

# Shot peening, laser surface melting and the cavitation erosion of an austenitic grey iron

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An austenitic flake graphite grey iron in the as-cast condition (AC) was laser surface melted (LSM), and the AC and LSM irons were shot peened (ACp and LSMp). The irons were eroded in distilled water and 0.02% and 3.0% NaCl waters at 50 °C using a 20 kHz, 15 µm peak-to-peak amplitude, ultrasonic device capable of electrochemical measurements. Laser surface melting eliminated the graphite flakes and formed a crack-free uniform layer of predominantly fine austenite and some martensite. The hardnesses of the AC, ACP, LSM, and LSMp irons were 200, 350, 700, and 750 HV, respectively. In distilled water, the erosion rate of the AC iron was reduced by factors of 0.80, 0.05, and 0.04, for the ACp, LSM, and LSMp materials, respectively. In salt water the corrosion rate was increased, and the corrosion-enhanced erosion rates of the AC, ACp, LSM, and LSMp materials were fractions 0.26, 0.16, 0.75, and 0.75, respectively, of the total erosion rate. Corrosion was highest in the irons containing graphite, but the effect of corrosion on the erosion rate was highest in the irons that did not contain graphite. Results of detailed metallographic examination are presented, and the mechanism of cavitation erosion damage is discussed.

## 1. Introduction

Cavitation erosion may be considered from a physical viewpoint as a fatigue process resulting from the cyclic stresses from the collapse of the bubbles [1], and hence a material will have a high resistance to cavitation erosion if it absorbs a large amount of energy during deformation and resists fracture. Simultaneous action of corrosion may increase the erosion rate considerably (see, for example, [2, 3]), and to have a high resistance to cavitation erosion in a particular solution the material must also in general have a high resistance to corrosion in that solution. Austenitic stainless steels have a high work-hardening capacity [4] and an outstanding resistance to corrosion, and these properties give austenitic stainless steels an excellent resistance to cavitation erosion in both distilled and salt waters [5].

Cast irons are more complex than steels, and grey irons, which contain graphite, are widely used as cylinder liners. Poor fuel quality increases the corrosive wear of diesel engines, and a substantial reduction in the amount of corrosion may only be achieved by the use of cast-iron liners with an austenitic matrix [6]. Austenitic grey irons are only occasionally used as cylinder liners [6, 7], but their use may be expected generally for components in hydraulic machinery whenever cavitation erosion occurs under severely corrosive conditions [8, 9]. Laser surface melting eliminates the presence and deleterious action of graphite flakes [3], and shot peening work hardens the surface and produces a residual compressive stress in the surface [10, 11] which resists fatigue and corrosion-fatigue [10, 12], stress-corrosion cracking

[13], and cavitation erosion [5, 14]. The processes may also be expected to increase the corrosion resistance, and it would therefore appear that they could be applied with advantage to austenitic grey irons. The present work investigated the effects of shot peening and laser surface melting on the cavitation erosion resistance of an austenitic grey iron with particular reference to the extent of the electrochemical corrosion and its influence on the erosion process.

## 2. Experimental procedure

A commercial iron with a typical composition range (wt %): total carbon 2.6 to 3.0, silicon 1.9 to 2.4, manganese 1.0 to 1.5, sulphur 0.10 maximum, phosphorus 0.3 to 0.6, nickel 13.5 to 15.0, chromium 1.2 to 2.0, and copper 5.5 to 7.5 was used. The microstructure consisted predominantly of randomly orientated graphite flakes (ASTM A247-67 form VII type A), in an austenitic matrix containing a discontinuous network of phosphide with no ferrite or cementite present. Specimens in four conditions were tested: as-cast (AC), as-cast and shot peened (ACp), laser surface melted (LSM), and laser surface melted and shot peened (LSMp).

