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Influence of ultrasonic cavitation on surface residual stresses in AISI 304 stainless steel

M. R. SRIRAMAN, R. VASUDEVAN
Department of Metallurgical Engineering, Indian Institute of Technology Madras, Chennai 600 036, India

The effect of ultrasonic cavitation in water on residual stress changes in AISI 304 stainless steel has been investigated. Studies indicate that high-intensity ultrasonic cavitation introduces a very high compressive residual stress at the surface (due to work-hardening) even for short durations of exposure at ambient temperatures. With increased exposure, the stresses become more compressive; however, they tend to reach a saturation value. Different combinations of temperature, time and cavitation intensity were tried out and the best effects were noticed for a treatment temperature of 5 °C. 304 stainless steel was chosen for the present study on account of its amenability to strong work-hardening. The test specimen was attached to the tip of an ultrasonic vibrator and immersed in the cavitating liquid, i.e. water. However, even in situations where the specimen was kept in a stand-off position close to the vibrator tip (with water in between) similar effects were noticed. The maximum depth of hardening was found to be about 70 μm. During this process, there was also a mild roughening of the surface. An incidental observation pertains to the formation of both "α" and "ε" martensites at the surface detectable by X-ray diffractometer recordings for specific conditions of cavitation treatment. The required high intensities of vibration in this study were obtained through an in-house built high-power ultrasonic generator working at a frequency around 20 kHz.

1. Introduction

Cavitation is defined as the repeated nucleation, growth and violent collapse of cavities or bubbles in a fluid arising out of pressure fluctuations due to vibrations or flow patterns in the system [1]. When a liquid is subjected to sufficiently high stresses, vapour-filled voids or cavities are formed at weak regions, this being accentuated by the presence of gaseous, liquid and solid impurities which act as nucleation sites. These cavities grow (under tensile conditions) and collapse (when subjected to compressive stresses or higher hydrostatic pressures), the driving force being the difference between the hydrostatic pressure and the vapour pressure of the liquid [1]. Ultrasonic cavitation (occurring under ultrasonic vibration conditions at 20 kHz) may set in at pressures as low as 0.3 MPa [2] while the collapse pressures can reach values even up to about 1000 MPa. The average size (radius) of the cavities formed in vibratory cavitation is usually around 10 μm, although it can reach 50 μm. The collapse time, t, of the cavity is related to its initial radius, R_0, the liquid density, ρ, and the hydrostatic pressure at collapse, P, by the following expression [1]

$$t \propto R_0 \left(\frac{\rho}{P}\right)^{1/2}. \quad (1)$$

While the surface tension and viscosity of the liquid are relatively insignificant, the compressibility of the liquid, vapour and the presence of any trapped gases has a profound effect on the final stages of the collapse. The cavities which are generated in large numbers form cavity clusters which, when subjected to increased hydrostatic pressure, collapse in a concerted manner, starting with the outer perimeter of the cluster and proceeding inward to the central cavity [1]. The central cavities, therefore, carry a tremendous amount of energy. Because of such a localized nature of the cavitation process, the implosion causes a significant temperature increase locally, that can reach even 5000 K. There is usually a noise signalling the progress of cavitation, known as cavitation noise. The well-known ultrasonic cleaning procedure is based on this principle of ultrasonic cavitation. However, the intensities involved for cleaning purposes are usually low, namely in the range of $0.5–5 \times 10^4$ W m^{-2} [2].

The present investigation was aimed at studying the influence of cavitation (in water) on the surface residual stresses in austenitic stainless steel (of 304 type). Previous studies on a 0.45% C steel and 4140 steel by Mathias *et al.* [3] indeed suggest that this principle could be used for introducing compressive residual stresses on the surface. The advantages of having compressive residual stresses at the surface are many,

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one such being the accompanying improvement in fatigue strength. Being a material with a marked propensity to work-hardening, an even stronger effect is to be expected in 304 stainless steel. However, the cavitation intensities obtained in conventional ultrasonic cleaners are inadequate for this purpose. The specimen itself needs to be set into high amplitude vibration in the liquid or alternatively held very close to the vibration source, with the liquid in between. Only under such situations is there a violent cavitation close to the sample. This (cavitation) treatment is analogous to shot peening with the exception that the shots, in this case, are not of metal (or glass) but of bubbles of water [4]. As a consequence, material erosion can also take place. However, for materials such as austenitic stainless steels (or even cobalt alloys), erosion may not be of much concern, because the energy of bombardment is more absorbed through (their) severe plastic deformation of the surface thereby limiting the possibility of surface erosion [5].

