Mechanism of bi-direction laser bending for micro systems

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Abstract

Laser-based non-contact micro-adjustment method is a way of going beyond limits of traditional mechanical techniques applied for precise alignment during assembly of miniature opto-electro-mechanical devices. This paper presents experimental and numerical investigation of thermal micro-bending mechanism, which allows for bi-directional deformation, i.e. either towards or away from the laser beam, dependent on the applied processing parameters. An experimentally validated numerical model explains behaviour of a stainless steel cantilever beam subject to the Nd:YAG laser pulse. With a constant pulse duration, the direction of bending depends on the laser beam power. The revealed mechanism of bending involves significant positive longitudinal plastic strain in certain material regions. The deformation results from a considerable temperature gradient across the width of the cantilever beam, with some contribution of the temperature gradient in the thickness direction. Application of the mechanism opens up new opportunities for the laser-based micro-adjustment technology.

Keywords: laser forming, laser bending, laser micro-adjustment, thermo-elastic-plastic deformation

1. Introduction

Laser-induced micro-deformations are widely applied in manufacturing processes of the electronic industry, e.g. in production of hard disk drives [3] and miniature electric relays [4]. The leading companies of the sector have patented numerous practical solutions based on local laser heating of material that allow precise, non-contact and fast positioning of parts and sub-assemblies, such as magnetic read/write heads, optical fibres, lenses and photodiodes [6]. Adjustment of critical dimensions with micrometer or milliradian accuracy is employed during assembly stages in mass-production [2].

The three fundamental mechanisms of laser-induced deformation identified to date are: the temperature gradient mechanism, the upsetting mechanism and the buckling mechanism. Activation of the pure upsetting mechanism results in homogenous plastic compressive strain distribution across material thickness, which yields material shortening and thickening in the heated region. It is applied for example in the laser micro-adjustment technology using two-bridge actuators [5].

Bending effect, i.e. the out-of-plane deformation, can be produced with the two other mechanisms. While the instability inherent to the thermal buckling mechanism is a limiting factor in its practical use, the temperature gradient mechanism has a drawback of producing bends always in one direction, i.e. towards the heat source (e.g. laser beam).

The paper presents experimental and numerical investigations of a thermal micro-bending mechanism, which enables bi-directional deformation, i.e. either towards or away from the laser beam, dependent on the applied processing parameters.

2. Experiments

The 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 created oxide layer.

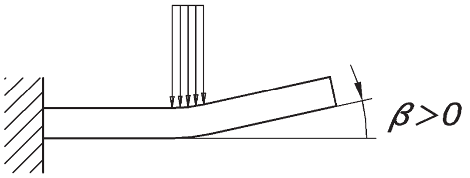

Figure 1: Schematic of the laser bending process. Definition of the positive angular deformation β.

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. Constant laser pulse duration 1.05 s was applied throughout the experiments with power levels ranging from 21 to 72 W. Fluctuations of the laser beam power are estimated as ±5% of the nominal value. Accuracy of pulse time duration was approximately ±0.05 s. Non-contact measurements of deformation were performed with a high-accuracy optical micrometer.

3. Numerical simulation

Sequentially coupled thermal and mechanical analysis using the finite element method was performed with the ABAQUS system. The power density distribution of the multimode laser beam was approximated by a top-hat model of constant intensity over the laser spot. Constant value of 0.77 was employed for the laser radiation absorption coefficient and material emissivity.

Three-dimensional linear 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.

Thermal dependence of material data as well as convective and radiative heat dissipation was respected in modelling. Material yield stress dependence on temperature was adopted from [1] using the 0.2% strain limit and the room temperature yield stress value 234 MPa

Elastic-perfectly plastic isotropic material model was applied. Material hardening was neglected, as plastic deformation occurs mainly at high temperature, where strengthening is substantially reduced by dynamic recovery processes. The Huber-Mises-Hencky yield criterion was employed.