Machined specimens were laser surface melted by the Laser Application Group of the AEA Technology Culham Laboratory. An incident power of 1 kW from a 1 kW industrial CO<sub>2</sub> laser and a workpiece speed of 10 mm sec<sup>-1</sup>, under a helium shield, was used to produce tracks 1.1 mm wide which were then overlapped. Machined specimens were commercially peened by the Metal Improvement Company, Derby.

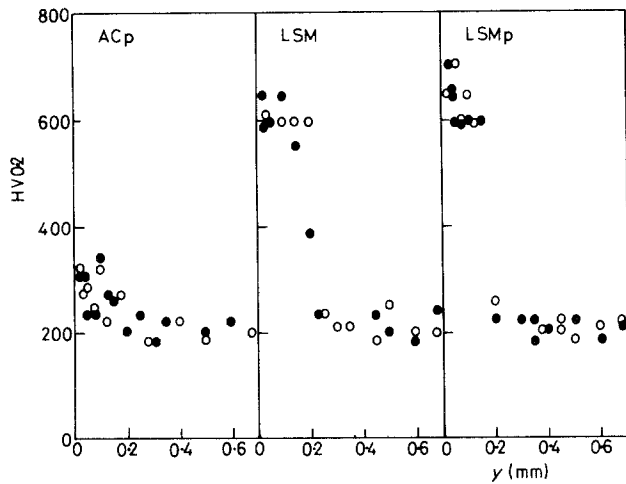


Figure 1 Hardness HV0.2 as a function of the depth below the surface,  $y$ , for the as-cast and peened (ACp), laser surface melted (LSM), and laser surface melted and peened (LSMp) coatings. (○, ●) Data from two separate traces.

The measured hardness profiles of the ACp, LSM, and LSMp specimens are shown in Fig. 1. It is seen that the depth of both the laser-melted and shot peened regions are approximately 0.2 mm. Shot peening increased the hardness of the as-cast material (approximately 200 to 220 HV) to about HV 350, while laser surface melting increased the hardness to 700 HV. Shot peening increased the hardness of the laser melted surface by about 50 HV. X-ray diffraction showed that laser surface melting retained the austenitic matrix of the as-cast material but also formed a small amount of martensite. Details of the microstructures of the laser surface melted coating and the shot peened layer are given later along with the results.

Specimens with an area  $113 \text{ mm}^2$  polished to a  $1 \mu\text{m}$  diamond finish were eroded in distilled water and 0.02% and 3.0% NaCl waters at  $50^\circ\text{C}$ , using a 20 kHz and  $15 \mu\text{m}$  (peak-to-peak) ultrasonic device fitted with a facility for electrochemical measurements. Full details of the apparatus, testing procedures, and metallographic techniques have been given elsewhere [2, 3].

### 3. Results

Erosion kinetics for all the materials consisted of an incubation period followed by a linear rate. Mass losses as a function of time for each of the materials eroded in 3.0% NaCl water are shown in Fig. 2, and full details from all the results are collected in Table I. It is seen that both shot peening and laser surface melting reduce the erosion rate, and that the effect of laser melting is much greater. Peening the LSM iron increases the erosion resistance but the effect is small. Salt in the water always increases the erosion rate, and it is to be noted that the effect of salt in the water is relatively small with the as-cast materials, but with the laser surface melted specimens the increase is considerable (see the ratios in Table I).

Electrochemical measurements taken during the course of an erosion test are shown in Table II.

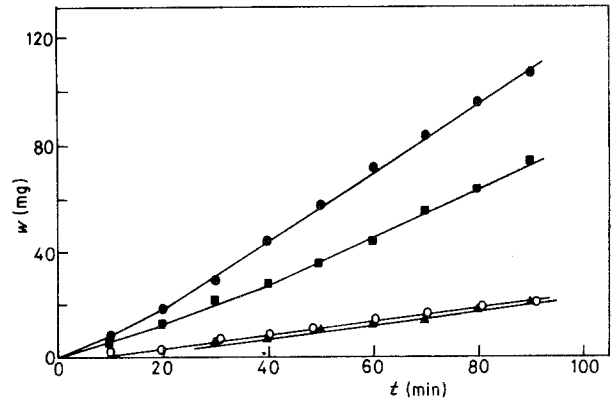


Figure 2 Mass loss,  $w$ , of an austenitic grey iron in various conditions eroded in 3.0% NaCl water as a function of time,  $t$ . (●) As-cast, (■) as-cast and peened, (▲) laser surface melted, and (○) laser surface melted and peened.

