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Laser shock micro-forming of stainless steel: thermal effects at high repetition ps-pulses

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Abstract

A solid-state ps-pulsed laser, emitting at 1064 nm and repetition rate from 0.4 to 10 kHz, was used to laser peen form thin stainless steel metal sheets (50 µm thick). The laser repetition rate and the scanning speed were adjusted to keep the pitch distance between consecutive laser pulses constant.

The effect of the treatment was measured by the bending angle induced. When using the lowest repetition rate, up to 90° bending angles are achieved. As the laser repetition rate increases, the bending angle is dramatically reduced although every sample was processed with the same total number of pulses and with the same pulse energy.

Despite the small temperature increase in the whole sample, the local accumulative thermal effect at high pulse repetition has a strong influence on the bending angle. High temperature relaxes the stress induced by laser peen treatment and thus prevents bending the sample.

Keywords: Laser peen forming; simulation; residual stress; LSP

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1. Introduction

The present work focuses on stainless steel 316L, a material widely used in medicine and the aerospace industry among others thanks to its high corrosion resistance. In order to improve this material lifetime, surface treatments were applied being laser shock processing (LSP) one of them. In LSP an intense shock using a nanosecond laser (Sano et al., 2006) is induced via laser ablation (Liao et al., 2016). Typically, the sample is placed under a transparent confining medium (typically water) and the laser light impinges on the material through it. The confinement medium allows us to increase the pressure due to the shock wave energy (Peyre et al., 1998).

In time LSP developed into other objectives such as laser peen forming (LPF) where the shockwaves are used to induce plastic changes in the samples curvature by inducing compressive stress on the surface (Hu et al., 2010). Those stresses elongate the sample to the lateral direction, this was simulated using FEM (J. L. Ocaña et al., 2004) (J. Ocaña et al., 2009). If we scan along the surface the deformation accumulates (Sagisaka et al., 2010). LPF has been used to bend titanium in combination with laser cutting (Sagisaka et al., 2015) where they proved the increase of the bending angle of the samples with laser pulse.

Allegedly, ultrashort lasers (picosecond and femtosecond lasers) due to their short time interaction allow the deposition of all energy beam on the material without plasma absorption and thus, avoiding thermal effects (Stuart et al., 1996). The combination of ultrashort lasers and LPF seems to be a great choice for micro shaping processing due to the bending capacity of the technique and the fact that it could be free of thermal damage. However, we want to prove the importance of temperature relaxion times (the sample does not cool down instantaneously) using picosecond lasers. High repetition rate and the overlapping pulses in a short time could rise the temperature and therefore, thermal events must be taken into account.

2. Experimental setup

A diode-pumped solid-state ps-pulsed laser (Ekspla Atlantic 355-60), emitting at 1064 nm, was used to laser peen form stainless steel metal sheets. The duration of laser pulse was 13 ps and the laser repetition rate (f) was varied from 1 to 20 kHz. The laser pulse energy used was 115 µJ, measured after the focusing lens using a thermal sensor with an accuracy of 3%.

Figure 1 shows the metallic sample held in a container with water and the laser beam focused on the sample surface using a fixed lens (Linos Focus-Ronar) with focal length of 58 mm. Laser gaussian beam waist at focus was ω_0 = 10 µm radius.

Metallic samples are 50 µm sheets of 316L Stainless Steel, which were laser cut in the shape of a “T” (Figure 1). The broader part of the T was glued on the edge of a microscope glass slide while the narrower part was held in a cantilever configuration. The cantilever is 5 mm long and 1 mm wide. Laser micro-forming was performed on the top side of the sample. The scanning X-direction is perpendicular to the cantilever and the laser started firing at least 1 mm outside the sample, avoiding any acceleration effect on the edges of the sample.

