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Laser Shock Microforming of Thin Metal Sheets with ns Lasers

José L. Ocaña*, M. Morales, J.A. Porro, J.J. García-Ballesteros, C. Correa

Centro Láser UPM, Ctra. de Valencia, km. 7.3. 28031 Madrid. Spain

Abstract

Continuous and long-pulse lasers have been used for the forming of metal sheets in macroscopic mechanical applications. However, for the manufacturing of micro-electromechanical systems (MEMS), the use of ns laser pulses provides a suitable parameter matching over an important range of sheet components that, preserving the short interaction time scale required for the predominantly mechanical (shock) induction of deformation residual stresses, allows for the successful processing of components in a medium range of miniaturization without appreciable thermal deformation.. In the present paper, the physics of laser shock microforming and the influence of the different experimental parameters on the net bending angle are presented.

Keywords: Laser Shock Microforming; Laser Plasma Interaction; Shock Waves; Numerical Simulation; Experimental Characterization

1. Introduction

The increasing demands in MEMS fabrication are leading to new requirements in production technology [1–3]. Especially packaging and assembly require high accuracy in positioning and high reproducibility in combination with low production costs.

Accurate positioning of smallest components represents an up-to-date key assignment in micro-manufacturing and initial assembly with widened tolerances complemented by a final micro-adjusting has proven to be a time and cost efficient alternative [2]. Provided that as mounted micro components are typically difficult to access and highly sensitive to mechanical forces and impacts, contact-free laser adjustment processes offer a great potential for accurate manipulation of micro devices.

Laser shock forming is a non-thermal laser forming method using the shock wave induced by laser irradiation to modify the curvature of the target [4,5]. It has the advantages of laser thermal forming (non-contact, tool-free and high efficiency and precision), but its non-thermal character allows the preservation or even improvement of material properties through the induction of compressive residual stress over the target surface, a feature enabling an improved resistance of shaped metal to resist corrosion and fatigue.

In this paper, the physics of laser shock microforming of thin metallic films is studied along with the influence of process parameters on the net bending angle. The experimental setup used for the validation experiments, sample fabrication details and experimental results on the practical conformability of test components are also presented.

* Corresponding author. Tel.: +34 91 3363099; Fax: +34 91 3365534.
E-mail address: jlocana@etsii.upm.es

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2. Physics of Laser Shock Microforming Processes

Laser shock microforming (LSμF®) is based on the application of a high intensity pulsed laser beam (I > 10^9 W/cm^2; τ < 50 ns) on a metallic target forcing a sudden vaporization of its surface into a high temperature plasma that immediately develops inducing a shock wave propagating into the material. In laser-induced shock processes, the material is stressed and deformed in a dynamic way, with strain rates exceeding 10^6 s^{-1}.

The plastic deformation induced by the shock wave generates a residual stress distribution in the material. Stress in the direction of the stripe (σ_{xx}) is compressive at the incident surface and tensile at the rear surface (see Figure 1a). This stress distribution produces a local bending (β_s) in the direction of the laser beam. Contrarily, the application of the laser pulse at a given distance d from the clamping generates a bending moment associate to the laser pulse energy. This bending moment can produce plastic deformation near the clamping so that, in this case, stress in the stripe direction (σ_{xx}) is tensile at the incident surface and compressive at the rear surface (see also Figure 1a). This stress distribution tends to produce a drag bending (β_b) in the opposite direction of the laser beam. The combination of these two effects produces the net bending angle (α), determined for small angles as the ratio between the apparent bar end displacement to the bar length (see again Figure 1a). This net bending angle can be optimized as a function of the laser characteristics, namely pulse duration, wavelength and energy and other process parameters, namely the laser spot radius, spot position and the nature and thickness of the metal stripe.