Typically, cavitation increases the corrosion current, and two points from the results are important. First, the corrosion currents of the as-cast irons increase with the time of erosion, whereas those of the laser-melted materials stay the same, and second, the increase in the corrosion of the as-cast material on cavitating is much higher (value 5.08 in Table II) than any other material.

All the eroded surfaces were examined using the scanning electron microscope and representative microstructures of the damage are shown in Fig. 3. Considerable damage had occurred with the as-cast and the as-cast and peened materials. In each case the damage was very similar, and this is illustrated for the as-cast material eroded in distilled water and 3.0% salt water in Fig. 3a and b, respectively. It is noted that in Fig. 3b the eroded surfaces were relatively smooth and showed none of the corrosion pock marks that were a feature of low alloy cast irons eroded in 3.0% salt water [2]. Only a small amount of surface damage

TABLE I Erosion parameters of an austenitic grey iron in various conditions eroded in distilled water and 0.02% and 3.0% NaCl waters

| Sample conditions <sup>a</sup> | Solution   | Incubation time (min) | Final linear rate, $r$ ( $\text{mg h}^{-1}$ ) | $r$ (salt) <sup>b</sup> |                 |
|--------------------------------|------------|-----------------------|---|-------------------------|-----------------|
|                                |            |                       |   | $r$ (salt)              | $r$ (distilled) |
| AC                             | Distilled  | 7                     | 56  | 1.0                     |                 |
|                                | 0.02% salt | 7                     | 56  | 1.0                     |                 |
|                                | 3.0% salt  | 6                     | 80  | 1.4                     |                 |
| ACp                            | Distilled  | 20                    | 45  | 1.0                     |                 |
|                                | 0.02% salt | 7                     | 40  | 0.9                     |                 |
|                                | 3.0% salt  | 10                    | 55  | 1.2                     |                 |
| LSM                            | Distilled  | —                     | 3   | 1.0                     |                 |
|                                | 0.02% salt | 25                    | 8   | 2.7                     |                 |
|                                | 3.0% salt  | 20                    | 16  | 5.3                     |                 |
| LSMp                           | Distilled  | —                     | 2   | 1.0                     |                 |
|                                | 0.02% salt | —                     | 4   | 2.0                     |                 |
|                                | 3.0% salt  | —                     | 16  | 8.0                     |                 |

<sup>a</sup> AC = as-cast, ACp = as-cast then peened, LSM = laser surface melted, LSMp = laser surface melted then peened.

<sup>b</sup> For any sample condition, ratio of rate in salt water to that in distilled water.