2. Experimental procedure

The material used for investigation contained 0.07 wt % C, 18.49 wt % Cr and 9.25 wt % Ni. The machined specimens (dimensions shown in Fig. 1) had a residual stress value of close to zero after electrolytic polishing with perchloric acid–acetic anhydride solution. The residual stress in all cases was measured by the X-ray $\sin^2\psi$ technique using a Rigaku stress analyser employing CrK_α radiation and the (3 1 1) line. The sample was mechanically coupled to the concentrator (also referred to as a horn) attached to a magnetostrictive transducer which, in turn, was energized by a power source (a detailed description of the equipment is given elsewhere [6]). It was then kept just immersed in about 500 ml water in a beaker and subjected to ultrasonic vibrations (Fig. 2a). The specimen was then vibrated at the desired amplitude at a frequency of 19 kHz, which is off-resonant, the resonant value being 21.8 kHz. Cavitation experiments were also carried out with the specimen not coupled to the horn but kept at a stand-off position, about 1.5 mm from the vibrating concentrator tip, as shown in Fig. 2b. In this case, the sample was fixed to a support that was firmly held in the beaker. The double arrows in Fig. 2 indicate the direction of vibration of the sample/concentrator. Before every insonation treatment, the sample (unless otherwise stated) was again electropolished to a low stress value. The experiments were carried out at room temperature (RT) for various vibration amplitudes up to the maximum of about 75 μm peak-to-peak (henceforth, the vibration amplitude quoted will refer only to the peak-to-peak value) for different exposure times. The displacement amplitude was measured using a non-contact sensor with associated electronics (described elsewhere [4]). (The amplitudes of vibration quoted pertain to the values obtained from measurements made with the sample vibrating in air. The actual values in water could be slightly lower.)

In addition, some experiments were also conducted at 55 °C (when cavitation in water is supposed to be

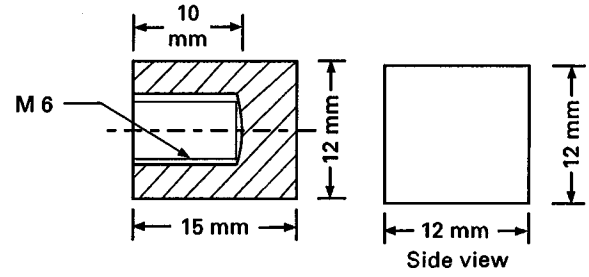

Figure 1 Typical dimensions of the specimen used for ultrasonic cavitation experiments (figure not to scale).

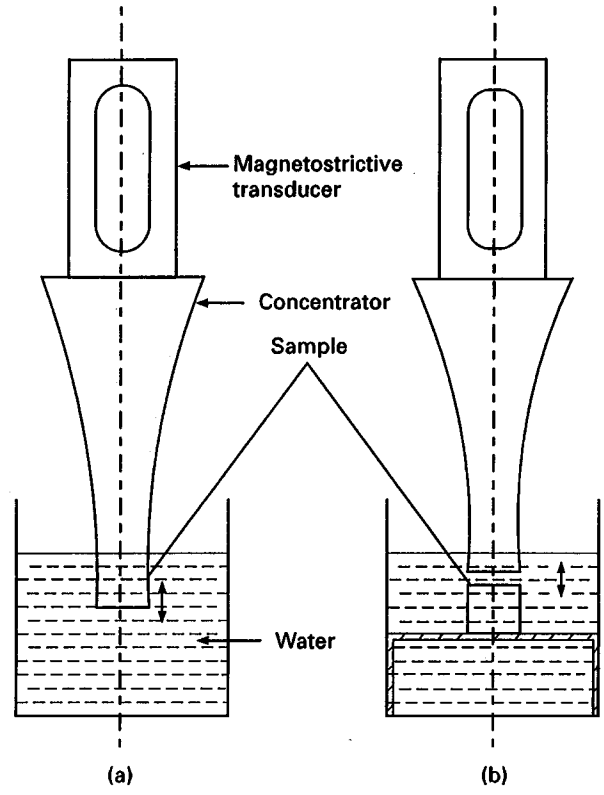

Figure 2 A schematic drawing indicating alternative positions of the sample for cavitation studies: (a) sample which is part of the vibrating system; (b) sample held stationary at a stand-off position (figure not to scale).

