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THE EFFECT OF SHOT PEENING ON THE CAVITATION EROSION OF PURE IRON AND AUSTENITIC STAINLESS STEEL IN DISTILLED AND 1% SALT WATERS

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Summary

Shot peening increased the surface hardness of pure iron and an austenitic stainless steel by factors of about 2.0 times and 1.7 times respectively and the metal was work hardened to a depth of about 0.3 mm. The resistance of the untreated and peened, iron and stainless steel, to cavitation erosion in distilled and 1% salt waters was investigated using a vibratory cavitation test. Shot peening reduced the amount of cavitation of pure iron and stainless steel by factors of about 0.7 times and 0.08 times respectively. Metallographic studies are presented and discussed in relation to the erosion processes.

1. Introduction

Shot peening is a mechanical process of hammering the surface of a metal with suitable pellets or shot, carried typically in a blast of air [1]. Each impact deforms the surface and, when the local stress in the workpiece is above the yield stress, the metal deforms plastically. On rebound of the shot the elastically deformed metal, which was in tension up to the yield stress, then contracts but is restrained by the metal which has flowed. Thus there is formed an indentation in which the surface is in residual compression and the subsurface is in balancing tension [1]. When applied repeatedly over the whole surface, shot peening has three major effects: it produces a residual compressive stress in the surface, it results in work hardening of the surface and it produces a roughened surface [2]. The surface compressive stresses are very effective in resisting stress–corrosion cracking [3] and they have been widely used to resist fracture by fatigue and corrosion–fatigue [1, 4].

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Cavitation erosion has been considered from a physical viewpoint to be a fatigue process resulting from the cyclic stresses induced from the collapse of bubbles [5] and so should be reduced by the effects of shot peening. Limited work has shown that shot peening does reduce the amount of damage due to cavitation erosion but that the decrease was only 7% for a plain carbon steel [6]. The present work investigates the effect of shot peening on the cavitation erosion of pure iron and an austenitic stainless steel in distilled and 1% salt waters.

2. Experimental details

Two single-phase metals were investigated. A high purity iron with a very low inclusion content, of composition 0.02 wt.% C, 0.02 wt.% Si, 0.2 wt.% Mn, 0.007 wt.% P, 0.006 wt.% S and 0.03 wt.% Ni, was supplied as bar, 21 mm in diameter, by the British Steel Corporation. The bar was normalized at 750 °C for 1 h to produce a large and uniform grain size. Austenitic stainless steel, grade 321 S31 (British standard 970), of commercial purity and nominal composition 0.08 wt.% C (maximum), 0.2 - 1.0 wt.% Si, 0.5 - 2.0 wt.% Mn, 0.045 wt.% P (maximum), 0.03 wt.% S (maximum), 17.0 - 19.0 wt.% Cr, 9.0 - 12.0 wt.% Ni and Ti stabilized, was supplied as annealed bar, 25 mm in diameter. The microstructure consisted of uniform grains of austenite although deep etching showed a banding along the axis of the bar. Specimens were machined with their working face a cross-section of the bar.

The machined specimens had an area of 200 mm^2 and the face was polished on 3/0 emery paper (roughness (centre-line average) less than 0.1 μm). The shot-peened specimens were commercially peened by the Metal Improvement Company, Derby. Details of the cavitation erosion testing procedure have been given elsewhere [7]. In outline, the specimens were eroded in distilled or 1% salt waters at 50 ± 2 °C by a vibratory system operating at 20 kHz and with an amplitude of 15 μm. Mass loss measurements ($\pm$0.1 mg) were used to follow the course of erosion and standard optical and scanning electron microscopy were used to examine the damaged surface.