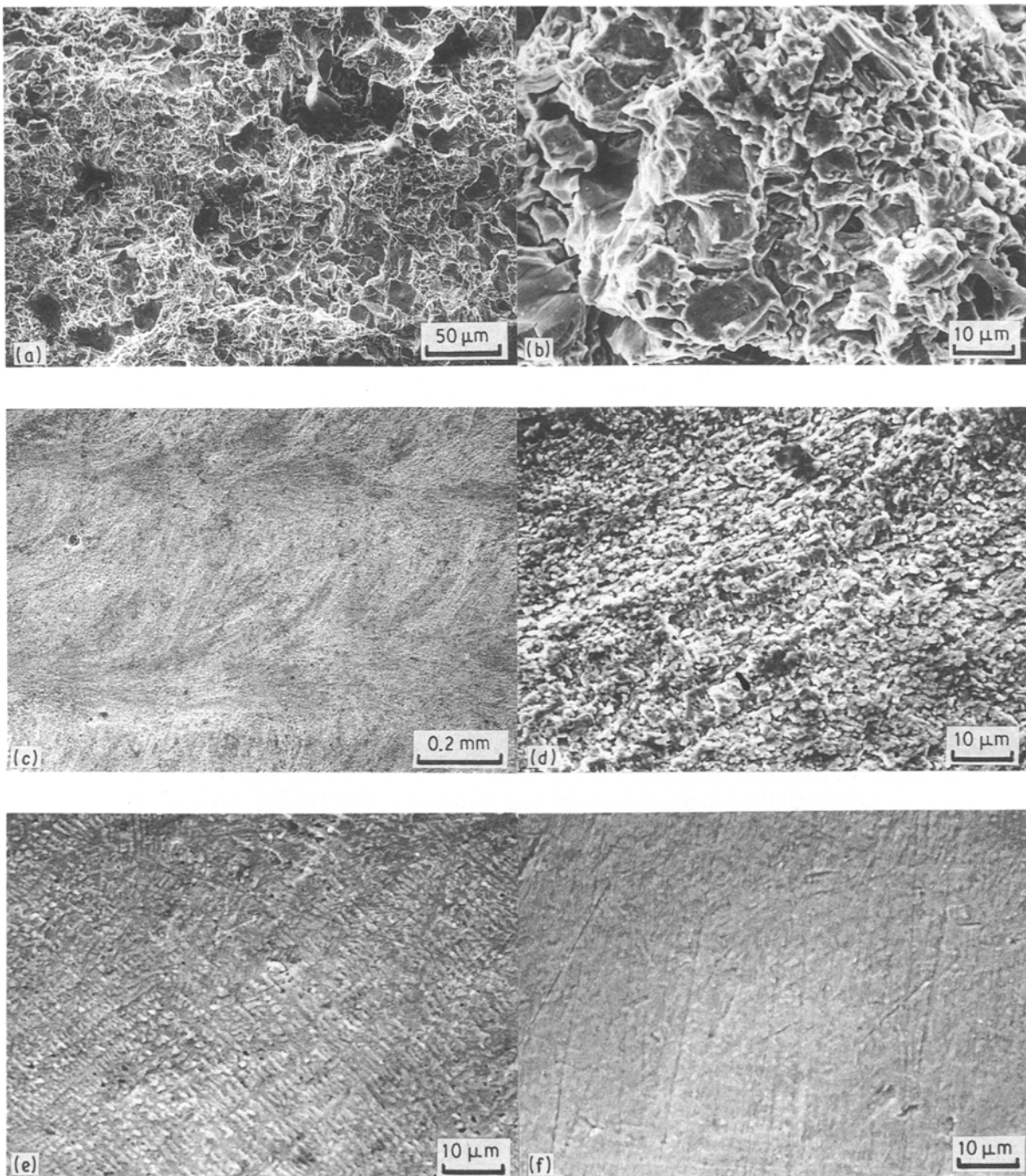


Figure 3 Surface of austenitic grey iron in various conditions eroded in distilled and 3.0% NaCl waters for various times. (a) AC in distilled water for 120 min, weight loss 98 mg, (b) AC in 3.0% salt water for 90 min, weight loss 107 mg, (c) and (d) LSM in distilled water for 120 min, weight loss 3 mg, (e) LSM in 3.0% salt water for 90 min, weight loss 20 mg, and (f) LSMp in 3.0% salt water for 90 min, weight loss 21 mg.

occurred in the laser-melted specimens (e.g. Fig. 3c, d and e) and in the LSM and peened specimens (e.g. Fig. 3f). The laser-melted surface was uniform, with little evidence of the individual tracks and the absence of cracks. This is in contrast to the massive cracks that occurred during solidification of the laser-melted layer on low alloy cast irons [3].

