PERIODICA POLYTECHNICA SER. TRANSP. ENG. VOL. 28, NO. 1–2, PP. 143–152 (2000)

EXPERIMENTAL RESEARCH ON LASER–MATERIAL INTERACTION

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Received: Oct. 1, 2000

Abstract

This paper presents a new method of real–time measuring technology to investigate the thermo–physical process of laser–material interaction during laser non–melting surface processing. In the thickness direction of the specimen, the temperature distribution was measured with Thermovision Infrared System in real–time. The dynamic micro–deformation of the specimen was studied using laser beam reflex amplifier system. Experiment results display the thermo–physical process of laser–material interaction and lay a foundation of further researching on the process of laser processing.

Keywords: laser–material interaction, temperature distribution and deformation distribution

1. Introduction

Laser processing technology is an advanced and highly efficient manufacturing method. It has been applied in airplane industry, defense industry, automobile industry, mechanical industry and material industry, etc. Due to extremely high laser output power density (more than 10^4 W/cm^2), extremely quick heating speed and self–cooling speed (10^3 – 10^6 °C/s) on the material surface, the process of laser–material interaction is regarded as a very complex thermo–physical process under the interaction between temperature, phase transformation and stress–strain. It relates to laser, material, thermal–physics, dynamics and many other scientific fields. After the interaction of laser beam with material, material deformation is the result of thermal deformation and transformation deformation cooperation. Final stress of material interior is superposition of thermal stresses and transformation stresses. When stresses there exceed the elastic limit of material, material will produce plastic deformation. If material is thinner such as sheet metal, it will get beneficial plastic deformation, which is laser sheet metal bending. If material is thick enough, it will not cause obvious plastic deformation, this stress is kept in the material and regarded as residual stress. Residual stress will have a great influence on the usage properties of the material. We expect that the residual compressive stress is produced on the material surface in order to improve bearing capacity of material.

Laser transformation hardening on the surface material and laser sheet metal bending are two different application fields in laser non–melting surface processing. Although experts have done lots of research on theory and experiment [1]–[16], due to lacking research on the thermo–physical process of laser–material interaction, the behaviour and regularity of strain–stress during the process have not been understood clearly. The technological parameters chosen by trial and error cannot ensure the optimal quality of treated surface and get the shape and direction of deformation expected.

This paper presents a new method of real–time measurement technology to investigate the thermo–physical process of laser–material interaction during laser non–melting surface processing. In the thickness direction of the specimen, the temperature distribution was measured with thermovision infrared system in real–time. The dynamic micro–deformation of the specimen was studied using laser beam reflex amplifier system. Experiment results reveal the thermo–physical process of laser-material interaction and lay a foundation of further researching on the process of laser processing.

2. Experimental Method

The experimental principle scheme for laser–material interaction is shown in *Fig. 1*.

