Influence of Shot-Peening on Fatigue and Corrosion-Fatigue Behavior of Structural Steel

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ABSTRACT

The influence of surface finish upon the fatigue/corrosion-fatigue behaviour of a weldable grade of structural steel has been studied in both air and artificial sea water. The results have shown shot-peening to have a harmful effect at high applied stress, while showing an increasingly beneficial effect at lower applied stress, in both air and in sea water. The increase in corrosion-fatigue life is thought to be due primarily to an extension of the initiation stage of the fracture process.

X-ray residual stress analysis performed on modified test specimens has indicated the presence of three distinct regions of surface stress relaxation during cycling.

Key Words : Corrosion-fatigue, structural steel, shot-peening, residual stress.

INTRODUCTION

The fatigue/corrosion fatigue performance of structural and engineering components is known to be strongly dependent upon the surface condition of the material.(1) The introduction of surface compressive stresses by shot-peening has been shown to substantially increase fatigue life in air.(2,3) However, under highly stressed conditions Kodama(4) and Kirk(5) have shown an adverse effect due to peening. Work by McClinton and Cohen(6) have indicated the development of deleterious tensile stresses in shot-peened material after cycling under high tensile loads.

The case for corrosion-fatigue is less well documented. Baxa et al(7) in a study of medium carbon steel in aqueous chloride solution have indicated shot-peening to substantially increase time to failure over unpeened specimens. Kovac and Kovich(8) observed a similar effect for low carbon steel tested in 3.0% sodium chloride after shot-blasting. The suggestion was made that de-localisation of the corrosion fatigue process together with delayed early crack propagation through the residually-compressed layer increases the time to failure. This suggestion was an alternative to the extension of the crack initiation stage.

This paper is concerned with the results of preliminary investigations into the effect of surface finish and residual stress upon the axial fatigue/corrosion-fatigue performance of a weldable structural steel, viz: BS 4360-50E.

The steel chosen is of 'node' quality which sees service in the critical constructional areas of offshore platforms, subject to both fatigue cycling and the corrosive environment of the North Sea. The corrosion-fatigue behaviour of structural steels in sea water has been comprehensively reviewed by Jaske et al.[9]

This research involves fully reversed axial fatigue tests performed in air and under freely corroding conditions in an artificial sea water, fully aerated and maintained at $4^{o}C$. Three surface finishes were selected for study : shot-peened, turned and polished. The work was supported by X-ray stress analysis, fractography, metallography, micro-hardness and corrosion potential measurements.

The general aim of the research is to obtain an understanding of the effects of surface finish on the corrosion fatigue behaviour of the steel in its parent plate form.

EXPERIMENTAL

The test material employed was a normalised, weldable grade steel type BS 4360-50E supplied in 32 mm plate. The chemical composition and mechanical properties are listed in Table 1. Metallographic investigation showed that a significant feature was the presence of a number of inclusions aligned predominantly in the rolling direction. Micro-probe analysis revealed these to contain elemental colonies of Mg and Al together with Ca, Mn and S.

Specimens were machined to the specifications outlined in fig.1 with gauge length cross sections of types A and B. The testing direction was parallel to the principal rolling direction. The same basic design was employed in both cases with a continuous 66 mm radius forming the gauge length. Type B specimens also incorporated two diametrically opposite flats to facilitate the precise determination of residual stress during fatigue cycling.

Type A specimens were used to obtain S-N data on several reproducible surface finishes, the preparation procedures for each are outlined below:

1. Turned surface A final dry cut of 0.125 mm depth was taken at a speed of 2000 rpm with a feed rate 0.038 mm per revolution using a tungsten carbide tool.

2. Polished surface All turning marks were removed with successive grades of emery by rotating the specimen in the lathe. A final 400 grit finish was obtained using a Morrison polishing machine to ensure all polishing marks were aligned in the testing direction.

3. Shot-peened surface The polishing procedure outlined for (2) was employed prior to shot peening to an Almen intensity of N -.008"-.012". Shot peening was performed by Metal Improvement Co Ltd, UK, to 100% coverage using 0.28 mm size steel shot. Residual macro-stress analysis (the experimental details of which have been published previously[10]), determined the peened layer to be .135 mm deep, see fig.2. Micro-hardness testing using a 20 g load showed the work hardened layer to extend approximately 0.6 mm . Ref.fig.2.