3. Results

Shot peening increased the surface hardness of the iron and stainless steel by about 100% and 70% respectively and affected the metal to a depth of at least 0.30 mm in both cases (Fig. 1). The surface roughnesses of the peened metals are shown in Figs. 2 and 3 and the presence of surface debris on the iron (Fig. 2) should be noted. A section of the peened iron surface showing the nature of the surface debris in more detail is presented in Fig. 4. The figure also shows the uniform annealed grains of the untreated iron (see

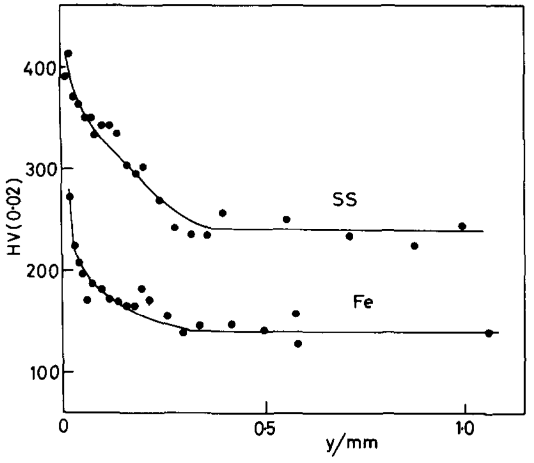


Fig. 1. The surface hardness of shot-peened stainless steel and pure iron.

Fig. 2. Surface topography of shot-peened pure iron. Marker 50 μm.

Fig. 3. Surface topography of shot-peened stainless steel. Marker 50 μm.

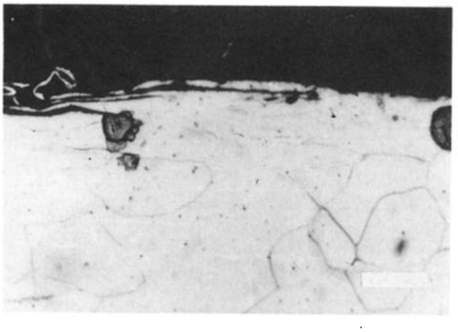


Fig. 4. Section of shot-peened pure iron. Etched with Nital. Marker 20 μm.

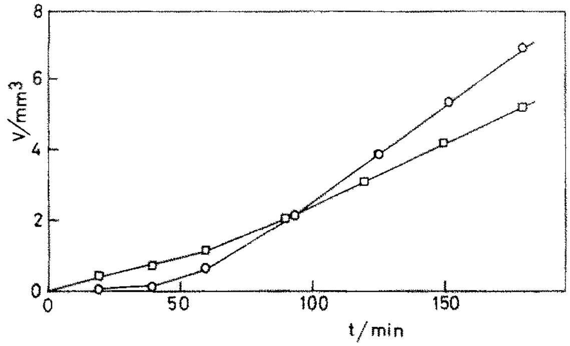


Fig. 5. The amount of erosion V of untreated (○) and shot-peened (□) iron cavitated in distilled water as a function of time t.

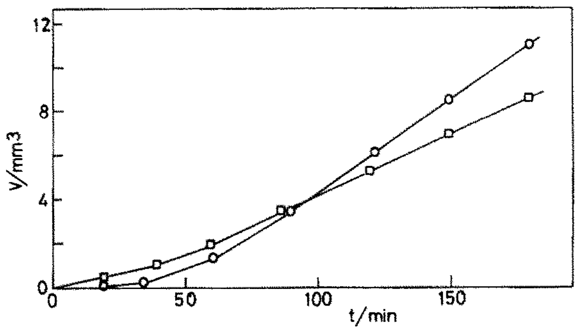


Fig. 6. V of untreated (○) and shot-peened (□) iron cavitated in 1% salt water as a function of t.

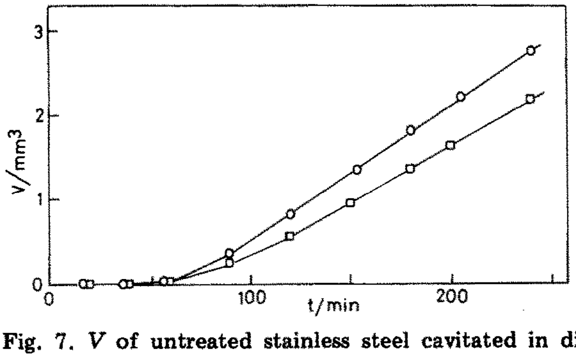


Fig. 7. V of untreated stainless steel cavitated in distilled water (□) and 1% salt water (○) as a function of t.

also Fig. 12) and the subsurface region of intense deformation caused by shot peening.