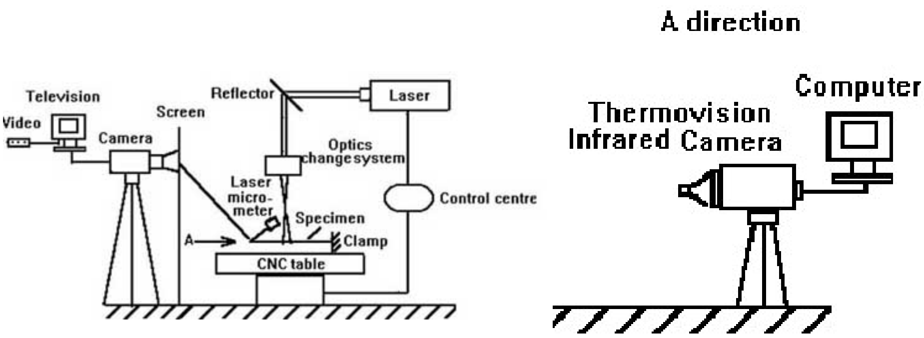


Fig. 1. The experimental principle scheme for laser–material interaction

A 1800 W CO_2 laser is used in continuous wave mode, its power density distribution is TEM_{00}. The wavelength of laser beam is 10.6 μm, focus length of lens is 254 mm. The laser beam is guided through an optical fiber cable from the controller to the laser beam head. On/off switch, the output power and pulse duration of it, and the movement of the $x-y$ table are controlled by CNC–program. CNC control unit accuracy is 0.005 mm. The specimen is clamped at one end as a cantilever beam and put 21 mm under focal point of lens (beam diameter on the specimen surface is 2 mm). The specimen is irradiated in the middle by the laser beam, the continued pulse duration is 0.782 s. A small piece of the plexiglas is stuck to its upper side of free end. Laser micrometer irradiates on the plexiglas and reflects to the screen stuck by a piece of coordinate paper in order to amplify specimen deformation. A camera used at a frequency of 24 Hz records the process of movement of light point during laser–material interaction. The television connected with the video displays the movement of light point recorded by camera. At the same time the thermovision infrared camera used at an image frequency of 6.25 Hz records the real–time temperature distribution in the thickness direction of the specimen in the heated region. Computer displays images recorded by the thermovision infrared camera.

The typical die material C45 (100 mm $\times$ 2 mm $\times$ 2 mm) and low carbon steel sheet St14 (100 mm $\times$ 2 mm $\times$ 2 mm, 100 mm $\times$ 2 mm $\times$ 1.5 mm) are chosen. Their chemical compositions are shown in *Table 1*.

Table 1. Chemical compositions, [%]

	C	Si	Mn	P	S
St 14	0.08	$0.03 - 0.1$	< 0.4	< 0.025	< 0.025
C45	$0.42 - 0.50$	$0.15 - 0.30$	$0.40 - 0.70$	< 0.04	< 0.04

The surface of material is sprayed with a graphite coating (Graphite 33) in order to enhance absorption of energy.

3. Experiment Results

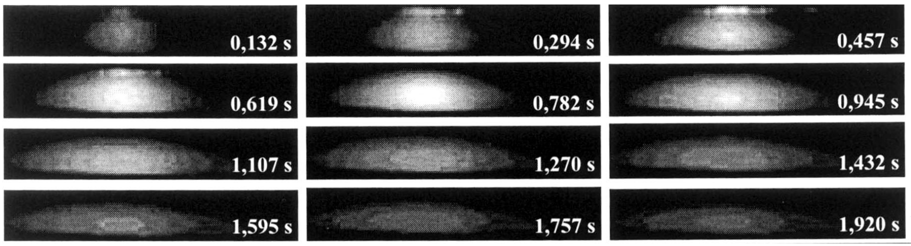
3.1. The Temperature Distribution

1. During the process of laser–material interaction, the temperature distribution images in the thickness direction of the specimen in the heated region are shown in *Fig. 2* and *Fig. 3*.

Fig. 2 and *Fig. 3* indicate the variation of temperature distribution during the process of laser–material interaction. This process comprises two phases, the heating phase and the cooling phase. When laser irradiates the specimen surface, light energy changes into heat energy in a very short time and then goes into the specimen very quickly. When laser beam switches off, the specimen will cool very quickly. But due to heat transfer, the effect of boundary can be seen obviously: heat energy transferring to the lower side surface is reflected into the specimen.

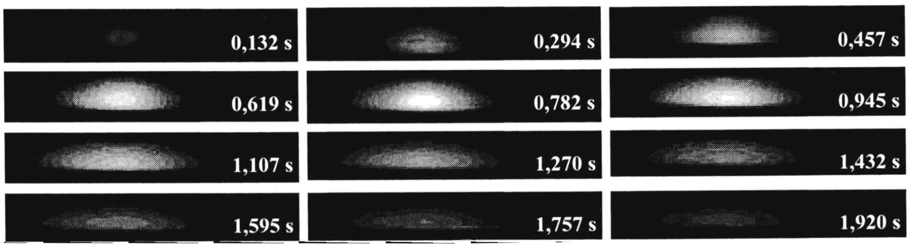
At the end of pulse duration, the temperature distribution images in the thickness direction of the specimen in the heated region are shown in *Fig. 4* and *Fig. 5*.