4. <u>Shot-peened and annealed.</u> Shot-peened samples were vacuum annealed at various temperatures for one hour and the residual macro-stress and micro-stress measured as shown in figs. 3 and 4 respectively. Micro-hardness tests were also carried out using 20 g loads. A one-hour annealing treatment at 500°C was then applied to the shot-peened specimens. This treatment removed all of the macro-stress and the majority of the micro-stress.

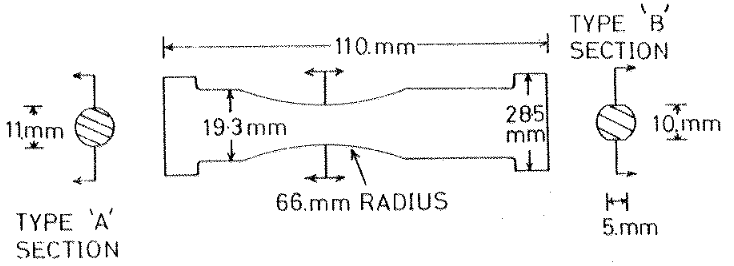
The average value for each surface finish together with the maximum and minimum values obtained are shown in Table 2.

Fully-reversed axial fatigue testing was carried out using a servo-hydraulic machine at a testing frequency of 5 Hz. Tests were carried out in air on polished and shot-peened specimens at room temperature. Cycles to failure were recorded up to $2x10^6$ cycles beyond which testing was discontinued.

Environmental tests were performed on all three surface finishes in a sea water similar to ASTM D1141-75 maintained at 4°C. At 8.0/8.2 pH calcarious deposition is likely which may affect the initiation process[9]. In this first series of tests the pH was initially adjusted to pH7 with a few drops of 1 M HCl and maintained between 7.0 and 8.0 during testing with minor additions of .1 M Na OH to minimise this influence. Thus the environment used may be slightly more aggressive. The effect of pH will be studied at a later stage with special attention being paid to cathodic protection.

Fully aerated sea water was pumped continuously from a 10 ℓ reservoir, through a cooling unit which produced a temperature of 4°C, and circulated through a Perspex cell surrounding the specimen. Tests were carried out under freely corroding conditions, the specimens being left in solution for two hours prior to cycling to ensure stable starting conditions. Corrosion potentials were measured continuously by means of a saturated calomel electrode and a high-impedance chart recorder. The sea water was changed weekly or before the start of an expected long term test. This was to ensure equivalent testing conditions and to reduce corrosive products in solution. Type B specimens were tested with surface finishes outlined in 2 and 3. Initial tests using these specimens involved measuring the residual stress after a given cycle number until specimen failure, in both air and sea water.

Figure 1



SPECIMEN CONFIGURATION

RESULTS

The air fatigue lives for shot-peened and polished specimens shown in fig.5 indicates the adverse effects of peening at high applied stress levels while showing an improvement at lower stress levels. A similar behaviour was observed in the sea water environment as shown in fig.6. The adverse effect of a turned finish is also evident.

The performance of the annealed shot-peened material tested in sea water is indicated in fig.7. Behaviour similar to that of polished specimens was found at lower applied stress levels in comparison to behaviour similar to as-peened material at high stress levels.

FRACTOGRAPHY

Failure of polished and shot-peened specimens in both air and sea water was found to have been initiated from the surface at well-defined origins. The cracking mode for specimens tested in air was found to be essentially ductile transgranular with the presence of numerous tear ridges. Final failure was by normal ductile void linkage.

Tests performed in sea water revealed a similar cracking behaviour although numerous secondary cracks and multi-crack branching at the major initiation sites were evident. A feature of shot-peened specimens fatigued at lower stress levels was the presence of a multi-initiation "rim" of cracking as shown in fig.8. This was not apparent for shot-peened specimens fatigued at high stress levels nor on any of the polished samples. Moreover no indication of this feature was present at the initiation area.

Fracture analysis of annealed specimens tested in sea water revealed multi-crack initiation allied to both inclusions and to the notching effect induced by peening.

The fracture surfaces of turned specimens cycled in sea water revealed multi-initiation from the base of the turning notches with little evidence of inclusion-initiated failure.

POTENTIAL-TIME TESTS

Measurement of corrosion potentials during the initial two-hour stabilisation period and during cycling revealed no clear differences in the electro-chemical behaviour of the surfaces tested.

During cycling the corrosion potentials continually became more electro-negative, exceeding the values obtained for uncycled freely corroding specimens. This suggests a continued breakdown of the surface film with an increasingly larger anodic region exposed to the electrolyte, probably in the form of corrosion-fatigue cracks.