The mass losses due to cavitation erosion are shown in Figs. 5 - 8 and some erosion parameters from these data are given in Table 1. For convenience we have called the intercept, of the final approximately constant

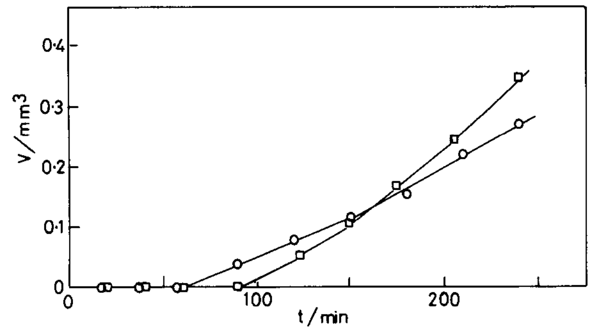
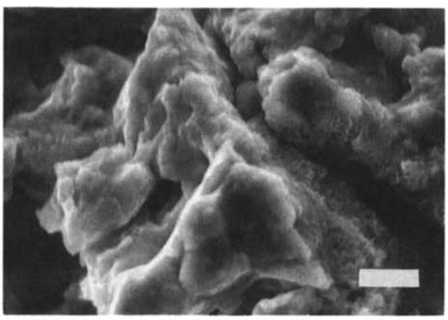


Fig. 8. *V* of shot-peened stainless steel cavitated in distilled water (□) and 1% salt water (○) as a function of *t*.



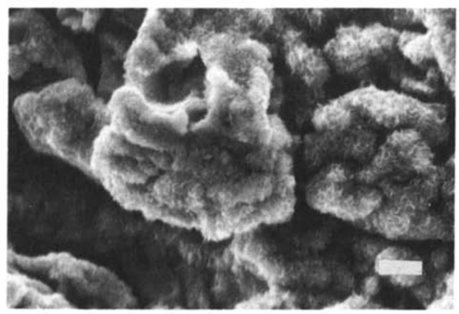


Fig. 9. Surface of shot-peened iron after erosion in distilled water for 180 min. Marker 2 μm.

Fig. 10. Surface of shot-peened iron after erosion in 1% salt water for 180 min. Marker 2 μm.

erosion rate on to the time axis, the (nominal) induction time. The outstanding feature of the data is the dramatic effect that shot peening has on reducing the cavitation damage of austenitic stainless steel. Overall, for both iron and stainless steel, in both distilled and salt waters, peening increases the resistance to damage and the presence of salt in the water increases the amount of damage. An exception is when salt is present in the case of peened stainless steel and this is commented on later. We may also note that, in an early stage of the test, peening increases the amount of damage to the iron (Figs. 5 and 6).

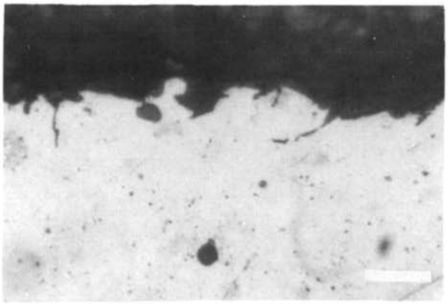
Metallographic details of the eroded iron are shown in Figs. 9 - 12. The general surface topography for iron eroded in both distilled and salt waters is similar (Figs. 9 and 10) but the surface of the iron eroded in salt water is covered with tiny pock marks (Fig. 10). After 20 min cavitation in distilled water the surface of shot-peened iron contained numerous small cracks all about 15 μm deep (Fig. 11) and this is approximately the thickness of the most severely work-hardened layer (see Fig. 1). After 180 min cavitation the

TABLE 1

Cavitation parameters for untreated and shot-peened pure iron and stainless steel in distilled and 1% salt waters