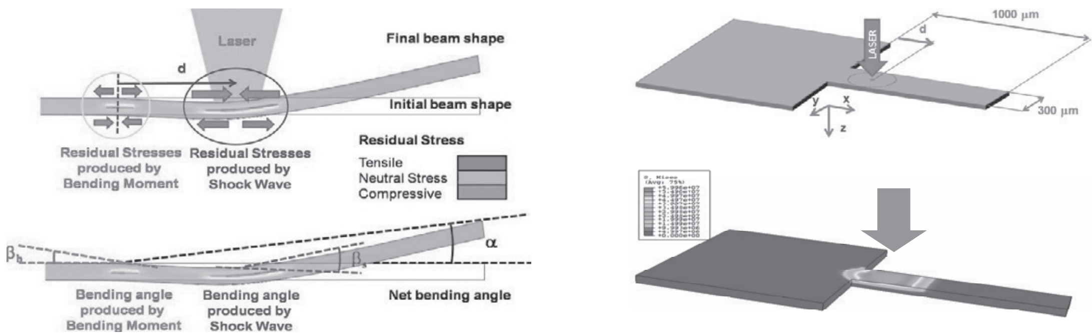


Figure 1. (a) Schematic diagram of thin sheet deformation and stresses and definition of bending angles in the LSμF® process.
(b) Typical test configuration used for the analysis of bending angles on a platform + strip ensemble. The influence of the relative position to strip edge of the laser beam incidence has been parametrically analyzed.

3. Numerical Simulation Results

The authors have developed a calculational system able to study laser shock microforming process [5–7]. It consists of two principal modules conceived for the analysis of plasma evolution (shock waves generation) and induced residual stresses (shock wave evolution and material plastic deformation) under two different but complementary approaches [7]. Provided that the effects to be analyzed are strongly non linear as a consequence of the leading role of material plastic deformations, the influence of the different process parameters (laser energy and laser spot position) on net bending angle have been studied with the developed numerical model.

In Figure 1b, a typical configuration used for analysis of the laser induced deformation on a metal strip geometry is shown. Appropriate sample dimensions have been chosen so that the bending effect can be properly characterized on the strip part and an efficient workpiece clamping can be simulated through the assumption of the platform side rigidity.

In Figure 2a, numerical simulation results on net bending angle of the metal sheet (α) as a function of the laser energy pulse are displayed together with the two components, β_s and β_b. The results show that, after a critical value of pulse energy, the bending angle (β_b) produced by the bending moment starts to have an important deleterious effect on the net bending angle (α): The higher pressure at the laser incidence region starts to saturate the residual stress distribution while the drag bending moment starts to be higher in value.

On the other hand, the numerical study of the net bending angle of the metal sheet as a function of the laser spot position, d, shows that, as a consequence of the combination of the two described main effects, a maximum is obtained when the laser spot is applied at a given distance d*. The residual stress distribution produced by shock waves is the same in all these cases, but when the laser is near the bulk material the bending angle is reduced because of the reduced bending moment (linearly increasing with d). For all these simulations, laser induced shock wave confinement by ambient air was assumed.

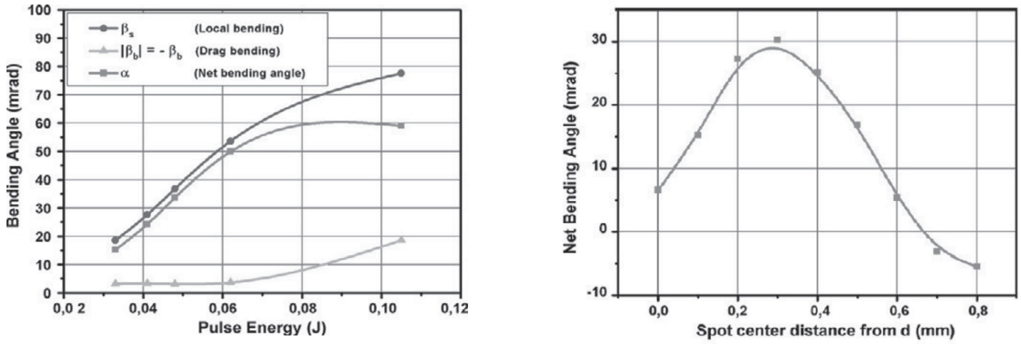


Figure 2. (a) Local bending, drag bending and net bending angle in reference thin sheet specimens subject to 10 ns laser pulses irradiation at d = L/3 as a function of laser pulse energy.
(b) Net bending angle of reference thin sheet specimens subject to 0.048 J, 10 ns laser pulses irradiation as a function of spot center distance from base, d.

