The suppression of cavitation and water droplet erosion by laser peening.

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Executive summary:

Laser peening is an effective way to suppress cavitation and water droplet erosion. Estimates based on experimental data on liquid impact erosion indicate that one can expect an increase in incubation time of approximately 14 times and a reduction of the erosion rate of approximately 6 times with laser peening. It would be very useful to quantify this estimation with actual tests of laser peened samples.

Analysis:

Cavitation , the collapse of air bubbles, is an efficient mechanism that generates material erosion in propellers , rudders, pump impellers and valves and in piping carrying hot liquids. As liquids flow through regions of low pressure bubbles can form. As the liquid re-enters areas of higher pressure the bubbles collapse thereby generating a pressure pulse and fast moving jets of liquid which locally impinge nearby surfaces and eventually begin to fatigue spall the surface material resulting in material erosion. Below we will discuss the processes producing erosion and will argue that the laser peening can strongly suppress the cavitation process.

Consider an empty bubble of size R collapsing to zero volume during the finite time $\tau=0.9 R\sqrt{\rho}/P$ where the P is the pressure in the liquid and ρ is the density. The velocity of the liquid and the pressure increase during the process of collapse is given by:

$$V^4 = \frac{2P}{\rho}\left(R_o/R(t)\right)^3 \qquad P(t) \sim 0.156\, P \left(R_o/R(t)\right)^3 \qquad (1)$$

In the real situation the collapse is arrested by the growth of internal pressure, liquid compressibility and viscosity. Nevertheless, the pressure is large enough to induce ionization and produce a plasma (sonoluminescence).

There are three main steps producing cavitation erosion.

First, when the collapse is arrested and rebounds a strong shock is produced. This shock impinges on the metal surface. It was believed before the nineteen sixties that the shock was a main source of damage [1,2]. The pressure, determined by the specific conditions of the process arrested the collapse at the minimal radius of the bubble. The theoretical estimate predicts a maximum pressure between 1 and 2 kbars dropping inversely (1/r) with the distance exceeding the initial bubble radius [2].

Second, during the sixties it was observed experimentally and explained theoretically that the interaction with the metal surface breaks the collapse spherical symmetry. As a result during the collapse a reentrant, fast moving jet is formed and directed to the metal surface. The mechanism of this jet formation is similar the jet formation obtained in shaped explosive charges. The jet velocity U can be estimated as[1]:

$$U = \alpha\sqrt{\frac{P}{\rho}}$$

Various models give a numerical value for α of about 10, but for some special shapes of the bubble it can be as large as 60 [1]. The jet thereby impinges the metal with subsonic velocity U producing a pressure pulse with amplitude

$$P' = ZU$$

where Z, is the liquid impedance. For water Z~$1.3*10^5$ g/sec cm^2. For α~10 the pressure can be 1.3 kbars (19 ksi).

Third, when the collapse arrests and the liquid motion rebounds the motion of the liquid becomes unstable and the bubble breaks into a cloud of small ones. The cloud collapses again producing another shock.

In all these situations the pressure is typically less than the Hugouniot Elastic Limit (HEL) and we do not expect the immediate damage to the metal surface, the damage becomes noticeable only after some time, after many bubble collapses generate a local fatigue failure.

The generally accepted explanation of cavitation damage is thus as follows [1]: Repetitive stresses due to the bubble collapse causes local surface fatigue failure and the subsequent detachment or flaking off of small pieces of material. It is consistent with the metallurgical evidence of damage in hard materials. The resultant surface usually has a jagged, crystalline appearance consistent with fatigue failure and is usually fairly easy to distinguish from the erosion due to solid particles, which has a much smoother appearance [2].

Physically, the situation is similar to the erosion of airplane and missile components by rain droplets [3]. The high velocity liquid droplet impacts generate localized pressure pulses similar to those produced by the bubble collapse. Typically, the pressure pulse is below the HEL and damage takes place as a fatigue failure. The damage is manifested only after some incubation time (number of impacts) and then, grows linearly with the number of impacts.

The results of multiple experiments on liquid impact erosion were fitted well by one simple relation. The description in [3] is based on similarity with torsion experiments and the parameters used to describe these experiments. The key parameter is the ultimate tensile stress σ_u. A useful factor S is defined as:

$$S = \frac{4(b-1)}{1-2\nu}\sigma_u \qquad (1)$$

with parameter b>>1 determined from the torsion fatigue experiments. The fit of the experimental data gives a value for the number of impacts N* after which erosion will start

$$N^* = 7 * 10^{-6}\left(\frac{S}{P}\right)^{5.7} \propto \sigma_u^{5.7} \qquad (2)$$

Here P is the pressure produced by the impact. To fit the experimental data the constant b for a long list of materials in [3] is b=20.9. Only for Cu and magnesium is b lower lower at b=17.6.

In the case of cavitation the expression (2) must be an average, in some way, over the variety of the possible pulse pressures. But the result must be proportional to $\sigma_u^{5.7}$.

When the sample is laser peened the imprinted compressive stress effectively increases the ultimate tensile stress, because one must initially overcome the compressive stress. Typically, one can expect an increase of the effective σ_u in peened material of about 60%. According to (2) it means that the increase in incubation time (number of pulses before erosion begins) of approximately 14.6 times.

Laser peening (LP) plastically deforms and leaves residual compressive stress deep into the subsurface metal layer. It is recognized that this greatly suppresses fatigue failure. The compressive stresses arrest the crack propagation and stop the erosion. The thick compressed layer, much thicker than the typical size of the erosion crater, usually in the range of 0.1-0.3 mm, indicates that laser peening must decelerate the material erosion.

The experiments demonstrate that when the erosion of the metal surface starts, the amount of removed material per unit of surface m increases linearly with the number of impacts [3].

$$m = \alpha(N - N^*) \qquad (3)$$

Fitting of the experimental data [3] gives for the constant α

$$\alpha \propto \left(\frac{P}{S}\right)^{3.99} \propto \frac{1}{\sigma_u^{3.99}} \qquad (4)$$

One can see that the increase in σ_u not only increases the incubation time, but also reduces the erosion rate. If the peening increases σ_u 1.6 times from (4) we will get a reduction of the erosion rate of 6.5 times.

Summary:

In summary laser peening can be an effective way to suppress cavitation erosion. The estimates based on experimental data on liquid impact erosion indicates that one can expect an increase in incubation time of approximately 14 times and a reduction of the erosion rate of approximately 6 times with laser peened samples.

References:

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