Solution	*Property*	*Fe*			*Stainless steel*		
		Untreated	*Peened*	*Ratio* $\left(\frac{peened}{untreated}\right)$	*Untreated*	*Peened*	*Ratio* $\left(\frac{peened}{untreated}\right)$
Distilled water	Induction time (min)[a]	55	30	0.55	80	110	1.38
	Volume loss after 180 min (mm^3)	6.93	5.17	0.74	1.37	0.19	0.14
	Final slope (mm^3 min^{-1})	0.050	0.033	0.66	0.014	0.0027	0.19
Salt water	Induction time (min)	50	20	0.40	70	60	0.86
	Volume loss after 180 min (mm^3)	10.98	8.54	0.78	1.83	0.15	0.083
	Final slope (mm^3 min^{-1})	0.085	0.054	0.64	0.017	0.0013	0.076
		Ratio $\frac{\text{property in salt water}}{\text{property in distilled water}}$					
	Induction times	0.91	0.68	—	0.88	0.55	—
	Volume losses after 180 min	1.23	2.12	—	1.34	0.81	—
	Final slopes	1.7	1.64	—	1.21	0.48	—

[a]Time intercept corresponding to extrapolation of final slope on to time axis.



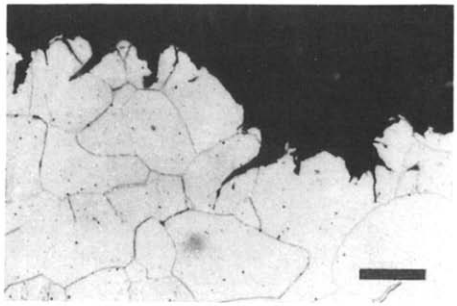


Fig. 11. Section of shot-peened iron after erosion in distilled water for 20 min. Etched with Nital. Marker 20 μm.

Fig. 12. Section of shot-peened iron after erosion in distilled water for 180 min. Etched with Nital. Marker 20 μm.

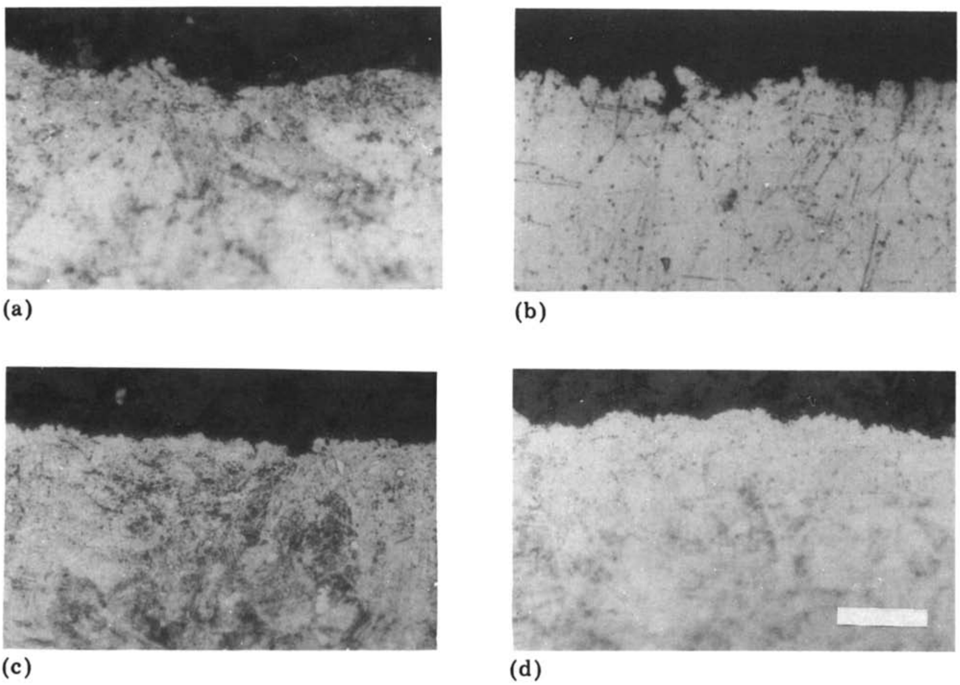


Fig. 13. Section of stainless steel after erosion for 240 min: (a) untreated, distilled water; (b) untreated, salt water; (c) shot peened, distilled water; (d) shot peened, salt water. Etched with Marbles reagent. Marker 20 μm.

outer layer of severely deformed metal has been removed and damage progresses by the formation of intergranular cracks of various depths, orientations and distribution with no metallographic evidence of the adjacent metal being deformed (Fig. 12). Metallographic preparation of the edge of the stainless steel was more difficult and microscopical details were less obvious owing to the smaller amount of damage. Figure 13 shows the sur-

