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Numerical and experimental investigation of cooling time in laser micro-adjustment of two-bridge actuators

Hong Shen [a,b,*], Zhenqiang Yao [a,b]

[a] School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] State Key Laboratory of Mechanical System and Vibration, Shanghai 200240, China

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ABSTRACT

Multiple thermal cycles are necessary in laser micro-adjustment to achieve required deformations. Between two consecutive thermal cycles, a cooling time is necessary for the workpiece to cool down. This paper presents two cooling criteria including the same temperature (ST) and the room temperature (RT) for laser micro-adjustment of two-bridge actuators. The effects of the scaled geometry of actuators on cooling time are investigated numerically and experimentally for different processing parameters under the present cooling criteria. Considering the influence of material properties on cooling time, numerical analysis is conducted for stainless steel and aluminum alloy materials. The effects of the cut-out shapes of actuators are studied using experimental methods. The numerical and experimental results show that the cooling time can be saved significantly when using ST cooling criterion, especially for the material with high thermal conductivity and large heat capacity. Moreover, it was found that the square cut-out actuator be the best choice for different scales if RT is applied. However, for large scales the circle cut-out actuator was found better if ST is used.

1. Introduction

The functionality of many micro-system devices such as DVD drives, hard drives or micro-optical systems crucially depends on the accurate geometrical adjustment of specific lenses, sensors or other functional devices. Instead of high precision manufacturing of each individual component and high accuracy assembly, it has turned out much cheaper and easier to micro adjust the specially designed actuators which connect the functional devices. Meanwhile, as mounted micro components are typically difficult to access and highly sensitive to mechanical forces and impacts, contact-free laser adjustment of actuators offers a great potential for accurate manipulation of micro devices [1].

Laser micro-adjustment derives from laser forming by transferring this technology to the domain of micro-systems. This process is typically based on temperature gradient mechanism (TGM) and upsetting mechanism (UM). Recently, laser micro-adjustment of actuators has attracted considerable attentions [2–10]. For example, Hagenah and Wurm [4] presented a concept and methodology to assist engineers in defining actuator geometries for laser adjustment in micro-technology in order to realize different movements of the actuator. Otto developed an analytical–numerical model to describe the thermo-elastoplastic deformation of two-bridge actuators [5]. Numerical and experimental attempts were also made to study the effects of varying heating duration on thermal upsetting of two-bridge actuators [7]. Shen explained the mechanism of deformations [8] and considered the size effects in simulation [10] during laser micro-adjustment of two-bridge actuators. However, due to the tiny deformation generated in a single thermal cycle, several iterations are required until the desired position of the functional component is finally reached within the given tolerances in laser micro-adjustment. Hence, the process steps of laser adjustment can become quite time consuming.

Cooling time in multi-scan laser forming has been investigated by some researchers. Hennige and Geiger [11] have experimentally investigated cooling effects in multi-scan laser forming of aluminum sheets using high pressure air cooling and water cooling. The effects of the forced cooling on laser forming process have been examined using both numerical and experimental methods [12]. Although these results showed that the forced cooling could be quite efficient, it is difficult to use these cooling methods in micro-systems because of the high sensitivity of the systems. Shen et al. [13] numerically studied the interval time between two sequent scans in laser forming under nature cooling condition, but the work

* Corresponding author. School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China. Tel.: +86 21 34206660; fax: +86 21 34206583.
E-mail address: sh_0320@sjtu.edu.cn (H. Shen).