Metallographic details of the laser surface melted coating and some eroded specimens are shown in Fig. 4. The base iron consists of austenite dendrites with particles of phosphide and clusters of graphite flakes (bottom part of Fig. 4a and Fig. 4b and c). Laser melting the surface eliminated the graphite flakes and formed very fine austenite dendrites and a fine interdendritic mixture (the coating in Fig. 4a, and Fig. 4d). The coating had only a small amount of porosity. The

effects of shot peening were not evident in the microstructure of either the ACp or LSMp specimens, although the effect of work hardening occurred to a depth of 0.2 mm (Fig. 1).

In the AC and ACp eroded specimens, extensive damage was associated with the graphite flakes (Fig. 4b and c), and there is some evidence that the phosphide resisted erosion. Thus in Fig. 4c regions of phosphide tended to be relatively unattacked. In 0.02 and 3.0% NaCl waters, the nature of the damage to the AC and ACp specimens appeared to be the same as that observed in distilled water except that the attack was deeper. All the LSM and LSMp specimens eroded in distilled or salt waters were virtually unaffected, and what damage that did occur was evenly spread over the surfaces with no localized attack (Fig.

TABLE II Corrosion parameters of an austenitic grey iron in various conditions corroded under static and cavitating conditions in 3.0% NaCl solution

| Sample condition <sup>a</sup> | Time of testing (min) | Static                            |                                   | Cavitating             |                        | Ratio                                     |
|-------------------------------|-----------------------|-----------------------------------|-----------------------------------|------------------------|------------------------|---|
|                               |                       | $E_{\text{corr}}^{\text{b}}$ (mV) | $I_{\text{corr}}^{\text{c}}$ (mA) | $E_{\text{corr}}$ (mV) | $I_{\text{corr}}$ (mA) | $\frac{I(\text{cav.})}{I(\text{static})}$ |
| AC                            | 5                     | -652                              | 0.43                              | -562                   | 0.76                   | 1.77                                      |
|                               | 90                    | -655                              | 0.58                              | -557                   | 2.95                   | 5.08                                      |
| ACp                           | 5                     | -665                              | 0.63                              | -555                   | 0.63                   | 1.00                                      |
|                               | 90                    | -660                              | 0.69                              | -550                   | 1.01                   | 1.46                                      |
| LSM                           | 5                     | -650                              | 0.40                              | -565                   | 0.71                   | 1.78                                      |
|                               | 90                    | -680                              | 0.42                              | -560                   | 0.70                   | 1.67                                      |
| LSMp                          | 5                     | -875 <sup>d</sup>                 | 0.44                              | -575                   | 0.61                   | 1.39                                      |
|                               | 90                    | -670                              | 0.55                              | -575                   | 0.61                   | 1.11                                      |

<sup>a</sup> See Table I.

<sup>b</sup>  $E_{\text{corr}}$  with respect to SCE.

<sup>c</sup>  $I_{\text{corr}}$  calculated from polarization resistance; see text.

<sup>d</sup> Uncertain value.

4d). In some cases (Fig. 4d) no evidence of damage could be seen.

#### 4. Discussion

Cavitation erosion may be considered primarily a process of fatigue due to the repeated stressing by the cavitation bubbles [1]. Shot peening decreases the erosion rate of the as-cast austenitic iron in distilled water by a factor of  $(45/56) = 0.80$  (Table I), and while this is substantial, it is far less than the factor 0.19 observed with stainless steels [5]. Thus it appears that

the presence of the graphite flakes (and perhaps the phosphide), in the iron decrease considerably the effectiveness of the residual compressive stress and cold work of shot peening to reduce cavitation erosion. Laser surface melting drastically reconstitutes the microstructure by eliminating the graphite flakes and refining the microstructure. This has a pronounced effect, and it reduces the erosion rate in distilled water by a factor of  $(3/56) = 0.05$  (Table I). Peening adds to this improvement, but the increase is relatively small.