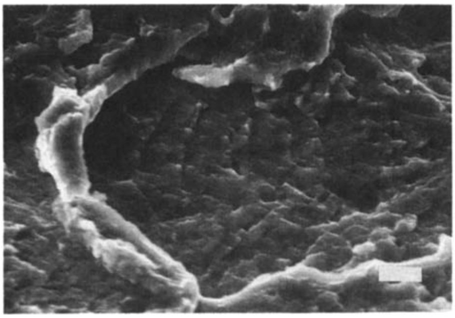


Fig. 14. Surface damage on shot-peened stainless steel eroded in distilled water for 240 min. Marker 2 μm.

face profile in section and it is seen that the unpeened surface in salt water is deeply pitted whereas the peened surface in salt water does not form any similar kind of pits. Details of the shot-peened surface after cavitation in salt water are shown in Fig. 14 where it is seen that the bottom of the damaged region is relatively flat and contains periodic markings similar to the arrest marks observed in fatigue.

4. Discussion

Shot peening produces a surface region in compression and a subsurface region in balancing tension [1]. A typical experimentally determined curve shows the depth of the compressive region to be roughly half that of the total depth of metal affected [8] and we assume in the present case (see Fig. 1) that at least 0.1 mm of metal from the surface is in compression. The maximum volume of metal lost (for iron) is about 10 mm^3 (Figs. 5 and 6) and for a surface area of 200 mm^2 this would correspond to a depth of metal lost of 0.05 mm. We assume that this is within the region of compression. This is given support by the constant cavitation erosion rate which starts at mass losses which must be well within the compression region close to the surface (Figs. 5 and 6). The mass loss due to cavitation erosion of stainless steel is so low (Figs. 7 and 8) that all the damage will be well within the compressive region.

A feature of the effect of shot peening on the cavitation erosion of iron in both distilled and salt waters is the initial faster erosion rate of the peened iron compared with the unpeened iron (Figs. 5 and 6). This is considered to be due to the extended laps and surface debris on the iron (Figs. 2 and 4) which will be easily detached during cavitation erosion. The effect of shot peening on the cavitation damage of iron in both distilled and salt waters reduces the damage by only a factor of about 0.7 times (Table 1).

Stainless steels have a much higher resistance to cavitation erosion than pure iron (Table 1). This is clearly due to the high work-hardening capacity of austenitic stainless steels [9] which resists the fatigue processes leading to cavitation damage [5]. Shot peening decreases substantially the cavitation damage (Table 1) since, in addition to the inherently high work-hardening capacity of stainless steels [9], the surface is severely cold worked (Fig. 1) and the metal is in residual compression. The effectiveness of shot peening in resisting the formation of pits and cracks is clearly shown in Fig. 13. Suh [10] has proposed a delamination theory of wear in which subsurface cracks nucleate and then propagate parallel to the surface to give lamellar wear debris. There was no evidence of this process with the iron but occasionally with the stainless steel there were flat-based regions which may have formed by this process and which had fatigue-like arrest lines on the bottom (Fig. 14).

Salt in the water typically increases the corrosion rate by forming local action cells. This appears to be the case with iron (compare Figs. 9 and 10) and peening does not appear to have any significant effect (Table 1). However, cavitation erosion in salt water is a conjoint action and it is not the local corrosion cells that are important but rather the formation of pits which would concentrate the mechanical stress. In view of this it is surprising that the presence of salt in the water decreased the amount of cavitation damage of the peened stainless steel (Table 1), but the effect is not substantial, and the result must be treated with caution since the amount of cavitation damage measured is quite small.

5. Conclusions

A pure iron and an austenitic stainless steel have been commercially shot peened and the untreated and peened metals eroded in a vibratory cavitation apparatus. The following conclusions are drawn.

Shot peening reduced the cavitation damage of pure iron by a factor of about 0.7 times in both distilled and 1% NaCl waters. Shot peening reduced the cavitation damage of stainless steel in distilled and 1% NaCl waters by 0.15 times and 0.08 times respectively.

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