THE INFLUENCE OF SHOT PEENING ON THE FATIGUE AND CORROSION FATIGUE BEHAVIOUR OF AN AUSTENITIC-FERRITIC STAINLESS STEEL

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ABSTRACT

The influence of shot peening on the air fatigue and corrosion fatigue behaviour of an austenitic-ferritic stainless steel has been studied. The air fatigue limit was only increased by 7 % after shot peening, caused by work softening of the deformed surface layer. In a 4 N sodium chloride solution, having a pH of 2 at 80°C the corrosion fatigue limit of the steel examined was increased by 70 % compared to the electrolytically polished state. This marked increase is due to a finer surface slip distribution caused by the interaction of bulk slip with the deformed surface layer. Shot peening had also an influence on the near surface micro crack growth. The compressive residual stress field leads to some sort of crack closure effect which lowers the crack growth rate.

KEYWORDS

Shot peening; corrosion fatigue; air fatigue; crack initiation; austenitic-ferritic stainless steel; compressive stress field; slip distribution; passive layer.

INTRODUCTION

Shot peening is a well known technique to improve surface hardness and air fatigue strength for a wide range of technical used alloys (Gessinger and Corti, 1980; Knight, 1978; Verpoort, 1980). The beneficial effect of shot peening on the fatigue behaviour of metallic materials depends on the introduced residual stress field and the work hardening characteristic of the material. Little data exist concerning the influence of shot peening on the corrosion fatigue behaviour of metallic materials. It is known, that under corrosion conditions which lead to general or localized corrosion attack, shot peening cannot improve the corrosion fatigue strength (Baxa and co-workers, 1978). Under pitting corrosion conditions only an increase in fatigue life time may occur because a) pit initiation and propagation are retarded by compressive residual stresses (Chastell and co-workers, 1979) and b) the micro-crack growth rate might be lowered by compressive stresses.

Under passive corrosion conditions, however, one would expect a beneficial effect of shot peening even on the corrosion fatigue strength, because the strengthened surface layer is not damaged by general or localized corrosion attack.

The purpose of the present work was, to verify this assumption by studying the effect of a shot peening treatment on the corrosion fatigue behaviour of a material that behaves fully passive in the choosen corrosion medium.

MATERIALS AND EXPERIMENTAL PROCEDURE

The material used in this investigation was an austenitic-ferritic stainless steel (DIN designation: X3CrMnNiMo2664), which is strengthened by a nitrogen addition of 0.4 %. Chemical composition, mechanical and mircostructural properties are listed in table 1. The steel has been hot rolled and solution annealed at 1050°C for half an hour followed by a water quench. The resulting microstructure is shown in Fig. 1. Parallel to the rolling direction the grains are markly elongated.

TABLE 1 Chemical composition, mechanical and microstructural properties of X3CrMnNiMo2664

Chemical composition	Mechanical properties	Microstructural properties	
% C = 0.03	σ_{UTS} = 860 MPa	structure:	$\alpha + \gamma$
% Cr = 25.9		% ferrite	= 50
% Mn = 5.4	$\sigma_{0.2}$ = 640 MPa	% austenite	= 50
% Ni = 4.1		mean grain diameter	= 12 μm
% Mo = 2.2	ε_F = 44 %		
% N = 0.4			

Round bar fatigue specimens with a diameter of 4.5 mm and a gauge length of 25 mm were machined from bar stock having a cross section of 60 x 15 mm^2. The specimen axis was parallel to the rolling direction. The specimens were mechanically prepolished before electrolytical polishing in perchloric acid electrolyte at a temperature of -40°C. The applied current density was $\sim$ 0.5 A/cm^2. During polishing the specimens were rotated at 50 rpm. At least 250 μm in diameter were removed to ensure that no residual stresses from machining and mechanical polishing were left.

Shot peening was done in an injector-type machine with the standard steel shot S 230 (SAE standard J 444) having a mean diameter of 0.6 mm and a hardness of 490 $HV_{0.1}$. Peening operation was carried out at a working pressure of 0.4 MPa for 4 min, while rotating the specimen at 100 rpm. This treatment resulted in an Almen-intensity of A2 = 0.2 mm, measured with a standard Almen-strip.

Fatigue experiments were carried out on a servo hydraulic fatigue testing machine (MTS) at a frequency of 10 Hz. The stress ratio was held constant at $R = \sigma_{min} / \sigma_{max} = 0$. Corrosion fatigue tests were done in a deareated 4 N sodium chloride solution at 80°C. Its pH of 2 was adjusted with hydrochloric acid. Air and corrosion fatigue limits were measured at $5 \cdot 10^7$ cycles.

RESULTS

During the shot peening treatment, the austenite grains near the surface are much more deformed than the ferrite grains. Figure 2 shows a metallographic section perpendicular to the specimen axis. A lot of slip lines are visible in the austenite grains (A). The ferrite grains (F) do not show such a slip band structure.