strongest [2]), as well as at 5 °C (to study the effect at temperatures lower than RT). While the temperature was controlled to ±2 °C for the 55 °C treatments, the experiments at RT and 5 °C were carried out without maintaining any control over the temperature. This resulted in the water being warmed up by a maximum of about 5 °C, for RT treatment, and by about 5–10 °C for the 5 °C treatment, depending upon the duration of the treatment, due to cavitation itself and the influence of the surrounding temperature. The treatment was continuously given for the desired duration in most cases, except with respect to those reaching 1800 s or above, when the treatment was broken up into smaller intervals of 900 or 600 s, depending upon whether the insonation was at RT or 5 °C, respectively.

The variation of stress below the surface was determined through successive electropolishing. The amount of material (i.e. surface layer) removed for a given electropolishing time was determined after

measuring the overall decrease in length of the specimen for complete electropolishing (which restores the residual stress), using a micrometer, on the assumption that the rate of electropolishing is uniform. In a few cases, perth-o-meter readings were also taken to determine the topographical nature of the surface. Slow step-scan X-ray diffractometer patterns using a Shimadzu (XD-D1) X-ray generator were carried out with a view to detecting possible martensitic transformations at the surface. Optical pictures of the cavitated surface were taken on selected samples using a Leitz microscope to observe surface features.

3. Results

An appreciable increase in compressive residual stress following cavitation treatment was clearly noticed every time. Even for an insonation period of just 18 s, the stress value was sharply enhanced. Fig. 3 shows the effect of ultrasonic cavitation at different vibration amplitudes (intensities) and exposure times at RT. A steep increase in compressive residual stress, proportional to the vibration amplitude, is seen during the initial stages of exposure. The difference narrows down with larger treatment times and appears to reach a saturation value at about 600 s.

With a view to determining the kinetics behind the build-up of compressive stresses, the specimen was, in a separate experiment, progressively subjected to cavitation for specific durations. The residual stress and roughness values were measured (Fig. 4). As stated before, the initial steep jump in the residual stress slows down later, reaching a saturation value. It is also seen (from Fig. 4) that prolonged cavitation only promotes erosion without any attendant benefits with respect to the residual stress value. Efforts to ascertain the incidental variation in hardness (superficial) were not very successful as uniform indentations could not be obtained because of topographic fluctuations (Fig. 5 shows a typical picture of a cavitated surface).

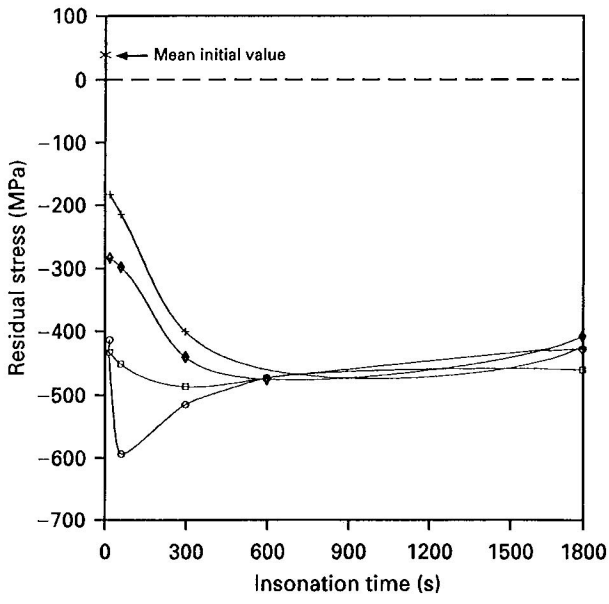

Figure 3 Residual stress changes due to ultrasonic cavitation at RT for vibration amplitudes of (○) 75 μm, (□) 35 μm, (◇) 20 μm and (+) 10 μm peak-to-peak (p–p).