4. Experimental Setup and Results

The practical irradiation system used in the experiments is essentially consisting of a Q-switched laser with emission at fundamental wavelength and providing a maximum energy of 2 J/pulse in a FWHM pulse length of 9 ns coupled through a conventional optical path to a XY motion stage allowing the precise positioning of the target. Beam focusing to the required spot size is performed by means of an adjustable focus optics within intensity limits allowed by the absence of air dielectric breakdown. In order to control this limitation and select the appropriate beam energy level for each particular experiment, a power attenuator is used (see Figure 3a). As laser-shock confining medium either ambient air or a water layer can be used

4.1. Experimental validation through the analysis of the effect of the laser beam-bending stripe relative position

With the aid of this irradiation system, the effect of the application of high intensity laser pulses to the bending of metal stripes (irradiation parameters given in table 1) was experimentally tested and compared to predictive numerical results obtained by the described numerical model. In the case reported in this paper, AISI 304 steel (material properties used for the simulation collected in Table 2) was used as target material with ambient gas as laser induced shock wave confining medium. In Figure 3b the dimensional features of the test stripes analyzed (all produced by the ML-100 micromanufacturing workstation available at the authors home Centre) are shown.

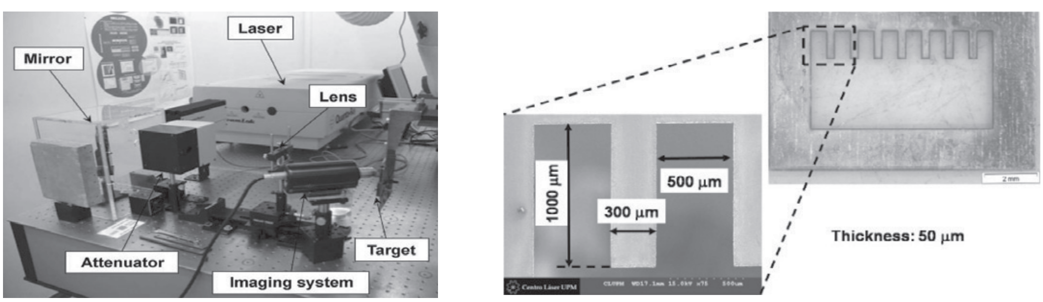


Figure 3. (a) Laser shock microforming experimental setup used at UPM Laser Centre
(b) Photograph and SEM view of a typical flat metal stripes set (one-side pinned) used for laser microforming parameters evaluation

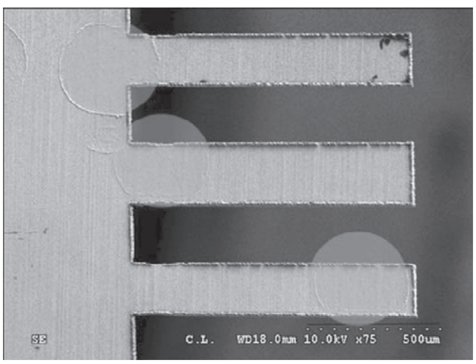
The contrast parameter between numerical and experimental results was the metal stripe deformation for a variable irradiation distance d. The deformation profiles were assessed by means of a LEICA ICM 1000 (λ=635 nm) confocal laser scanning microscope. In Figure 4a, the relative positions of the laser incidence to the stripe edge are shown for three relevant positions and in Figure 4b the comparison of the bending profiles of the stripes to the theoretical predictions is displayed, the contrast between theoretical and experimental results being quite satisfactory.

Table 1. Experimental Laser Shock Microforming parameters

Property	Value
AISI 304 sheet thickness (μm)	50
Confining layer	Air/Water
λ, Nd:YAG laser wavelength (nm)	1064
E_p, Energy per pulse (J)	1.651
τ, Pulse length FWHM (ns)	9
R, Unfocused beam radius (mm)	14
R_m, Mask radius (μm)	750
E_{pm}, Energy per pulse (after mask) (mJ)	57
E_{pml}, Energy per pulse (after mask and lens) (mJ)	54
Spot radius (μm)	150
Spot center position relative to stripe edge, d (μm)	-100-850

Table 2. Mechanical properties of stainless steel AISI 304.