Salt in the water increases the erosion rate (Table I). However, with the AC and ACp materials the increase

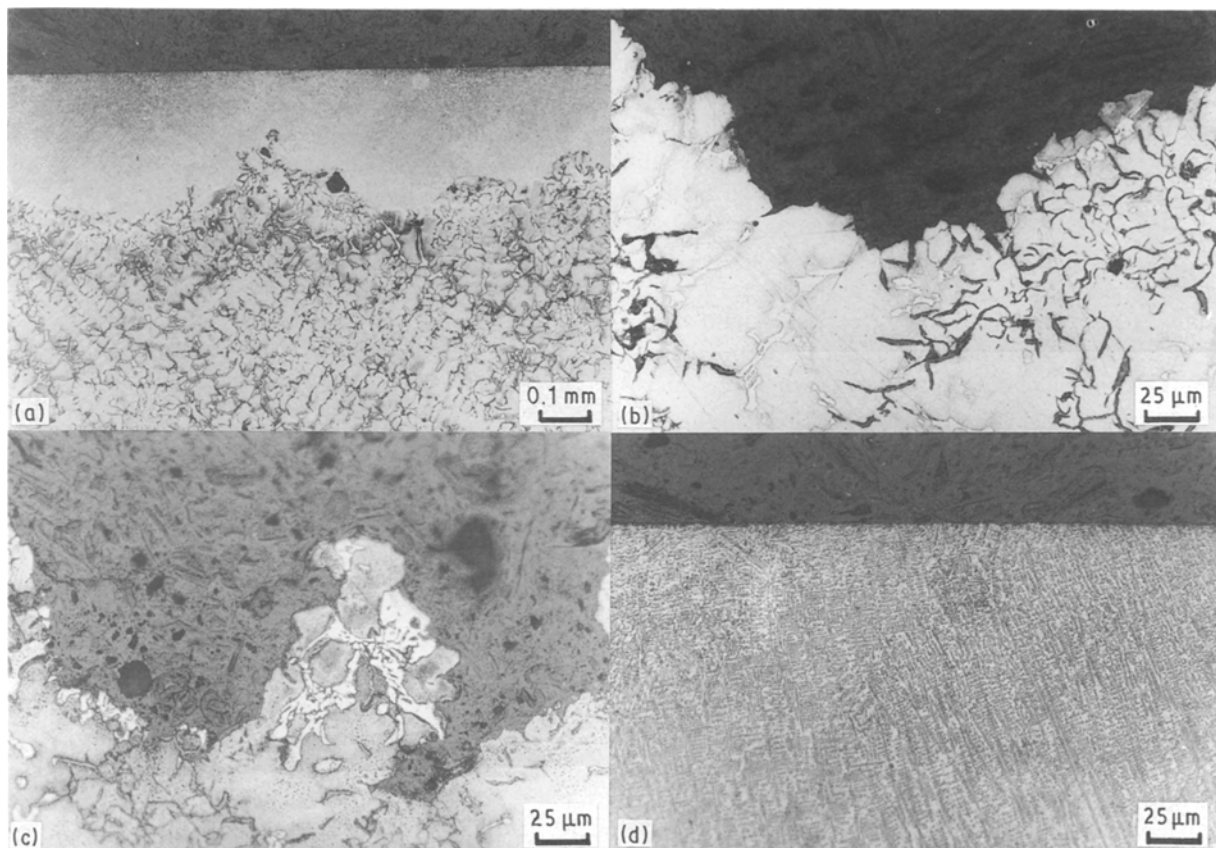


Figure 4 Metallographic sections of an austenitic iron: (a) laser surface melted layer (not eroded), (b) AC eroded in distilled water for 120 min, weight loss 98 mg, (c) ACp eroded in distilled water for 120 min, weight loss 74 mg, and (d) LSMp eroded in 3.0% salt water for 90 min, weight loss 21 mg. Optical micrographs; etched Marbles reagent.

is small (by factors of 1.4 and 1.2, respectively), whereas the increase with the LSM and LSMp materials are much larger (by factors of 5.3 and 8.0, respectively). Thus it would appear that the corrosion pits formed in salt water are important in promoting fracture in the laser-melted material, whereas in the as-cast material such corrosion pits are relatively ineffective compared with the stress-concentrating action of the graphite flakes present.