The beam was scanned along the surface by moving the sample with two computer-controlled X and Y linear translation stages, also shown in Figure 1. The pitch distance (P_x) between consecutive laser pulses was 1 µm and the pitch distance between consecutive lines (P_y) was varied to get different treated areas. The laser repetition rate and the speed of the X-direction stage were adjusted to keep the same P_x while varying the time between laser pulses ($\tau = 1/f$).

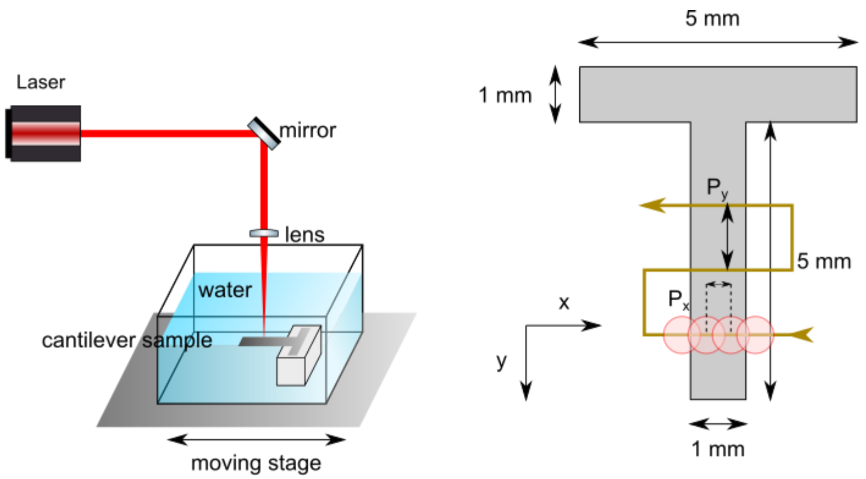

Figure 1: Experimental setup and laser scanning. The figure at the left shows the basics of the experimental setup. The gaussian beam is directed and focused on the cantilever section of the sample which is submerged under water (confining medium). The figure of the right shows the geometry of the sample and the way the laser is working on it. Starting from the lower position the stage moves as the axes are displayed. It also shows the horizontal pitch (P_x), distance between laser shots and the vertical pitch (P_y), distance between lines

The sample is set on top of a holder, so the focus beam is on the cantilever section, but the sample remains underwater. Going through one of the walls of the container, a water pipe pours filtered distilled water inside the volume while a drainage pipe takes it out. The water circulates through these two pipes thanks to a water pump. The aim after this is to ensure there is a constant water level between the sample and the air but, above all, keep the water clean.

The laser spot on the sample was 48 µm, which represent the diameter of the affected zone by a single laser pulse measured by confocal microscopy. Therefore, the beam overlapping using P_x = 1 µm was 97.9%. We want to emphasize that throughout the experiment, although f is varied, the number of shots per point never changes, we achieve that changing the scanning speed with the repetition rate.

3. Results and discussion

After irradiating an area of length (L) the sample is modified with a bending angle (δ). The curvature radius (R) is que quantity that links the two first using equation (1)

$$L = R\delta \qquad (1)$$

In order to obtain δ we measured the slopes of the non-treated region with respect the horizontal, obtaining for the curvature radius the following equation

$$R = \frac{L}{\varphi} = \frac{L}{\delta} = \frac{L}{\pi \pm \alpha_1 - \alpha_2} \qquad (2)$$

Where α_1 and α_2 are the angles of the slopes and sign of the first depends on whether the slope is positive or negative. Figure 2 shows different samples with different bending angles (and radius of curvature), the straight parts are easy to measure to obtain α_1 and α_2.