Property	Value
ρ, Density (kg m^{-3})	7896
ν, Poisson's ratio	0.25
E, Elastic modulus (MPa)	193
T_m, Melting temperature (K)	1811
Johnson–Cook constants	
A, (MPa)	350
B, (MPa)	275
C	0.022
N	0.36
M	1
$\dot{\varepsilon}_0$ (s^{-1})	1



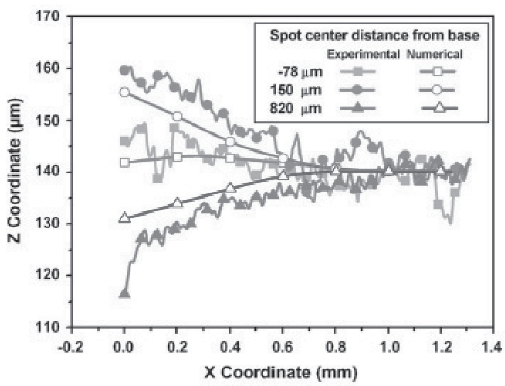


Figure 4. (a) SEM images of relative position of laser incidence to stripe edge for three relevant values of d
(b) Comparison of the numerical simulation bending profiles obtained for the three treated stripes to the experimental results obtained through confocal microscopy.

4.2. Analysis of the effect of repeated application of laser pulses on the bending capability of stripes.

Additionally to the described theory-experiment validation procedure, and in order to assess the effect of multiple laser pulses on the final conformability of the considered specimens, the stripes irradiation by different number of laser pulses (up to 25) was accomplished. The irradiation was again made in ambient air as laser induced shock confining medium.

In Figure 5a the SEM view of a particular specimen (AISI 404, 50 μm thick) irradiated with 25 pulses is shown in comparison to a non-irradiated sample, and in Figure 5b a plot is provided showing the progressive effect of an increasing number of applied pulses in the conformation final angle of a typical specimen: the clear effect is shown of the practical conformability of the metal and the saturation effect originated by the progressive influence of residual stresses induced by previous pulses.

This saturation effect may considered as a major limitation for the practical application of the technique to real life problems for which substantially higher bending angles are needed. However, a proper handling of the laser induced shock wave through the use of an inertial shock confining layer can provide spectacularly improved results, as will be shown in the next point.

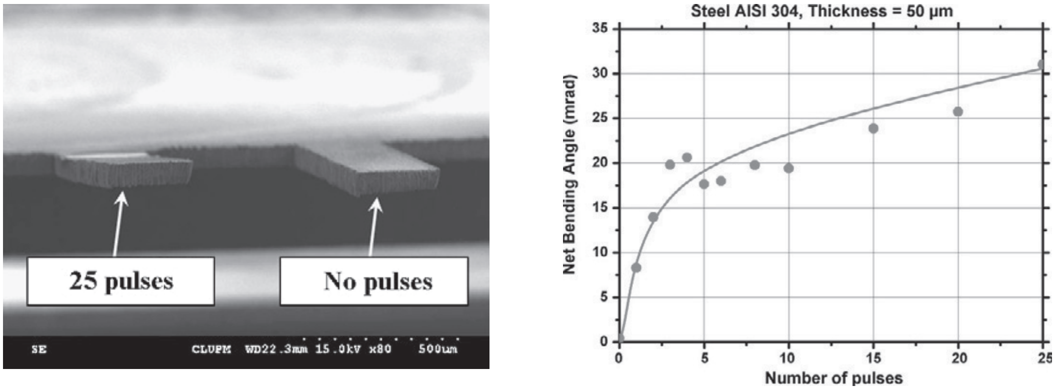


Figure 5. (a) SEM images showing the comparison between a non-formed metal strip and one laser shock formed by incidence of 25 laser pulses.
(b) Diagram showing the saturation effect of the laser shock forming process under ambient air shock confinement. Points correspond to experimental results and the line corresponds to an estimated tendency.