Corrosion is intimately related to the salt in the solution by increasing the conductivity of the solution and depassivating and pitting the metal surface [15]. After 5 min cavitation, the corrosion currents for the AC, ACp, LSM, and LSMp materials were similar (0.76, 0.63, 0.71, and 0.61 mA, respectively; Table II). This reflects a similar surface condition, area, and local solution chemistry. The currents stay the same for 90 min for the LSM and LSMp materials where very little surface damage has occurred. But for the AC iron there is a large increase to 2.95 mA. It is assumed this is due to the large area of the eroded surface (Fig. 3a and b), and also, possibly, to the increased acidity and depassivation within the deep cavities [15]. The decreased corrosion of the ACp material compared with the AC material is probably due to the compressive action of the peened surface resisting dissolution.

Cavitation erosion in a corrosive environment is a complex conjoint action, and it is not so much the average current measured, but rather the local current producing stress-concentrating pits, that is important. With the present surface area and material, a current of 1 mA corresponds very approximately to metal dissolving at a rate of  $1 \text{ mg h}^{-1}$ . Hence assuming that erosion in distilled water is 100% mechanical action, then the corrosion enhanced erosion for the as-cast material is  $80 - 56 - 2.95 = 21 \text{ mg h}^{-1}$ . The corrosion enhanced erosion for the ACp, LSM, and LSMp materials is similarly calculated to be 9, 12 and  $13 \text{ mg h}^{-1}$ , respectively. Thus the fraction of the damage due to corrosion-enhanced erosion in the AC, ACp, LSM, and LSMp materials is 0.26, 0.16, 0.75, and 0.81, respectively. While these figures are approximate, they nevertheless show clearly the influence of corrosion on cavitation erosion in corrosion environments. In particular, it is seen that when the microstructure does not contain inherent cracks or notches, e.g. graphite flakes, or it resists crack formation by deformation, then the effect of corrosion is very important.

## 5. Conclusions

An austenitic flake graphite grey iron in the as-cast condition (AC) has been laser surface melted (LSM), and the AC and LSM irons have been shot peened (ACp and LSMp). The irons have been eroded in distilled water and 0.02% and 3.0% NaCl waters at  $50^\circ\text{C}$  using a 20 kHz ultrasonic facility with a  $15 \mu\text{m}$  peak-to-peak amplitude. The conclusions are drawn.

1. Shot peening increases the hardness of the AC iron ( $\approx 200 \text{ HV}$ ) to a maximum of  $350 \text{ HV}$ . The iron is affected to a depth of  $0.2 \text{ mm}$ .

2. Laser surface melting forms a uniform layer  $0.2 \text{ mm}$  thick, free of cracks, with a hardness  $700 \text{ HV}$ , consisting of a very fine microstructure predominantly of austenite with a small amount of martensite. Shot peening increased the hardness of the LSM coating to  $750 \text{ HV}$ .

3. Shot peening and laser surface melting reduced the cavitation erosion rate of the AC iron in distilled water by factors of 0.80, 0.05, and 0.04 for the ACp, LSM, and LSMp materials, respectively.

4. Salt in the water increased the erosion rate. The corrosion enhanced erosion rate of the AC, ACp, LSM, and LSMp materials is calculated to be fractions 0.26, 0.16, 0.75, and 0.81, respectively, of the total erosion rate.

5. Corrosion under cavitation conditions is highest after extended erosion for the AC iron. But the effect of corrosion on the erosion rate is lowest in the AC iron, and highest in the LSM and LSMp irons which do not contain any stress-concentrating graphite flakes.

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