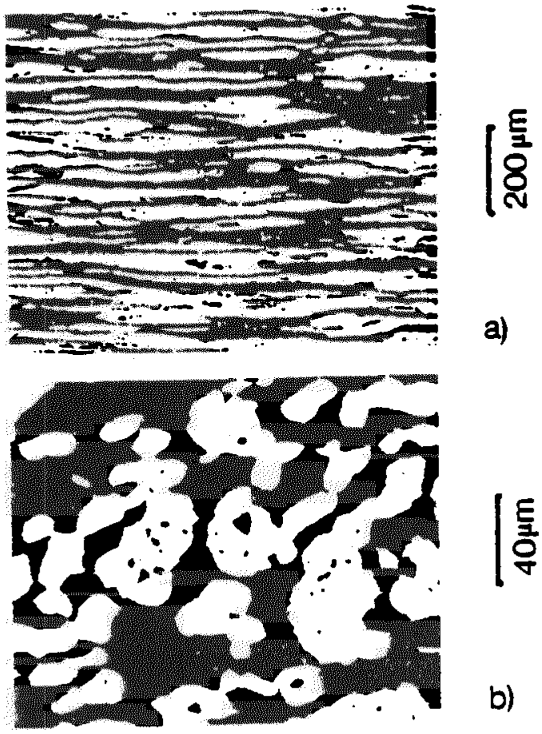


Fig. 1. Microstructure of X3CrMnNiMo2664
a) parallel to rolling direction
b) perpendicular to rolling direction.

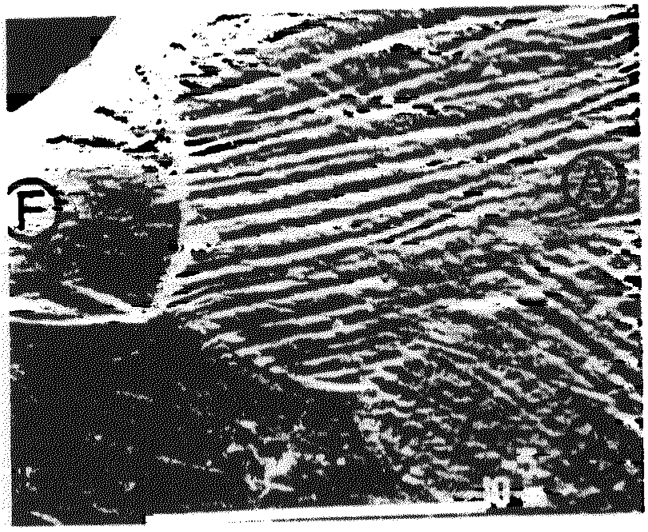


Fig. 2. Deformed austenite grains after shot peening.

The thickness of the deformed surface layer could be measured with micro hardness measurements at shot peened specimens in their radial direction. Figure 3 shows a plot of the hardness as a function of the radial distance from the specimen surface. In the as peened state (black dots) the maximum hardness value near the surface is 440 $HV_{0.1}$ and decreases with increasing distance from the surface to the bulk material hardness of 305 $HV_{0.1}$. The thickness of the deformed layer is approximately 200 µm. The black triangles within the same plot indicate the hardness curve for a shot peened and fatigued specimen. It will be discussed later.

Fatigue cracks in air and under corrosion always initiated in austenite grains along slip bands. Fatigue testing showed that the choosen shot peening treatment has much less influence on the air fatigue limit than on the corrosion fatigue limit. The air fatigue limit for polished specimens is 550 MPa. Shot peening raised the air fatigue limit only by 7 % to 590 MPa. As Fig. 4 shows, the influence of peening is much greater on the corrosion fatigue limit, which is raised from 260 MPa for the polished state up to 440 MPa for the shot peened state.

Scanning microscopy showed a marked difference between electrolytically polished specimen surfaces and shot peened ones after fatigue cycling. At a stress level of 450 MPa under corrosion conditions, extrusions had developed along slip band on the electrolytically polished specimen surface (Fig. 5a). The surface appearance of a shot peened specimen, fatigued under the same conditions as mentioned above is shown in Fig. 5b. No slip lines were detected on this surface. Shot peening not only changes the appearance of the specimen surface, but also has an influence on the near surface fracture morphology. A comparison of the fracture surfaces of a polished and a shot peened specimen is shown in Fig. 6. The actual crack growth direction is marked by an arrow. The fracture surface of the unpeened specimen (Fig. 6a) shows a cleavage like fracture of the ferrite grains and a more ductile fracture of the austenite.