4.3. Analysis of the effect of repeated application of laser pulses on the bending capability of stripes.

Profiting by the experience accumulated by the authors in the field of application of laser shock pulses for compressive residual stresses induction in metallic materials [8,9] through the use of a dielectric confining layer (possibly solid but most frequently liquid), the analysis of the influence on laser shock microforming performance of a water layer was theoretically and experimentally analyzed.

According to the authors' results on the analysis of the plasma influence on the confinement pressure of targets subject to Laser Shock Processing (see Ref. [10]), the effect of a dielectric confining medium of a decisive element for the attainment of peak pressure values high enough to motivate the induction of an intense shock wave propagating in the material and inducing a field of residual stresses in a narrow layer close to the surface. The effect of such confining layer has been shown to enhance the pressure peak value up to 10 times in the case of water with a layer thickness in the range of several hundreds of microns.

In the case of laser shock microforming of thin metal sheets, the net effect of the induction of such field of residual stress results directly in an appreciable deformation, much more evident than in the case of microforming in ambient air. A sample of this enhanced forming capability is shown in Figure 6a, where the effect of a single "confined" laser pulse on a 100 µm thick, bilaterally-pinned AISI 304 steel stripe can be observed to be much more evident than the corresponding to ambient air process. Additionally, in Figure 6b, the application of the confined mode laser shock microforming process to an angle steering optical fiber alignment device is shown, the practical capabilities of the application of the technique to real world devices being evident.

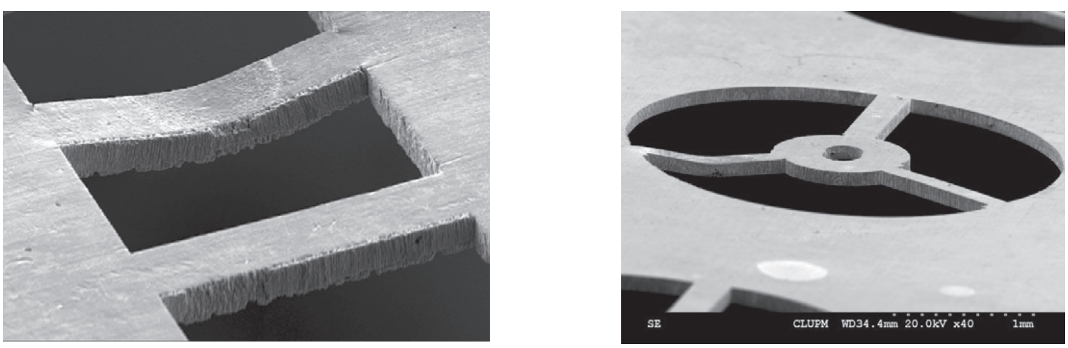


Figure 5. (a) SEM image showing the forming effect of a single laser pulse in confined mode applied to a 100 µm AISI 304 steel stripe in contrast to a similar non-formed stripe.
(b) SEM image of the application of the laser shock microforming technique in confined mode to the bending of the angle steering arms of a 100 µm thick AISI 304 steel optical fiber alignment device (arm bent with 5 laser pulses).

5. Discussion

According to the previously presented results, the practical feasibility of the laser shock microforming process developed on the basis of ns range GW/cm^2 lasers and ambient air confinement (LSμF®) has been demonstrated, not only from a practical point of view, but in close consistency with the relevant expected physical effects following high intensity laser interaction, very suitably addressed by the developed calculational model.

Further to the validation of this model, the authors have proven the practical feasibility and controllability of finite angle microforming by sequential accumulation of laser pulses on a given specimen, then opening the way for a practical technology implementation.

Additionally to this fact, the possibility of drastically improving the laser bending performance by means of the laser shock microforming process confinement by a thin water layer (CM-LSμF®) has been both theoretically and practically demonstrated, so that the prospects for the applicability of the technique to fast processing in MEMS production are clearly opened.

Acknowledgements

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