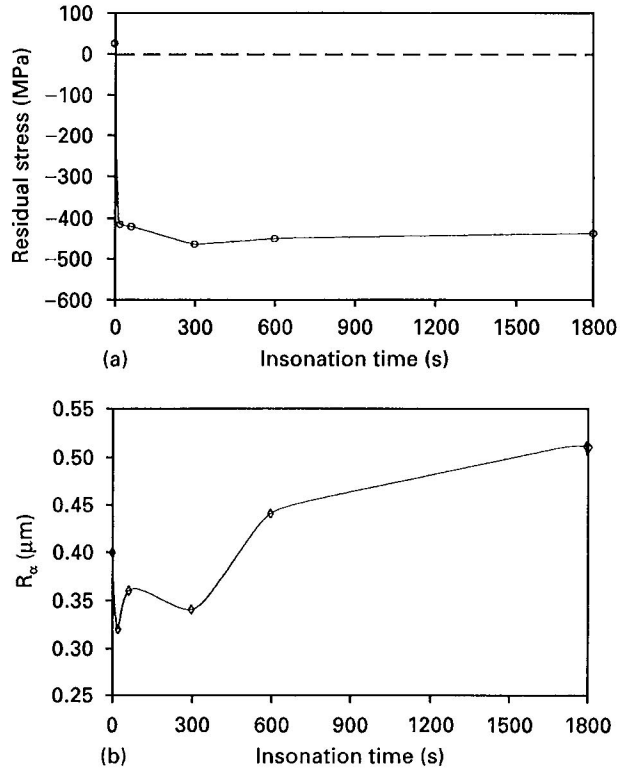

Figure 4 Effect of ultrasonic cavitation at RT at 75 μm p–p amplitude on (a) residual stress build-up, and (b) surface roughness.

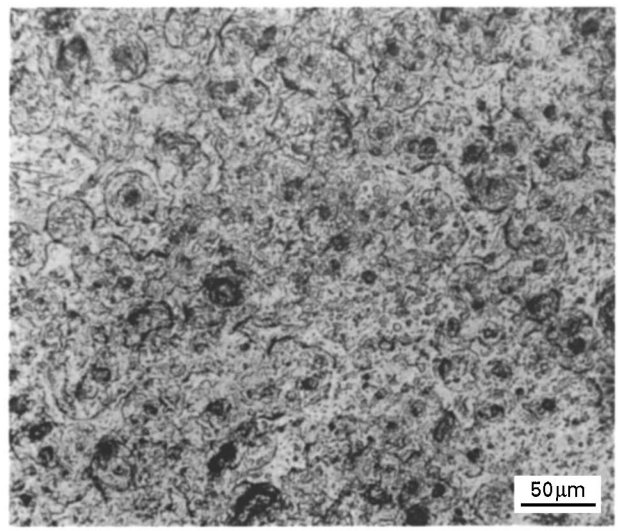

Figure 5 Optical micrograph of a sample subjected to ultrasonic cavitation at RT for 600 s at 75 μm p–p amplitude.

A depth-wise variation in stress for RT insonated specimens was determined for (a) 75 μm amplitude for different exposure times, and (b) 35 μm amplitude for 300 s exposure (Fig. 6). Although it was seen that even a treatment of as short a duration as 18 s enhances the compressive stress to around −420 MPa, the depth to which the effect is felt is only of the order of 30–40 μm from the surface. The depth of hardening seems to diminish for exposure times longer than 300 s, with a 1800 s treatment giving only about 40 μm