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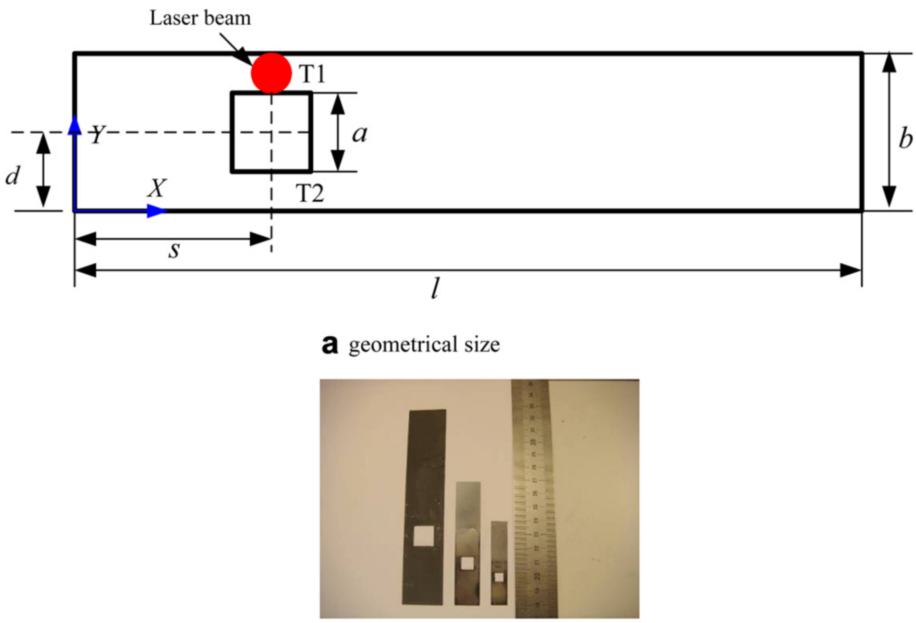

a geometrical size

b scaled actuators

Fig. 1. The sketch of a two-bridge actuator.

was only for the laser forming of traditional sheets/plates, which cannot be applied for the laser micro-adjustment of actuators.

In this paper, we present two cooling criteria for laser micro-adjustment of two-bridge actuators. The cooling time of different geometrically scaled actuators of stainless steel and aluminum alloy materials is investigated using finite element methods. Experimental analysis is carried out to examine the numerical results for the actuators of stainless steel material. Using the presented two cooling criteria, the effects of the cut-out shape of actuators on cooling time are also examined experimentally. Finally, the influence of cooling criteria on the deformations of actuators is numerically investigated.

2. Cooling criteria

The two-bridge actuator is a metal sheet with a cut-out, as shown in Fig. 1. When one bridge of the actuator is heated by a pulsed laser, the temperature at the heated bridge increases greatly until the pulse ends. Then, the heated bridge cools down due to the heat conduction and heat loss (convection and radiation), while the temperature in the rest part of the actuator may increase continuously to some extent. During the cooling process, two situations are listed as follows,

(1) the actuator is not cooled sufficiently, but the heated and un-heated bridges have the same temperature, i.e. $T_1 = T_2$; and
(2) the actuator is cooled sufficiently to room temperature, i.e. $T_1 = T_2 = T_0$,

where T_1 and T_2 are the temperatures at the middle of the heated and un-heated bridges, respectively, and T_0 is the room temperature, as shown in Fig. 1. Therefore, two simple cooling criteria are considered as the same temperature cooling criterion (ST) and the room temperature cooling criterion (RT). Both for numerical simulation and experimental analysis, the temperatures are considered identical if the difference between two temperature values is less than 1 °C.

3. Numerical simulation

The general governing equation of heat conduction for the three-dimensional transient problem can be expressed as follows,

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{1}$$

where ρ is the material density, c is the specific heat, T is the temperature, t is the time, k is the thermal conductivity, x, y and z are the coordinates in the rectangular coordinate system (Fig. 1). The boundary conditions of the governing Equation (1) can be expressed as follows:

$$T = \overline{T} \tag{2}$$

$$k\frac{\partial T}{\partial n} = h(T_a - T) + \epsilon\sigma\left[(T_a + 273)^4 - (T + 273)^4\right] = (T_a - T)\overline{h}(T) \tag{3}$$

$$\overline{h}(T) = h + \epsilon\sigma(T_a + T + 2\times 273)\left[(T_a + 273)^2 + (T + 273)^2\right]$$
$$k\frac{\partial T}{\partial n} = q \tag{4}$$

where $\overline{T}$ is the temperature on the boundary, n is the normal coordinate of the boundary, T_a is the environment temperature surrounding the boundary, h is the convection coefficient (W/m^2 °C), ϵ is the surface radiation factor, $\sigma = 5.67\times 10^{-8}\ W/m^2K^4$

Table 1
Dimensions of actuators for different scales (mm).

Scale	l	b	t	$a = d$	s	r_0
4	60	12	0.2	6	20	1.5
6	90	18	0.3	9	30	2.25
8	120	24	0.4	12	40	3
10	150	30	0.5	15	50	3.75
16	240	48	0.8	24	80	6
32	480	96	1.6	48	160	12