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The effects of design parameters on the laser-induced in-plane deformation of two-bridge actuators

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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. The two-bridge actuator is an on-board structure that allows for adjustments with micrometer, sub-micrometer or sub-miliradian accuracy. Successful industrial application of the method requires a thorough understanding of mechanics of the laser-induced deformation process. The effects of two fundamental design parameters, i.e., the width and the distance between the bridges, on in-plane plastic deformation of the actuator are examined in this work. Experimentally validated theoretical model explains how design parameters, material data and laser pulse parameters affect the final deformation angle of the actuator. The derived mathematical formulae show dependence of the constraint ratio, thermal stresses and thermally-induced plastic deformation on the design parameters of the structure. The proposed solution can be used for optimization of two-bridge actuators.

1. Introduction

Micro-technologies play increasingly important role in modern industry, but miniaturization and complexity of micro devices present a big challenge for conventional methods of assembly and adjustment. It is difficult to achieve micrometer, sub-micrometer or sub-miliradian accuracy of positioning and alignment of components in mass-production using traditional assembly methods. The main reasons are: the limited access for mechanical tools and the existence of the spring-back phenomenon in metallic parts [1–4].

Thermally induced plastic deformations have been utilized in forming and shape correction of metal beams and plates for a long time [5,6]. Laser heating enabled development of laser forming methods, i.e., shaping of objects by heating with a laser beam [7–10]. Laser forming capability to produce very small plastic deformations of metal and non-metal components with a non-contact method has been attracting considerable attention of industrial and academic research centers [4,11–17].

Application of laser forming techniques in manufacturing of complex mechatronic products requires a thorough understanding of mechanics of deformation in the involved processes. The underlying phenomenon of the laser forming method is the emergence of plastic compressive strain of a material that is heated and cannot freely expand. This effect has been utilized in the three fundamental mechanisms of laser forming [18–20]. The restraint due to the nonlinearity of temperature gradient through the material thickness is exploited in the temperature gradient mechanism (TGM). It results in bending, i.e., out-of-plane deformation of the material. If temperature has uniform distribution through the material thickness, but thermal expansion of the heated region is constrained by the rest of the workpiece, then the upsetting mechanism (UM) is active. The heated region undergoes in-plane shortening and gets thicker. Under the buckling mechanism (BM) the bending deformation results from the thermal-elastic–plastic buckling of the material.

Two-bridge actuator is one of the basic structures developed for micro-adjustment tasks. A sheet metal part is designed so as to include two connections (bridges) between two regions of the actuator. One of the bridges is locally heated with a laser beam. Thermal elongation of the bridge is hindered by the other bridge, which provides the necessary restraint for UM to be activated. Under suitable laser heating conditions (pulse power and duration) plastic compressive deformation of the heated bridge is produced. Heating of one material surface involves existence of the temperature gradient through the material thickness and so TGM component also contributes to the actuator deformation. Shortening of the bridges is utilized for adjustment and alignment tasks.

One of the most important problems facing micro-technology is design of actuators [21,22]. The two-bridge actuator geometry is defined essentially by the width of the bridges and the distance between longitudinal axes of the bridges. The latter dimension will