STRESS-RELAXATION BEHAVIOUR

The initial results obtained using type B peened specimens at high stress levels in air and in sea water are shown in fig.9. The degree of stress relaxation appeared to be similar in both cases.

A comparison at a lower stress level in air between polished and peened material is given in fig.10. A similar relaxation profile is apparent. At fracture, however, the peened material exhibits a tensile surface residual stress, while the polished fracture stress is zero. Tensile surface residual stresses were also measured on the other fractured peened specimens.

DISCUSSION

The fatigue/corrosion fatigue behaviour of this steel in both air and sea water is clearly influenced by the surface condition of the material. Under highly-stressed conditions shot-peening has an adverse effect on fatigue behaviour, while at lower applied stress levels an increasing beneficial effect is observed.

A shot-peened surface not only contains a high compressive residual stress but a layer of heavily cold-marked material. In a corrosive solution this plastic deformation may increase the tendency of the material to react with the environment[8]. Potential-time results, however, indicate no such tendency in this case, either prior to or during cycling. Differences in corrosion potential are likely to be small in a fully-aerated solution in which oxygen diffusion has a large influence on corrosion behaviour. Thus potentiostatic polarisation studies will be required in order to elucidate this aspect. A micro-notching effect together with a relaxation of residual compressive stress during cycling are other factors which must be included in an evaluation of behaviour. It is apparent in this study that the influence of inclusions on the crack initiation process is also important. Eklund[11] examined the corrosion at slag inclusions in a carbon steel and observed preferential attack of calcium aluminate precipitates surrounded by a rim of calcium/manganese sulphide. This rim is attacked if it has a high calcium content. The precise nature of the corrosive attack has not yet been evaluated here. Inclusions do appear, however, to have a direct influence upon the initiation process. The detailed examination of the polished and shot-peened fracture surfaces showed that the major corrosion fatigue cracks were associated with deep pits. The two-hour stabilising period may have tended to accentuate this process.

The corrosion-fatigue behaviour of the shot-peened material at low applied stress levels revealed multi-initiation and evidence of delayed crack growth similar to that observed by Baxa et al[7] and Kovac and Kovich[8]. This feature could only be detected at locations away from the major initiation area. It is proposed that at low stress levels the slow growth of the major crack allows secondary cracks to initiate and propagate from the micro-notches present at the shot-peened surface. This initiation of secondary cracks is caused by the increase in stress resulting from the reduced specimen section. The presence of the surface residual compressive stress has the effect of retarding early crack propagation resulting in the type of cracking behaviour observed in fig.8. Evidence for this is given by the cracking behaviour of the annealed specimens. Major fatigue crack initiation was not only linked to inclusions but to the micro-notching effect at the surface, which became important when the residual compressive stress was removed.

Due to the presence of inclusions the initiation stage of the corrosion fatigue process is reduced. It is therefore proposed that the improvement provided by shot-peening at the lower applied stress levels tested is due primarily to an increase in the length of the initiation stage of corrosion-fatigue failure. The improvement is probably caused by the beneficial influence of shot-peening on the inclusions. In the absence of inclusions a mechanism similar to that suggested by Baxa et al[7] and Kovac and Kovich[8] would probably be expected.

The turned specimens gave the lowest fatigue lives at all stress levels. This is due to a combination of transverse notches and surface tensile residual stress.

The corrosion-fatigue behaviour of annealed shot-peened specimens was similar to that of polished specimens at the lower applied stress levels. The slight tendency for an increase in life may be due to the retention of a small proportion of work hardening. The notching effect due to peening appears to have no greater influence on initiation than the presence of inclusions at lower applied stress levels. At higher stress the effect of the environment is considerably reduced. The notching effect then exerts a considerable influence. This results in the lower corrosion fatigue life which was similar to that obtained for as-peened specimens.

Tests of stress relaxation were carried out using four type B specimens in the low cycle region. The relaxation profiles for each specimen were similar in that three stages were apparent:

(1) an initial sharp fall in residual surface stress during the first cycle.

(2) a linear region in which the residual surface stress was either constant or falling very slowly.

(3) a tertiary region in which the rate of stress relief increased rapidly.

The precise nature of the stress relaxation process is under further investigation. It is thought at this stage that surface yielding may be responsible for the initial fall in stress. This is followed by a region of dynamic equilibrium in which recovery and work-hardening processes are involved. The rapid stress relaxation stage will be associated with the increase in true stress levels. At fracture the shot-peened specimens were found to contain a tensile surface residual stress. This is perhaps caused by cyclic hardening.