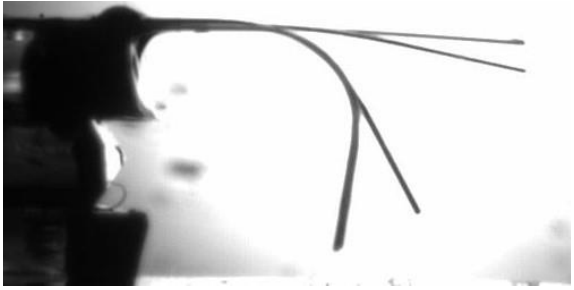

Figure 2. Different samples that the only thing that changes is their repetition rate. Maximum bending (smaller radius of curvature) corresponds to low repetition rate whereas the minimum (higher radius) goes with the bigger repetition rate

A set of experiments using the same energy and treating a 1 mm length area were carried varying the repetition rate but not the number of pulses per spot (we had to change the scanning speed accordingly) as it is shown in Figure 3. Radius of curvature is a more suitable magnitude for the process description because if we double the length of the treated area, we double the bending angle, but the radius of curvature remains the same due to equation (1).

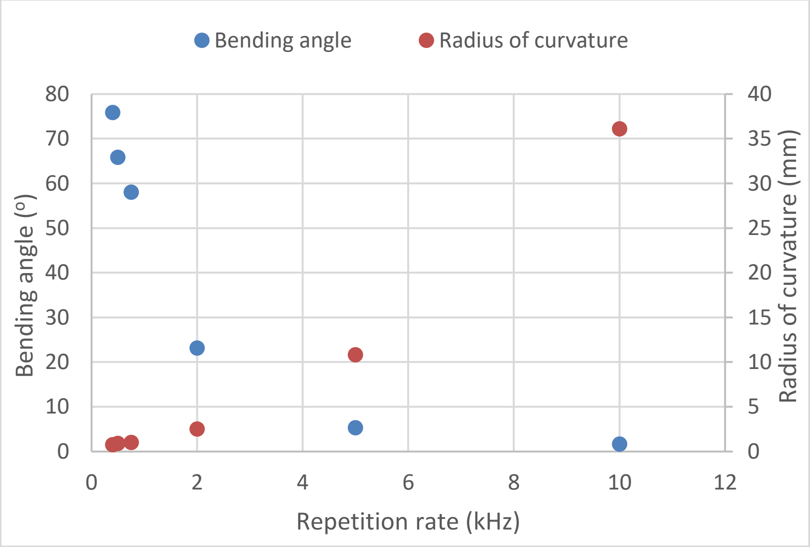

Figure 3. For the same density of energy, the repetition rate clearly affects the process being useless for bending at higher values

If the thermal effects were negligible, as the literature suggests, the same radius of curvature should have been obtained because the mechanical treatment would be the same all the time. Instead, when the repetition rate is very high the samples exhibit higher radius (more like straight lines). We explain this because at high repetition rate the sample does not cool downs completely and the following shots rises the temperature relaxing the stresses the shockwaves had induced. Figure 4 is a thermal simulation that reflects this observation.

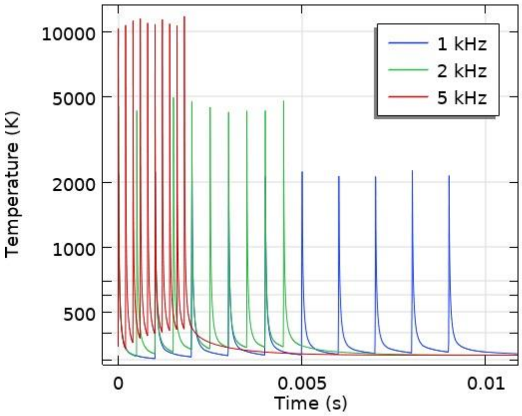

Figure 4. Thermal simulation for ps radiation using different repetition rates. At low repetition rate the sample cools down and the next shot meets a sample with room temperature, as the f increases the next shot happens at the tail of the cool down of the previous one.

4. Conclusions

This research has shown how a picosecond laser can be used to reshape samples by inducing compressive stress via shockwave. The proper way to describe the geometry of the bending process is by using the radius of curvature. The processes can be separated into those with a low and high repetition rate, being the former those in which what counts are the mechanical effects where compression stresses are induced and the latter, pulse overlap can increase the temperature high enough to relax those stresses. Figure 2 summarizes all these points.

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