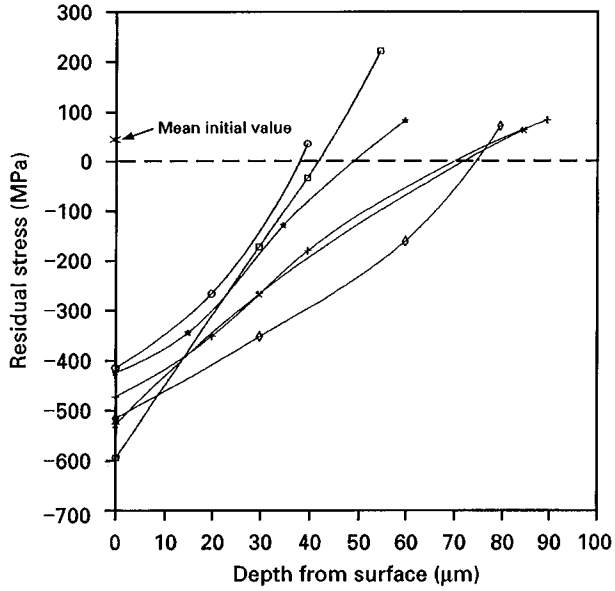

Figure 6 Residual stress profile beneath the specimen surface for RT ultrasonic cavitation at 75 μm p–p for (○) 18 s, (□) 60 s, (◇) 300 s, (+) 600 s, (*) 1800 s and (×) at 35 μm p–p amplitude for 300 s.

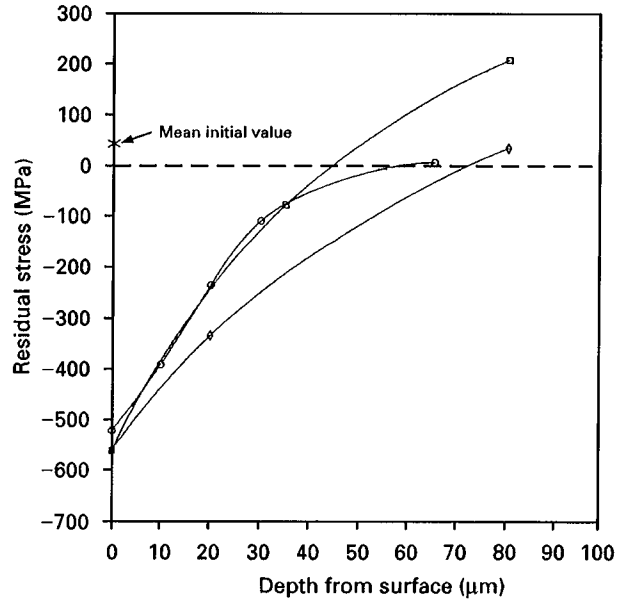

Figure 8 Residual stress profile beneath the specimen surface for ultrasonic cavitation at (○) 55 °C for 300 s at 75 μm p–p, and at 5 °C for 300 s (□) 75 μm p–p, (◇) 35 μm p–p amplitude.

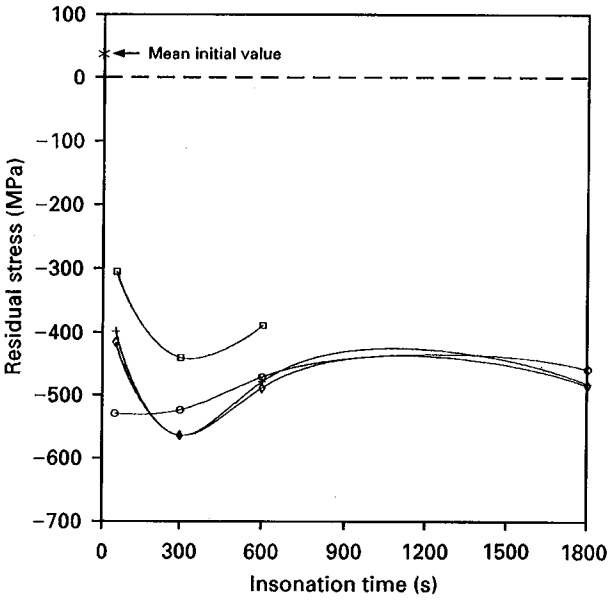

Figure 7 Residual stress changes due to ultrasonic cavitation at 55 °C for (○) 75 μm p–p, (□) 20 μm p–p, and at 5 °C for (◇) 75 μm p–p and (+) 35 μm p–p amplitude.

