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AND COMMITTEE ON MECHANICS
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7th European Conference on Structural Control

Book of Abstracts and Selected Papers

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LASER MICRO BENDING MECHANISM FOR HIGH-PRECISION ADJUSTMENT IN MECHATRONIC SYSTEMS

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Abstract

The laser-based non-contact micro-adjustment method is widely applied in manufacturing and assembly of micro-electro-mechanical and micro-opto-electro-mechanical systems (MEMS and MOEMS). Due to miniaturization requirements and design considerations the access to these devices is frequently possible from one side only. This creates difficulties when laser-induced two-way micro-bending is needed – both towards, as well as away from the applied laser beam. Presented paper reports experimental and numerical investigations of a thermal micro-bending mechanism, which enables such adjustments, dependent on the applied processing parameters and using simple prismatic bar. A 3D finite element method (FEM) model has been developed to study the behaviour of a cantilever stainless steel beam heated with a stationary laser beam. Experimentally-validated numerical model allowed an analysis of temperature, strain and stress fields during the heating and cooling cycle to explain the mechanism of laser-induced micro-deformation.

Keywords:
laser forming, laser bending, non-contact adjustment, micro-adjustment, applied thermomechanics

1. Introduction

Application of laser technology makes it possible to perform highly accurate adjustment of components, which are difficult to access using traditional tools and are sensitive to mechanical forces. The energy input by the laser beam into the work-piece can be easily and precisely controlled. Since 1980's laser-induced micro-deformations are applied in manufacturing processes of the electrical and electronic industry, e.g. in production of miniature electric relays [1] and hard disk drives [2-4]. The leading companies of the sector have patented numerous practical solutions based on local laser heating of metallic and non-metallic materials that allow precise, non-contact (remote) and fast micro-scale shape corrections for positioning and alignment of parts and sub-assemblies, such as magnetic read/write heads, optical fibers, lenses and photodiodes [5-9].

Adjustment of critical dimensions with micrometer or milliradian accuracy in small metallic components is applied with laser-driven actuators during assembly stage in mass-production and it allows relatively large tolerances in the preceding production stages [10]. The high precision and cost-effectiveness in the assembly technology of micromechatronic systems is achievable due to the concept of the "on-board" (integrated) actuators, which are parts of the final product [10, 11]. The potential of the laser beam as a means of energy transport for optothermal microactuation is intensively investigated to expand practical applications of micro-opto-electro-mechanical systems (MOEMS) [12, 13]. Alignment accuracy 0.1 micrometer in mass-production of photonic devices operating in the near-UV wavelength range was addressed with the laser-driven three-bridge actuator concept [14, 15]. Effective analytical model was developed to describe behaviour of two-bridge actuators [16]. A separate direction in research on laser-controlled micro-adjustment is related to the application of shockwaves generated using nano-, pico- or femtosecond laser pulses [17-20],

The three fundamental mechanisms of laser thermal forming identified to date are: the temperature gradient mechanism (TGM), the upsetting mechanism (UM) and the buckling mechanism (BM) [21]. Dependent on laser processing parameters, part dimensions and topology, different shape changes are produced by pulsed or continuous local heating of the material [22, 23, 24]. The temperature gradient mechanism has a drawback of producing bends always in one direction, i.e. towards the heat source (e.g. the laser beam). Such deformation is termed concave [25] or positive [26] bending in the literature and the related angular deformation is assumed positive in this work. The opposite deformation is termed convex [27] or negative [26] bending.

Lee and Lin [28] investigated deformation of a 304 stainless steel plate heated with a line-shaped CO2 laser beam. One case of negative bending was observed for a stainless steel specimen (0.5 mm thick, 150 mm long) in the cantilever arrangement, for laser power 1 kW and heating time 0.5 s, where material melting occurred.

Wang et al. [29] presented research on dynamic micro-deformations of cantilever beams made of St14 and C45 steels and heated with a CO2 laser beam of the Gaussian intensity distribution. They attributed the negative final angular deformation of a C45 carbon steel sample to the effect of the martensitic transformation and the involved volumetric expansion of the heat-affected region near the laser-heated surface.