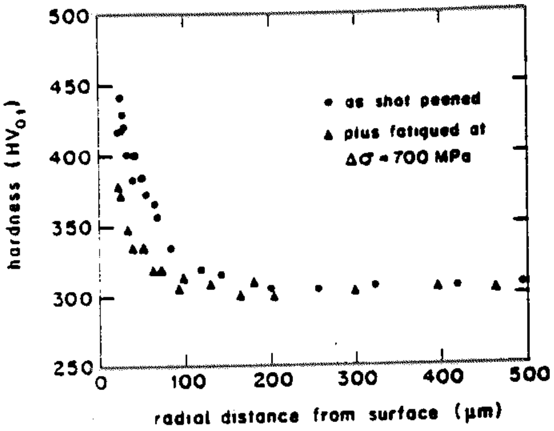


Fig. 3. Near surface hardness after shot peening.

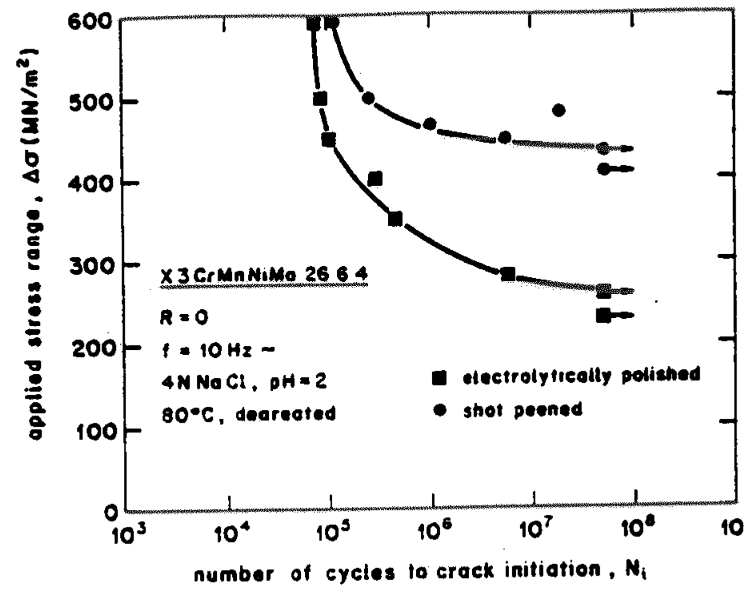


Fig. 4. SN-curves for polished and shot peened specimens.

The fracture surface in the zone, deformed by shot peening (Fig. 6b) shows, that the crack borders have been pressed together during microcrack growth. The final overload fracture of the specimen was not affected by shot peening.

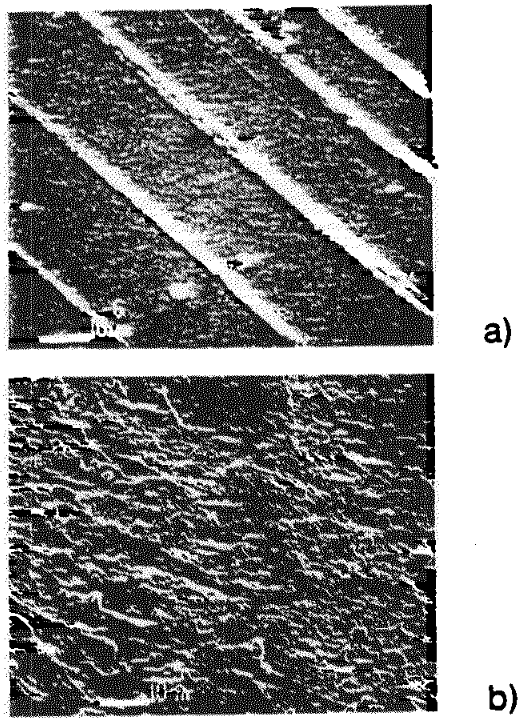


Fig. 5. Surface appearance after fatigue loading a) polished, b) shot peened specimen.