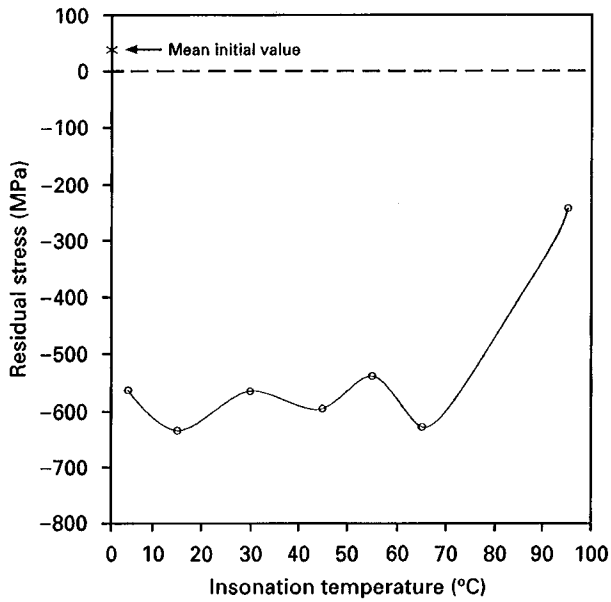

Figure 9 The effect of water temperature on residual stress for 300 s insonation at 75 μm p–p amplitude.

depth. Based on this study, the maximum depth of hardening achievable seems to be about 70–80 μm.

Fig. 7 shows the results with regard to 55 and 5 °C treatments. It is observed that a treatment at 55 °C does not produce any significant advantage over a room-temperature treatment, with respect to residual stresses, despite cavitation supposedly being stronger at that temperature. However, as before, saturation is reached in about 600 s. Interestingly, at 5 °C there seems to be no effect of an increased amplitude, with both 35 and 75 μm producing similar results. The depth of hardening for a 55 °C treated sample at 75 μm amplitude was about 35 μm (Fig. 8). However, at 5 °C the depth of compressive residual stresses is more for a 35 μm amplitude than for a 75 μm amplitude. It should be noted that the surface residual stresses are almost identical for the two amplitudes of vibration.

Fig. 9 shows the stress value obtained for a cavitation treatment time of 300 s at 75 μm amplitude for different water temperatures (from 5 °C up to boiling point). It is seen that the values are more or less close, in the range of − 550 to − 650 MPa, except at 95 °C, when the value is much less, being around − 200 MPa.

Table I shows the results obtained at RT and 5 °C for a stationary specimen (stand-off arrangement) when kept at a distance of about 1.5 mm from the vibrator end. Compressive residual stresses are set up, although at a slower rate, in comparison to the case of a vibrating sample. With increased separation,

TABLE I Effect of ultrasonic cavitation on residual stresses–comparison between a vibrating sample and a stationary sample

Condition	Time (s)	Residual stresses (MPa)	
		With vibrating sample configuration	With stationary sample configuration (stand-off distance = 1.5 mm)
At RT at 75 μm p–p[a] amplitude	18	− 413.8	–
	60	− 594.3	− 376.6
	300	− 514.8	− 447.2
	600	− 472.7	− 527.6
	1800	− 423.6	− 358.9
At RT at 35 μm at p–p[a] amplitude	300	− 527.6	− 335.4
At 5 °C at 35 μm p–p[a] amplitude	300	− 561.9	− 428.5

[a] Peak-to-peak.

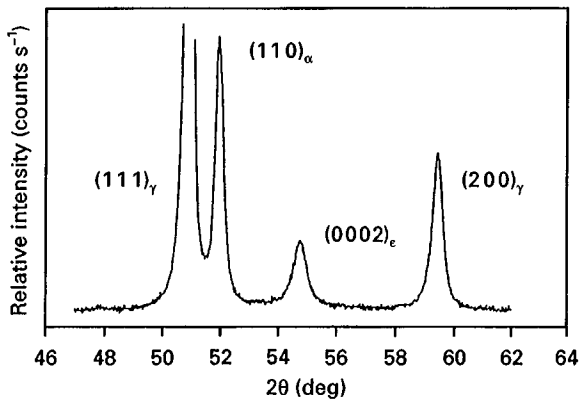

Figure 10 X-ray diffractometric recording of the specimen surface, ultrasonically cavitated at 5 °C for 3600 s at 35 μm p–p amplitude.