Fig. 4 and *Fig. 5* indicate the distribution of maximum temperatures recorded during the process of laser–material interaction. It is obvious that because the



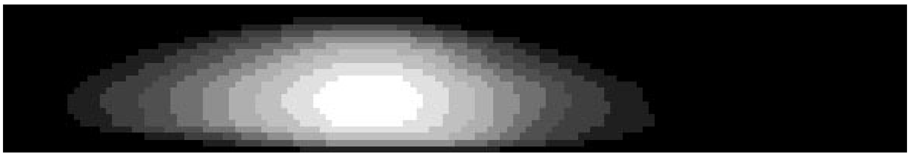
Material: St14; Thickness: 2 mm; Laser output power: 100 W; Time of process: 1.92 s

Fig. 2. Variation of the temperature distribution during laser–material interaction



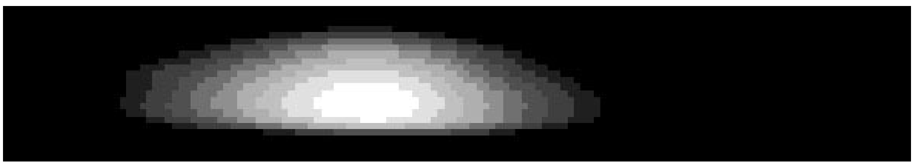
Material: C45; Thickness: 2 mm; Laser output power: 100 W; Time of process: 1.92 s

Fig. 3. The variation of the temperature distribution during laser–material interaction



Material: St14; Thickness: 2 mm; Laser output power: 100 W; Pulse duration: 0.782 s

Fig. 4. The temperature distribution image at the end of pulse duration

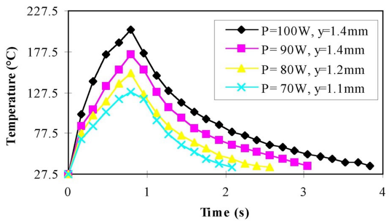


Material: C45; Thickness: 2 mm; Laser output power: 100 W; Pulse duration: 0.782 s

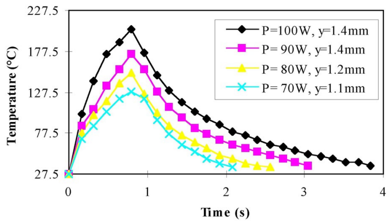
Fig. 5. The temperature distribution image at the end of pulse duration

specimen thickness is finite, heat energy conducted to the lower side surface is reflected into the specimen and makes temperature of specimen thickness direction in one position reach the maximum. This position of the maximum temperature depends on the energy absorbed by specimen.

2. During the process of laser–material interaction, the variation of temperature versus time in the specimen thickness direction is shown in *Fig. 6*.



Material: St14; Thickness: 2 mm
Pulse duration: 0.782 s



Material: C45; Thickness: 2 mm
Pulse duration: 0.782 s

Fig. 6. The variation of temperature versus time

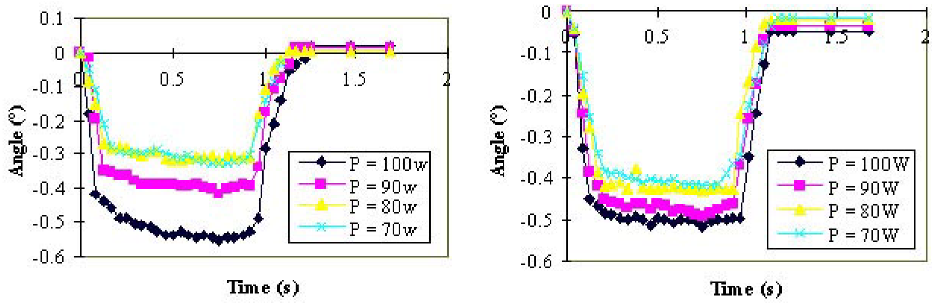
Fig. 6 indicates that the recorded maximum temperature increases with the laser output power improvement, but the position of the maximum temperature is different. For material St14, the position of the maximum temperature moves toward the lower side. This means that the more energy is absorbed by material, the larger the depth of the heat conductance inside the material is. At the same time, the more the heat energy that conducts to the lower side surface, is reflected into the specimen, the nearer to the lower side the position of the maximum temperature recorded is. However, for material C45, the position of the maximum temperature is almost constant. This is the reason why the phase transformation occurs in the material. In the pulse duration, the austenitic transformation needs absorb the heat. The more the energy absorbed by material, the more the heat absorbed by the austenitic transformation is.

3.2. The Dynamic Micro–Deformation Distribution

The variation of the dynamic micro–deformation versus time during laser–material interaction is shown in *Fig. 7*.