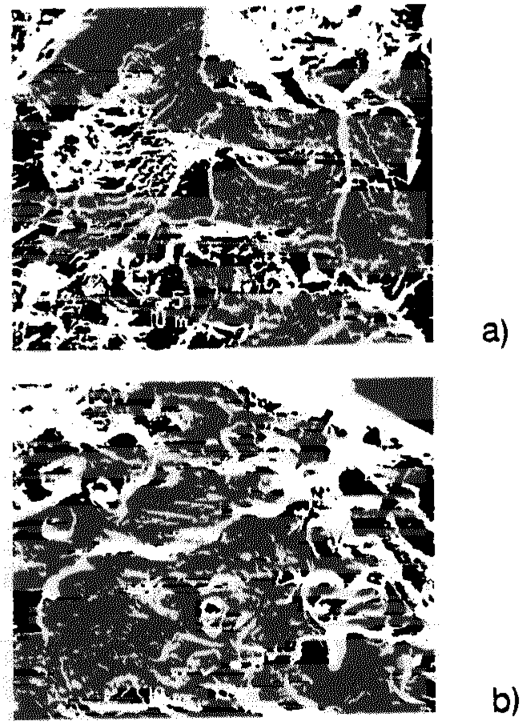
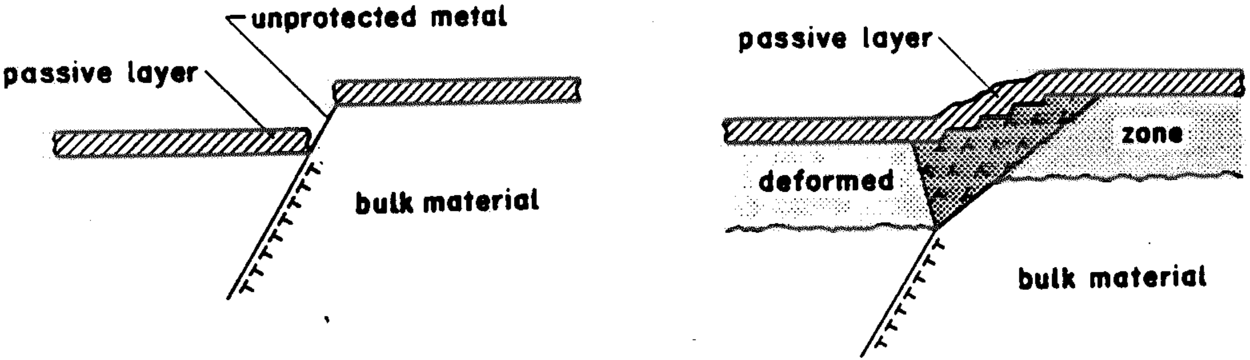


Fig. 6. Fracture surface of a) polished and b) shot peened specimen.

DISCUSSION

The experimental work showed, that shot peening can be applied to increase the corrosion fatigue limit of a material which is fully passive under the choosen corrosion conditions. The beneficial effect of shot peening on corrosion fatigue crack initiation can be explained with the "passive-film-rupture-model" (Laird and Duquette 1972). In the unpeened state, slip steps produced by cyclic deformation may rupture the passive layer on the metal surface, as shown schematically in Fig. 7a. Thereafter, the corrosion medium attacks unprotected metal. During the following repassivation a certain amount of metal is dissolved. Repetition of this film rupture-repassivation mechanism leads to a small notch along the slip band and finally to a growing corrosion fatigue crack.

Shot peening produces a highly deformed surface layer with an increased hardness and compressive residual stresses (Leverant and co-workers, 1979).
Slip bands produced by cyclic deformation of bulk material have to react with that deformed surface material. This interaction leads to a finer slip distribution and decreases the surface slip step height (Fig. 7b). The result is, that much higher bulk deformation (or higher stresses) are required to produce slip steps that are high enough to rupture the passive layer and cause corrosion fatigue cracking. Therefore, shot peening increases the corrosion fatigue limit of a passive material or alloy.



a) unpeened: passive layer rupture

b) shot peened: finer slip distribution

Fig. 7. Influence of shot peening on corrosion fatigue crack initiation (schematic).

The much smaller increase in air fatigue limit by shot peening is due to the work softening of the deformed surface layer during cyclic loading at relatively high stress ranges (more than 90 % of yield strength). A comparison of the hardness curves shown in Fig. 3 indicates clearly the decay of hardness after fatigue cycling at 700 MPa. High stress levels not only decrease the hardness but also decrease the compressive stresses (Leverant and co-workers, 1979). Those two effects indicate clearly, that the potential of shot peening is limited to medium stress ranges. The individual limit for each material is a function of peening intensity, work hardening and work softening characteristics, and has to be determined experimentally. As near surface fractography showed, shot peening also influences the microcrack growth. The compressive stress field within the deformed layer leads to some sort of crack closure and therefore to a slower crack growth rate resulting in a longer fatigue life.

This work showed that shot peening is a useful surface treatment to increase the corrosion fatigue limit of metals and alloys, that behave fully passive in the choosen corrosion medium. The applied shot peening treatment has not been optimized for the steel used. More work is required to find the optimum shot peening parameters to achieve the highest possible corrosion fatigue limit for the steel used. Also the understanding of micro crack growth in layers, deformed by shot peening, has to be extended.

CONCLUSION

1) The corrosion fatigue limit of an austenitic-ferritic stainless steel in acid, hot sodium chloride solution is increased nearly 70 % by shot peening.

2) This increase is due to a reduction of slip step height caused by the interaction of bulk material slip with the highly deformed surface layer.

3) The same shot peening treatment increases the air fatigue limit of the steel used in this investigation only by 7 %. This smaller effect is due to work softening of the deformed surface layer at high stress levels.

4) Shot peening seems to retard micro crack growth within the deformed zone by some sort of crack closure effect.

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