Kodama[4] observed a similar fall in compressive residual surface stress in the first stress cycle followed by a gradual fall with continued cycling. Tensile stresses were not found in the fractured specimens that he examined. Neff[12], on the other hand, observed that an initial compressive surface residual stress was replaced by a residual tensile surface stress, at fracture, after cycling at high applied loads.

The tensile stresses measured prior to failure by McClinton and Cohen[6] were not observed in this investigation. However a much shallower case depth of 0.135 mm was employed here which is thought essential when improvement under axial conditions is to be expected.

It is clear that further work is necessary to elucidate the factors and mechanisms involved in the corrosion-fatigue behaviour of the steel.

CONCLUSIONS

The following conclusions have been drawn from this preliminary investigation:-

1. The presence of inclusions have a significant influence upon the initiation stage of the fracture process.
2. Under high applied stress levels shot-peening has a detrimental effect upon fatigue life both in air and in sea water.
3. At lower applied stress levels shot-peening has an increasingly beneficial effect upon fatigue life in both air and sea water.

4. The increase in corrosion-fatigue life at the lower applied stress levels for shot-peened material is thought to be due primarily to an extension of the initiation stage of the fatigue process.

5. Potential-time results indicated no measurable differences in the corrosion behaviour of the surfaces tested. A more detailed examination will be necessary in order to confirm this finding.

6. X-ray residual stress results indicate the presence of three distinct regions of surface stress relaxation during cycling for polished and shot-peened specimens.

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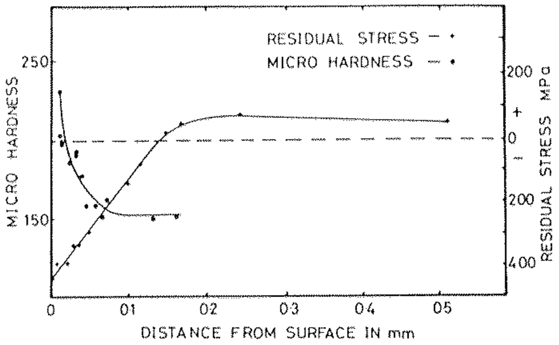
TABLE 1 B.S.4360 50E Chemical Analysis and Mechanical Properties

Mechanical Properties	Yield strength - MPa			Ultimate tensile strength - MPa					Elongation - %	
	397-441			545-607					23-30	
Chemical Analysis	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Nb
	.15	.40	1.42	.013	.003	.06	.02	.1	.14	.033

TABLE 2 Surface Residual Stress Analysis

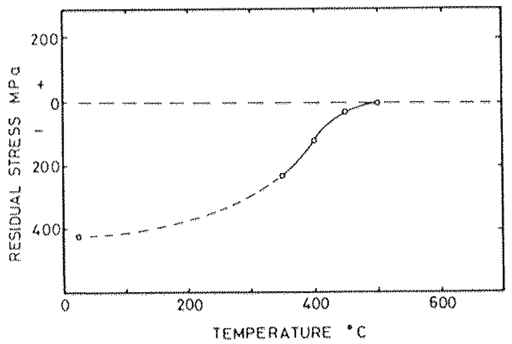
Surface Finish	Surface Residual Stress -MPa Mean	Max	Min
Turned	+121.7	+141.3	+ 85.49
Polished	-158.23	-195.1	-145.5
Shot-peened	-359.3	-366.1	-355.0

Figure 2



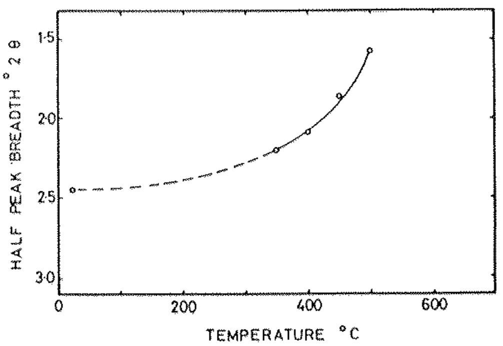
RESIDUAL STRESS (CORRECTED FOR LAYER REMOVAL) AND MICRO-HARDNESS PROFILES FROM THE SURFACE OF SHOT-PEENED MATERIALS.

Figure 3



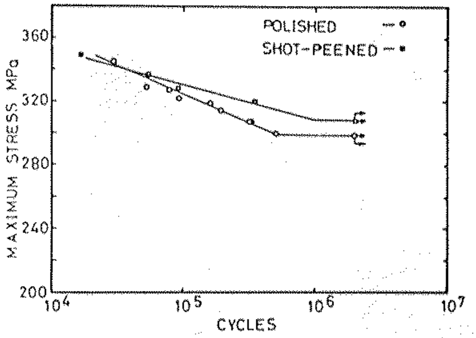
EFFECT OF ANNEALING TEMPERATURE UPON RESIDUAL MACRO-STRESS IN SHOT-PEENED MATERIAL.