Fig. 7 indicates when the laser beam irradiates the specimen surface, the specimen deforms away from the laser beam because of thermal expansion.

With continual pulse duration, the deformation is larger and larger. But due to heat conductance, heat energy that conducts to the lower surface is reflected into the specimen and makes temperature of the specimen interior improve. This decreases the deformation and makes the curve show a constant value for a short time after the pulse duration finishes. After laser beam switches off, because the temperature

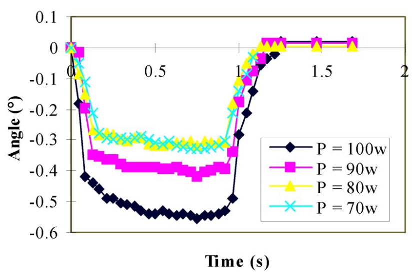


Material: St14; Thickness: 2 mm
Pulse duration: 0.782 s

Material: C45; Thickness: 2 mm
Pulse duration: 0.782 s

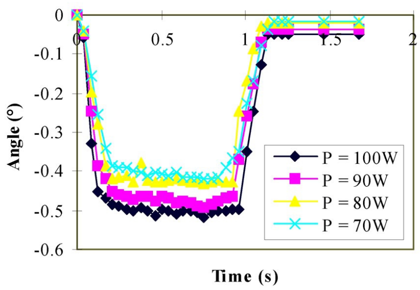
Fig. 7. The variation of the dynamic micro–deformation versus time during laser–material interaction

is falling, the specimen contracts and the deformation of the specimen away from laser beam reduces gradually. For material St14, the specimen deforms towards the laser beam at last. But for material C45, due to the martensitic transformation, volume expansion decreases the deformation towards the laser beam and makes the specimen deform away from the laser beam finally. The value and direction of final deformation depend on the energy absorbed by the specimen. It is obvious that the higher the laser output power, the larger the deformation.



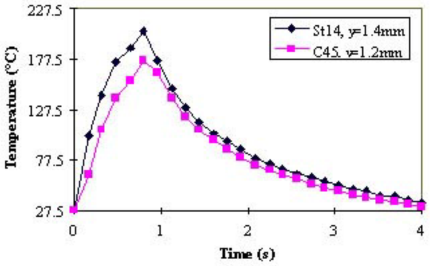
Material: St14; Thickness: 1.5 mm
Pulse duration: 0.782 s

Fig. 8. The influence of laser output power on the temperature distribution



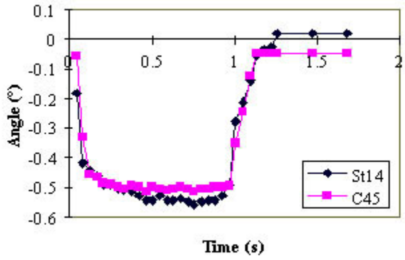
Material: St14; Thickness: 1.5 mm
Pulse duration: 0.782 s

Fig. 9. The influence of laser output power on the dynamic micro–deformation



Thickness: 2 mm
Laser output power: 100 W
Pulse duration: 0.782 s

Fig. 10. The influence of the composition of material on temperature distribution



Thickness: 2 mm
Laser output power: 100 W
Pulse duration: 0.782 s

Fig. 11. The influence of the composition of material on dynamic micro–deformation

4. Discussion and Conclusion

4.1. The Influence of Technological Parameters on Laser–Material Interaction

The main factors influencing laser–material interaction are laser output energy, the composition peculiarities of the material and the specimen thickness. Their effects are expressed as different temperature distributions and different dynamic micro–deformation distributions. Experiments display the variation of temperature and dynamic micro–deformation versus time during laser–material interaction under the condition of different laser output power, material and specimen thickness. The detailed analyses are shown as follows.

1. The influence of laser output power on the temperature distribution and the dynamic micro–deformation are shown in *Fig. 8* and *Fig. 9*.

Fig. 8 indicates that the higher the laser output power is, the higher the maximum temperature recorded is. That means that the energy absorbed by the specimen determines the temperature value of the specimen. In addition, the position of the maximum temperature moves toward the lower side due to improvement of the depth of the heat transferring into the material interior and the heat energy that conducts to the lower side surface is reflected into the specimen.