4. Results and conclusion

Figure 2 presents results of experimental measurements and numerical calculation of the angle of bend during laser heating and shortly afterwards.

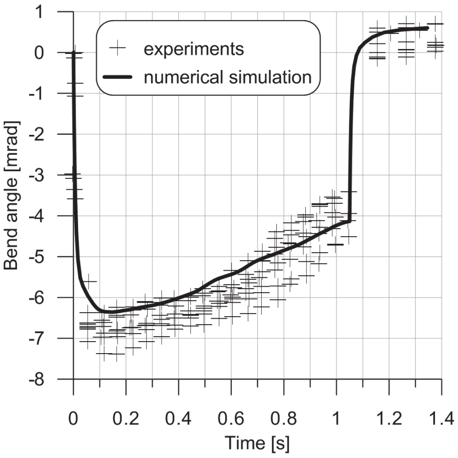

Figure 2: Time runs of the bend angle in experiments and numerical simulation for the laser power 59 W.

Dependence of the final bend angle on the applied laser beam power is shown in Fig. 3.

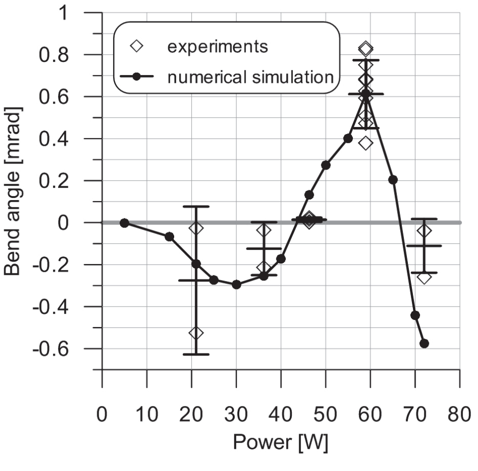

Figure 3: Dependence of the final angle of bend on the applied laser beam power. Error bars represent sample standard deviation.

Some discrepancy between numerical results and experimental measurements, seen for the highest power level 72 W in Fig. 3, can be attributed mainly to the poor accuracy of the material yield stress value at temperatures above 1000°C. Taking into account limited accuracy of the available material data, the obtained simulation results are regarded as satisfactory validation of the numerical model.

Figure 3 reveals a new effect in laser micro-bending. Dependent on the applied laser beam power, with constant pulse duration, either positive or negative final angular deformation can be obtained. Mechanism of this deformation can be explained considering thermal gradients in the directions of axes 2 and 3, and the resulting distribution of longitudinal plastic strain component ε_{11}^{pl} (PE11), as shown on one of the two symmetric halves of the model (Fig. 4).

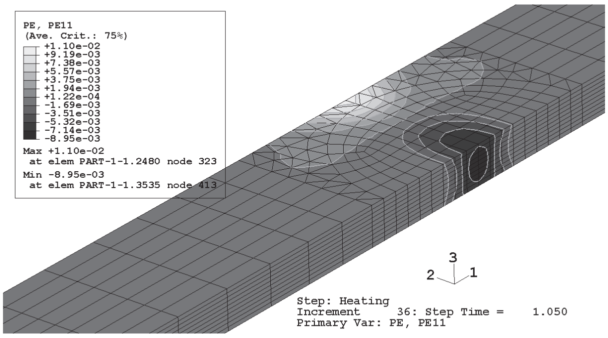

Figure 4: Distribution of plastic strain component ε_{11}^{pl} at the end of heating stage for laser power 59 W.

Plastic strain distribution results from a considerable temperature gradient across the width of the cantilever beam, i.e. in the direction of axis 2, with some contribution of the temperature gradient in the thickness direction (axis 3), at the highest temperature during thermal cycle. Final deformation of the beam is a result of a play between negative strain in the central region and positive strain close to the edges of the beam, both influenced by the temperature gradient in the thickness direction. Application of this mechanism opens up new opportunities for the laser-based micro-adjustment technology.

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