however, the values diminished, as is only to be expected. For a specific case of 600 s insonation at RT at 75 μm amplitude, while the residual stress value for a stand-off distance of 1.5 mm was − 527.6 MPa, the value decreased to −445.2 MPa and −263.8 MPa for stand-off distances of 3 and 4 mm, respectively. However, the depth of hardening with a stand-off arrangement for a treatment at RT for 600 s at 75 μm amplitude was found be almost unaltered, namely around 60 μm.

Another interesting observation was that, in most cases, along with an increase in compressive residual stress, a martensitic transformation took place even at ambient temperatures. In fact, two types of martensites, α (b c c) and ε (h c p), were seen to be formed. While epsilon was primarily present for an RT-treated sample, both types of martensite were observed at 5 °C. For an extreme case of prolonged cavitation at 5 °C at 3600 s, both α (1 1 0) and ε (0 0 0 2) lines were of noticeably strong intensity (Fig. 10). It was interesting to note that the alpha martensitic line was stronger than even the (2 0 0) line of austenite. However, neither phase showed up when the insonation temperature was 55 °C, thus perhaps indicating that the M_d temperature for this material is around or a little below 50 °C.

4. Discussion

The results show that ultrasonic cavitation bombardment produces effects similar to shot peening. Severe work-hardening of the surface is seen to take place resulting in the build-up of very high compressive residual stresses. At RT, the maximum possible value seems to be obtained at a shorter time with increasing intensity of vibration, following which only minor variations by way of readjustments take place. The values obtained for an amplitude of 35 μm itself are quite high and it may not be necessary to use higher intensities of cavitation. This tendency on the part of the stress to saturate has also been observed in AISI 4140 steel by Mathias *et al.* [3].

It is seen that a 5 °C treatment at 35 μm amplitude is adequate to produce the best effects. The introduction of compressive stresses of the same order right from a temperature of about 65 °C down to 5 °C, at least at the surface, shows that cavitation in water at 75 μm amplitude is very powerful at all temperatures around ambient.

The depth of hardening generally appears to be in the range of 30–70 μm with the highest value of 70 μm obtained for a 300 s treatment. The depth of compressive stresses could appear a little small compared to conventionally shot-peened surfaces, probably because the "impactors" here are not solid shots but only water bubbles. The momentum transfer thus cannot be expected to be felt over large distances beneath the surface [4]. Nevertheless, the depth may still be adequate for improving fatigue or wear resistance in many cases.

One other effect of cavitation is to cause undulations on the surface as can be detected by a perth-ometer. This is because of an erosion action that the surface experiences due to cavitation, leading to the alternate formation of ridges and valleys. However, the R_a values are generally seen to be on the lower side as compared to shot peening. Even for the extreme case of prolonged exposure up to 3600 s at 5 °C at 35 μm amplitude, the roughness, R_a, reaches only a value of 0.63 μm. The lower roughness could be due to the combined effects of a finer-scale impingement and a high work-hardening of the material.

The differences in the residual stress values between vibrated specimens and specimens held in a stand-off arrangement are only to be expected. The separation between the two becomes very important as seen from the results. This again is in conformity with the findings of Mathias *et al.* [3]. The effect of intensity is more pronounced here. This may be an interesting method for hardening small objects at selective locations.

5. Conclusion

Ultrasonic cavitation produces shot peening-like effects. Appreciable values of residual stresses (extending to reasonable depths) can be introduced on the

metal surface at fairly high intensities of cavitation. In highly work-hardening materials, such as 304 stainless steel, this could well be done without any significant erosion of the surface. While in most cases the intensity corresponding to a vibration amplitude of 35 μm is found to be adequate for a vibrating specimen configuration, it may be beneficial to employ higher vibration amplitudes for hardening specimens held in a stand-off position. Such an intense vibration is usually not obtained from conventional ultrasonic cleaners but only through special high-power ultrasonic systems as used here.

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