Zhang and Xu [30] analysed laser bending of silicon microcantilevers, which are applied in extremely sensitive physical, chemical and biological sensors, e.g. in the atomic force microscopy. The laser beam of wavelength 524 nm (a frequency doubled Nd:YLF laser) operated with 20 ns pulses and 2 kHz repetition rate. The laser spot of diameter 8 micrometers traversed across 0.6 micrometer thick silicon cantilever. The obtained sensitivity of bending was 3.5 microradian. The microcantilever tip deflection was about 1.3 nm at 14 microradian bending angle. The authors indicated that such a technique is simple to implement and very useful for applications involving arrays of cantilevers for parallel chemical and biological sensing. However, its limitation is the one-directional bending only, always towards the laser beam.

A considerable difficulty in application of laser actuator technology arises when a component to be processed is accessible from one side only. To solve such a problem specially designed actuators were proposed [10, 31, 32]. In the so-called actuator with embossment, the positive or negative bending can be achieved dependent on the location of the thermal upsetting material region (above or below the neutral axis of the component cross-section) [10].

In order to achieve the bi-direction control of the bending deformation a two-stage technique has been invented by which the positive bending is produced with the temperature gradient mechanism, while the displacement in the opposite direction is produced due to laser-induced material annealing [33, 34]. However, such technique requires at least two applications of laser heating, using different processing parameters, and followed by cooling periods.

Presented paper reports experimental and numerical investigations on a thermal micro-bending mechanism, which enables deformation of a simple prismatic bar either towards or away from the laser beam, dependent on the applied processing parameters. A 3D finite element method (FEM) model has been developed to study the behaviour of a cantilever stainless steel beam heated with pulses of a stationary laser beam. Experimentally-validated numerical model allowed an analysis of temperature, strain and stress fields during the heating and cooling cycle.

2. Experiments

Samples of dimensions 50 x 4.05 x 0.55 mm made of 18-8 type stainless steel, clamped in the cantilever arrangement, were heated with a stationary Nd:YAG laser beam (Fig. 1). They were annealed prior to laser bending experiments in 400°C for a half an hour in order to reduce initial residual stresses and to increase coupling of laser radiation due to the created oxide layer. The transverse electromagnetic mode TEM_{mn} of the applied laser beam exhibited a multimode character. The laser beam was defocussed to obtain a spot of diameter 3.6 mm on the material surface. The spot was located on the longitudinal axis of symmetry of the specimen (Fig. 2). Laser operated in the continuous wave (CW) mode. Fluctuations of the laser beam power were estimated as ±5% of the nominal value. Accuracy of pulse time duration was approximately ±0.05 s.

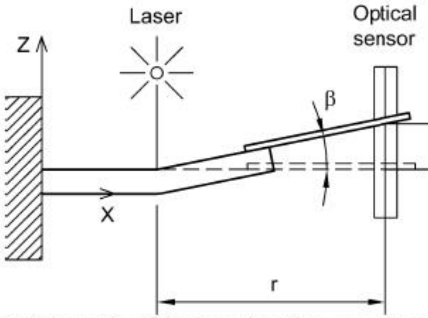


Fig. 1. Schematic of the laser bending experimental setup.
The definition of the positive angular deformation $\beta > 0$.

Non-contact deformation measurements were performed with a high-accuracy CCD micrometer Keyence LS-7070M. In order to achieve a high accuracy of optical measurements, an additional element of high-quality surface and low mass (a syringe needle) was attached to the specimen. Its displacement was measured and recorded during laser heating and after cooling down the sample to the initial material temperature. Fast deformation measurements were required during the phase of laser irradiation, while the highest accuracy was needed to precisely measure the final value of angular deformation. Both requirements were satisfied by dynamic control of the averaging number parameter of the optical micrometer.

Angle β of the bending deformation induced by the laser pulse was calculated from the linear vertical displacement w (Fig. 1) measured with the micrometer. The following formula was used: $\beta = \arctan(w/r)$, where r is the distance between the laser spot centre and the measurement location ($r = 48.8$ mm). Angular deformation is considered positive (concave) when the moving segment of the specimen rotates in the direction of the incident laser beam ($\beta > 0$), as show in Fig. 1.

