are shown in Figs 10 and 11.

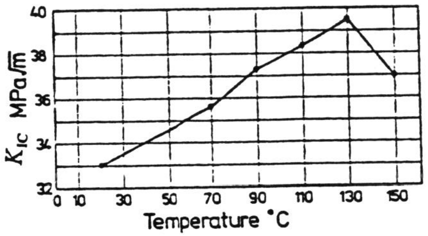

Fig. 10. Apparent fracture toughness of A1-6351-T6 as a function of temperature at a preload of $K_I \approx 22.5$ Mpa $\sqrt{m}$. Note: one specimen tested per point.

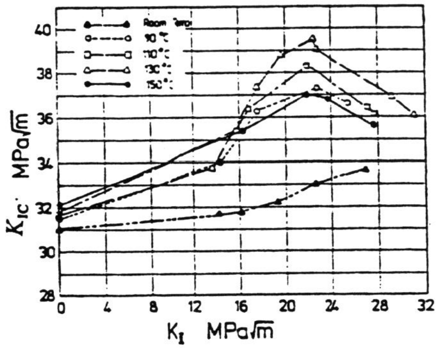

Fig. 11. Apparent fracture toughness as a function of preload K_I at different heating temperatures. Note: one specimen tested per point except when zero preload was applied at room temperature where the average value for three specimens is shown.

From Fig.10, it can be observed that for a preload stress intensity of 22.5MPa$\sqrt{m}$, the fracture toughness values increases to a maximum of 39 MPa$\sqrt{m}$ at approximately 130° C. On further increase in temperature, the fracture toughness decreases.

Fig. 11 shows the changes in fracture toughness as a function of preload at various temperatures. It can be observed that the fracture toughness increases with an increase in preload until a maximum was reached. The fracture toughness decreases with subsequent increase in preload.

It should be pointed out that for this aluminium alloy, it is susceptible to crack growth under a static load in room temperature. For the present investigation, it was anticipated that some stable crack growth occurred during preload and heating; the higher the temperature and preload, the higher would be the crack growth. For Fig. 10 and 11, all the fracture toughness values were calculated based on the original crack length and had not included stable static crack growth under an applied load and temperature.

For selected specimens, crack growth under static load and temperature were obtained by marking the crack front just before unloading. The corrected fracture toughness values are tabulated in Table 2. As shown in Table 2, the trend of decreasing fracture toughness value with increasing preload at higher temperature is no longer apparent.

Table 2. Comparison of K_{IC} values calculated with and without stable crack growth

Specimen number	Temp. of preload (°C)	Preload K_I Mpa $\sqrt{m}$	K_{IC} precrack only $\sqrt{m}$	K_{IC} precrack plus stable crack growth $\sqrt{m}$
E	90	25.5	36.6	42.3
F	110	27.3	36.4	39.2
A	130	13.7	33.1	33.1
B	130	22.5	39.1	46.1
G	150	21.9	37.0	39.9
C	150	23.7	36.8	39.7
D	150	27.6	35.6	42.3

CONCLUSIONS

A new procedure of introducing compressive stress around critical region has been described. It involves the simultaneous application of heat treatment and an applied stress simultaneously. Investigations indicated that the technique can be used for retardation of fatigue crack growth of cracked components, improvement of fatigue life of components with stress raisers and welded components, and improvement of fracture toughness for components containing stress concentration.

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