Figure 4



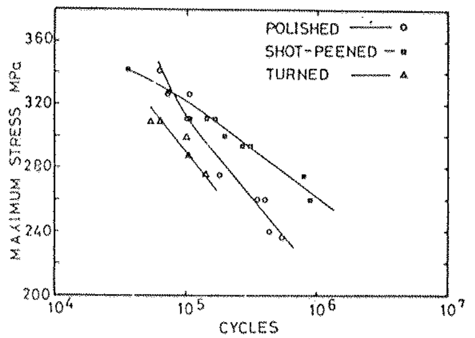
EFFECT OF ANNEALING TEMPERATURE UPON MICRO-STRESS IN SHOT-PEENED MATERIAL

Figure 5



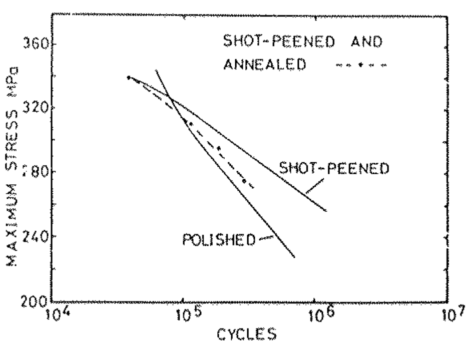
AIR FATIGUE BEHAVIOUR OF POLISHED AND SHOT-PEENED SPECIMENS

Figure 6



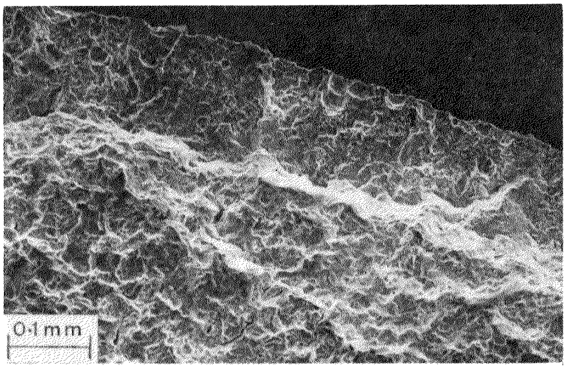
EFFECT OF SURFACE FINISH ON CORROSION-FATIGUE BEHAVIOUR

Figure 7



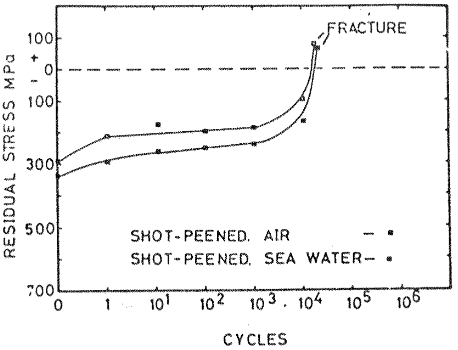
EFFECT OF ANNEALING ON THE CORROSION-FATIGUE BEHAVIOUR OF SHOT-PEENED SPECIMENS

Figure 8



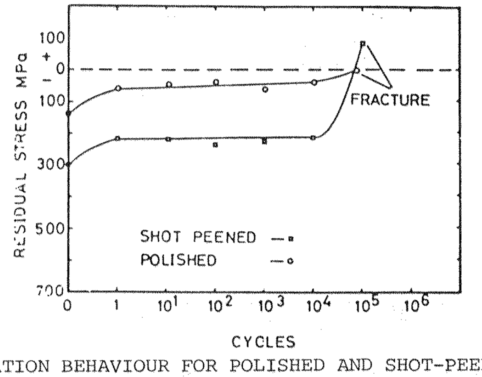
RIM OF MULTIPLE CORROSION-FATIGUE CRACK INITIATION ASSOCIATED WITH SHOT-PEENED SPECIMENS FAILED AT LOW STRESS.

Figure 9



STRESS RELAXATION BEHAVIOUR FOR SHOT-PEENED TYPE B SPECIMENS TESTED AT 350 MPa IN AIR AND SEA WATER.

Figure 10



STRESS RELAXATION BEHAVIOUR FOR POLISHED AND SHOT-PEENED TYPE B SPECIMENS TESTED AT 322 MPa IN AIR.