3. Numerical simulation

Numerical simulations were conducted using the Finite Element Method (FEM). The thermal-mechanical sequentially coupled analysis was conducted in two separate steps: (1) determination of temperature field under prescribed heat load and boundary conditions, and (2) elastic-plastic incremental analysis of stress and strain due to the calculated temperature field. The calculations were performed with the ABAQUS system [35]. Energy input from the laser beam was treated as a surface heat source, since the absorption of the infrared radiation by metals is typically confined to a layer several tens of nanometres thick. Three-dimensional linear finite elements with 6 and 8 nodes were used: wedge elements DC3D6 and hexahedral DC3D8 for thermal problem, and compatible elements C3D6 and C3D8 for mechanical problem. Ten layers of elements were applied in the thickness direction of the specimen in order to accurately model the gradient of temperature and the bending effect. Only one half of the specimen was modelled taking the advantage of its symmetry. The spatial profile of power density over the laser beam transverse cross section was approximated by a top-hat model of constant intensity. The absorption coefficient of laser radiation by the material was assumed 0.77, as typical for the laser radiation of 1.06 micrometer wavelength incident on the stainless steel surface covered with oxide layer. The laser spot location is shown in Fig. 2, while Fig. 3 presents the mesh of finite elements in that region. Heat dissipation through free convection and radiation was taken into consideration in the numerical model.

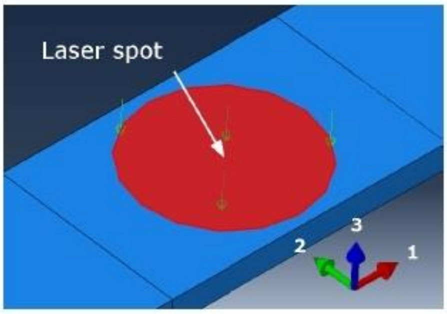


Fig. 2. Laser spot location.

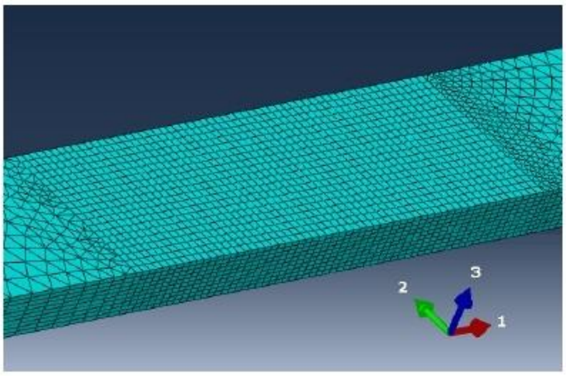


Fig. 3. A mesh of finite elements in the laser spot region.

Thermal dependences of the following material properties were taken into consideration: thermal conductivity, specific heat, thermal expansion coefficient, Young's modulus, Poisson's ratio and density [36]. In order to achieve possibly high modelling accuracy, the yield stress dependence on temperature was based on data presented by Chen and Young [37] for the austenitic stainless steel. Their characteristics were recalculated using the room temperature yield stress value 234 MPa for the steel used in this research [38]. The Huber-Mises-Hencky yield criterion was employed in modelling of material behaviour.

5. Results and discussion

In order to clearly present the bend angle time-runs during laser heating and the subsequent material cooling, the logarithmic axis for the process time is employed in Fig. 4. During the phase of heating the specimen bends with negative angular deformation due to the presence of a high temperature gradient over the material thickness. Plastic (tensile) deformation starts to appear in the edge regions of the specimen after approximately 0.05 s of laser heating. The final bend angle values after laser irradiation for 1.05 s were: (1) positive for laser beam power 59 W, (2) close to zero for power 46.3 W and (3) negative when the power was 36.2 W. The comparison of experimental and numerical simulations results (Fig. 4) shows a good agreement.