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Nomenclature

α	coefficient of linear thermal expansion
a	width of the actuator
A	absorption coefficient
b	distance between longitudinal axes of the bridges
β	in-plane angular deformation of the actuator
β_{PL}	in-plane plastic angular deformation of the actuator
c	specific heat
C_{PL}	function of dimensionless parameter of the bridge width W_{2B}
E	Young's modulus
ε^T, ε^E, ε^{PL}	thermal, elastic and plastic strain components
$d\varepsilon$, $d\varepsilon^T$, $d\varepsilon^E$, $d\varepsilon^{PL}$	increments of strain: total, thermal, elastic and plastic
ε_1^T, ε_1^E, ε_1^{PL}	thermal, elastic and plastic strain components of bridge 1
F_1, F_2	internal forces in bridges 1 and 2
g	material thickness
h	heat convection coefficient
J	moment of inertia
κ	thermal diffusivity
L, ΔL	initial length of bridges, total change in length
L_1, L_2	lengths of bridges 1 and 2
ΔL^T, ΔL^E, ΔL^{PL}	thermal, elastic and plastic deformation components
ΔL_1^T, ΔL_1^F, ΔL_1^{PL}	thermal, elastic and plastic deformation components of bridge 1
ΔL_2^T, ΔL_2^F	thermal and elastic deformation components of bridge 2
λ	thermal conductivity
M_1, M_2	moments of forces in bridges 1 and 2
P	laser beam power
P_h	rate of heat dissipated by convection
P_{PL}	threshold laser beam power
q	heat flux density
r	radius
R	constraint ratio
R_{2B}	constraint ratio of the heated bridge in the two-bridge actuator
ρ	density
S	cross-sectional area
S_h	surface area of convective heat transfer
σ_1	normal stress in bridge 1
σ_{PL}	yield stress
t, t_h	time, pulse length
t_{PL}	threshold pulse length
T, T_0, ΔT	temperature, initial temperature, change in temperature
T_{av}	average temperature
T_{PL}	critical temperature
v	linear displacement
w	bridge width
W_{2B}	dimensionless parameter of the bridge width
x_{PL}	position of the critical isotherm T_{PL}

be here termed the distance between bridges for short. These fundamental design parameters strongly influence actuator's operating characteristics such as the range and resolution of adjustment. Behavior of two-bridge actuators has become the subject of intensive investigations over the past several years [23–30]. However, the role of the most important design parameters has not been thoroughly investigated and highlighted yet.

Majority of the research into behavior of two-bridge actuators dealt with a single geometry of actuator or with actuators scaled proportionally in all dimensions [24–29]. Sakkiettibutra et al. [29] numerically investigated relation between actuator's geometrical scale and laser micro-adjustment parameters. Shen et al. [24], [27] performed a finite element method (FEM) analysis and explained in-plane and out-of-plane deformation by coupling of UM and TGM. Samples with a square, circular and diamond cut-outs were used in experimentally validated FEM analysis of the cut-out geometry influence on temperature, stress and deformation of two-bridge actuators [28]. All samples used in that research had the same distance between bridges and the smallest width of bridge was constant. Size effects on the mechanical behavior of the two-bridge actuator were considered using material flow stress modified with respect to the actuator geometrical scale and material grain size [25]. Geometrically scaled samples were used in numerical and experimental study on cooling time of the actuator [26]. Influence of the cut-out shape (square, circle and diamond) was also considered, although the ratio of the minimal bridge width to the distance between bridges was always kept constant in that study.

In the recent numerical and experimental study on in-plane and out-of-plane deformation of two-bridge actuators Zhou et al. [30] used samples with the same bridge width and various distances between bridges. The authors noted that various magnitudes of in-plane or out-of-plane deformations can be achieved by carefully designing the actuator and laser heating parameters. However, no quantitative general dependences describing actuator's behavior were derived from the results of simulations.

The effects of material properties were analyzed numerically using data of two materials: stainless steel and an aluminum alloy [30]. It was concluded that behavior of actuators significantly depends on materials used. However, results of the presented there FEM simulations did not provide designers with detailed description of the role of particular thermo-physical and thermo-mechanical material properties in actuator's behavior.

This paper aims to study the effects of the distance between bridges and the bridge width on the laser-induced in-plane deformation of two-bridge actuators. The analysis is based on a theoretical model [31], almost entirely analytical. Analytical modeling of such complex thermo-elastic–plastic processes seems to be impractical, if not impossible at all. However, closed form solutions that explicitly show the role of each significant process parameter are of great value for practicing engineers, who are involved in the application and development of new technologies. The analytical approach is able to extent our understanding of the basic physical mechanisms involved in the processes of interest [32]. Successful analytical modeling requires application of reasonable simplifications and indispensable experimental verification.

2. Theoretical model

The structure under concern is a laboratory model of the two-bridge actuator. It consists of two deformable bridges (1, 2 in Fig. 1) and two regions considered as rigid (3, 4 in Fig. 1).

The bridges are separated by a rectangular cut-out. Among different cut-outs' shapes, which have been reported in literature, the rectangular shape assumed here is best amenable to analytical treatment. Shen et al. [28] analyzed the effect of the cut-out shape on the maximum material temperature attained due to laser