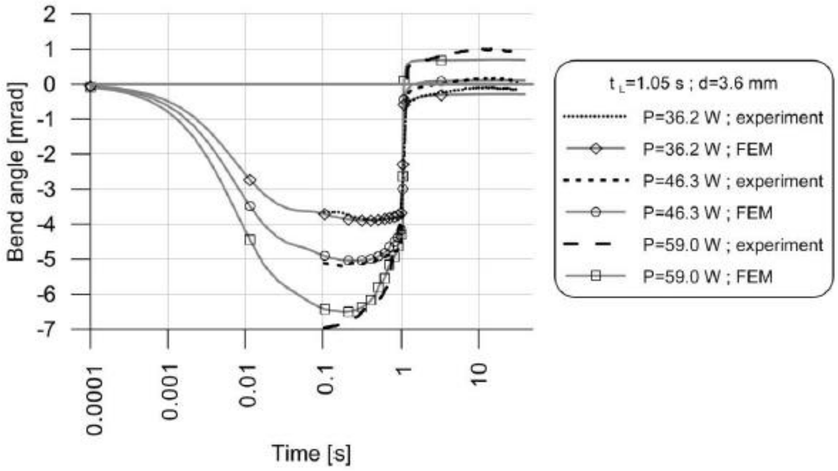


Fig. 4. A comparison of experimental and numerical time-runs of the bend angle for pulse length 1.05 s, laser spot diameter 3.6 mm and laser power 36.2, 46.3 and 59 W.

Using the experimentally-validated numerical model, the negative bending behaviour was further analysed in cases when the laser beam power was 36.2 W and the pulse length was 0.25, 0.5 and 0.75 s (Fig. 5). Results of numerical simulations show that the effect of negative bending can be achieved and controlled by suitable selection of laser beam power and the duration of the laser irradiation. A similar thermomechanical behaviour was observed and analyzed by Mucha at al. [39] and in a research with the moving laser beam [40, 41].

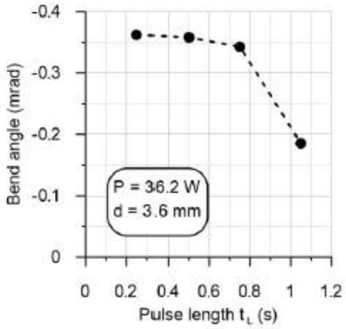


Fig. 5. Bend angle dependence on the pulse length for negative bending deformation cases.

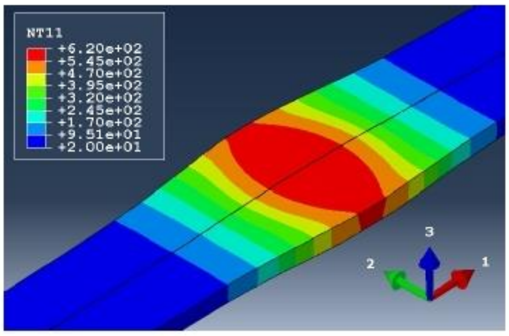
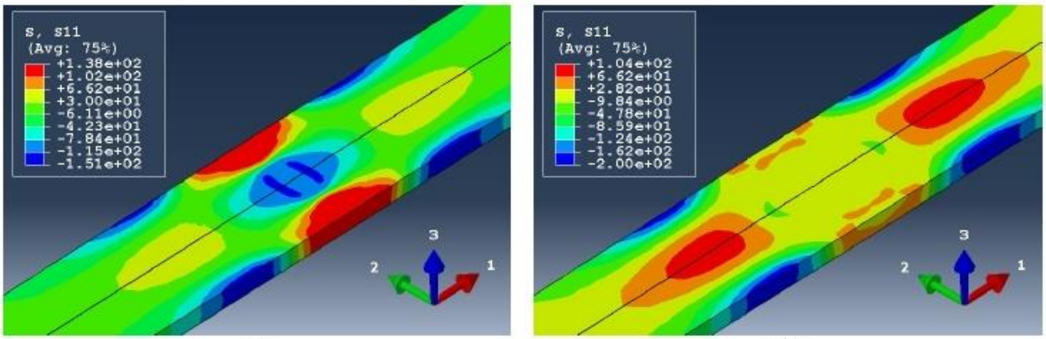


Fig. 6. Temperature distribution at time 1.05 s (power 36.2 W, deformation scale factor 20).

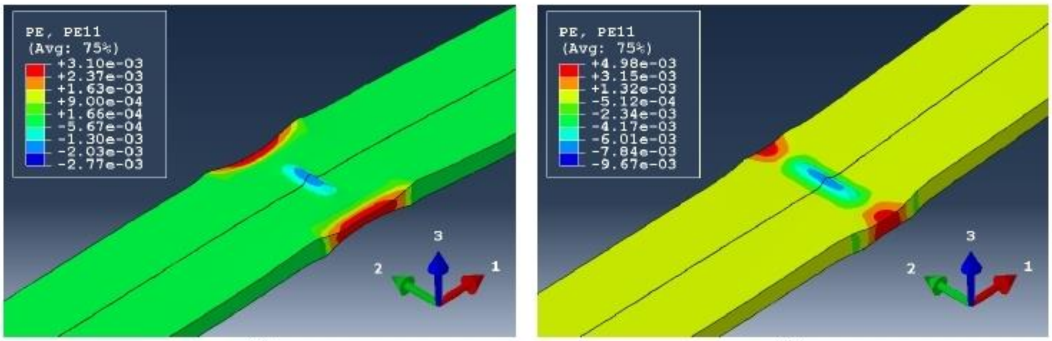
An example of the calculated distribution of material temperature is presented in Fig. 6 (power 36.2 W, pulse length 1.05 s). A similar distribution was obtained for laser beam power 59 W, but with the maximal temperature value 938 °C, while for power 36.2 W it was 635 °C.



(a) (b)

Fig. 7. Longitudinal stress component S11 at time 1.05 s: (a) power 36.2 W, (b) power 59 W. Deformation scale factor 1

Figures 7 (a) and (b) show differences in distribution of the longitudinal stress component S11 in the region of laser spot, at the end of laser pulse 1.05 s, for laser beam power 36.2 W and 59 W, respectively. The characteristic of thermomechanical response for the case of power 36.2 W is the occurrence of high tensile stress zones in the edge regions, while for the power 59 W such zones are located close to the longitudinal axis of symmetry. In both cases the central region located directly under the laser spot is initially under compression due to thermal expansion of the material, with gradually occurring effect of the yield stress decrease with the increase of temperature.



(a) (b)

Fig. 8. Longitudinal plastic strain component PE11 in the final state:
(a) power 36.2 W, deformation scale factor 500, (b) power 59 W, deformation scale factor 100.

As a result of intense longitudinal stretching in the edge regions, long zones of positive longitudinal plastic strain component PE11 occur there for power 36.2 W, after laser heating for 1.05 s and subsequent cooling the material down to the initial (room) temperature (Fig. 8a). In the case of power 59 W, the material stretching regions are much smaller, while the central region of negative strain PE11 is considerably larger (Fig. 8b). In both cases the laser pulse length was 1.05 s, and the thermal load differentiated only in the applied power. The specimen behaviour in the case of the smaller heating power resembles the effects of the buckling mechanism, hence the final angular deformation is negative, while for the higher power the processing conditions favour the temperature gradient mechanism to play a more pronounced role in the deformation process. Maximal difference between temperatures of the upper and bottom specimen surface is 46 ºC for laser power 36.2 W, and 74 ºC for laser power 59W.

6. Conclusions

Presented experimental investigations and numerical simulations explained mechanism of bi-direction laser-induced micro-bending. It was found that the final angular deformation of a prismatic cantilever beam, heated from one side with a stationary laser beam, can be negative or positive, dependent on the applied laser power. The magnitude of angular deformation can also be controlled with the laser pulse duration. The studied mechanism of bending involves a significant positive longitudinal plastic strain in the edge regions of the beam. Final deformation of the beam is a combined result of the negative longitudinal strain in the central region and the positive strain close to the edges, with a contribution of the out-of-plane deformation due to the temperature gradient across the thickness direction. Negative laser micro-bending may find numerous practical applications in manufacturing of MEMS and MOEMS, as the miniaturization and integration requirements usually limit the access to these devices to one-side only.

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