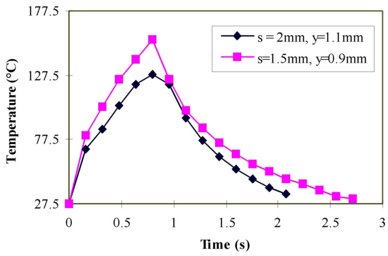
Fig. 9 indicates that the higher the laser output power is, the larger the specimen deformation during laser–material interaction is. This is the reason that the value of thermal expansion depends on the temperature distribution in the specimen. However, the specimen deformation depends on the value of thermal expansion.

2. The influence of the composition of the material on the temperature distribution and the dynamic micro–deformation are depicted in *Fig. 10* and *Fig. 11*.

Fig. 10 indicates that under the same technological parameters, the position of the maximum temperature of material C45 is nearer to the upper side. This is the reason that the phase transformation occurs in the material. In the pulse duration, the austenitic transformation needs absorbing the heat.

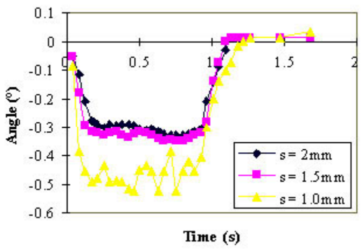
Fig. 11 reveals that under the same technological parameters, the composition of the material has a great influence on the final deformation of the specimen. For material St14, the specimen deforms towards the laser beam at last. But for material C45, due to the martensitic transformation, volume expansion decreases the deformation towards the laser beam and may cause the specimen deformation away from the laser beam, finally.

3. The influence of the specimen thickness on the temperature distribution and the dynamic micro–deformation is demonstrated in *Fig. 12* and *Fig. 13*.



Material: St14;
Laser output power: 70 W
Pulse duration: 0.782 s

Fig. 12. The influence of the specimen thickness on temperature distribution



Material: St14;
Laser output power: 70 W
Pulse duration: 0.782 s

Fig. 13. The influence of the specimen thickness on dynamic micro–deformation

Fig. 12 shows that under the same technological parameters, the thinner the specimen is, the more the heat energy is that transfers into the lower surface and is reflected into the specimen. So the corresponding temperature is higher. At the same time, the relative position to the thickness of the maximum temperature is nearer to the lower side.

Fig. 13 indicates that under the same technological parameters, the thinner the specimen is, the larger the specimen deformation is. This is the reason that the thinner the specimen is, the less the section moment of the specimen is. So the specimen produces the more deformation under the same energy interaction. But if the specimen is thin enough a strong vibration is caused during laser–material interaction. Experiment result will be affected.

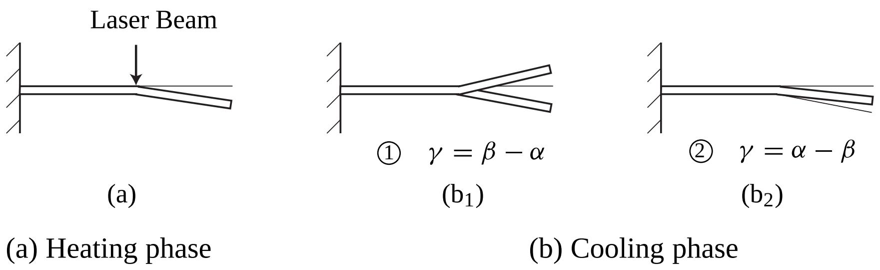


Fig. 14. The thermo–physical process of laser–material interaction

4.2. The Thermo–Physical Process of Laser–Material Interaction

Experimental result shows that the thermo–physical process of laser–material interaction is divided into heating phase and cooling phase.

- Heating phase
  When the laser beam irradiates on the specimen surface, the temperature on the upper surface in the heated region increases rapidly (not exceeding melting point of material). Strong temperature gradients mainly occur in the thickness direction of the specimen. Due to large thermal expansion and low yield stress on the upper surface at a high temperature, the material heated region produces compressive plastic deformation and causes material to accumulate. So the specimen deforms away from the laser beam. With a continual pulse duration, the deformation is larger and larger. But due to heat conductance, heat energy that conducts to the lower surface is reflected into the specimen and makes the temperature of the specimen interior improve. This decreases the deformation and makes the curve of specimen deformation show a constant value for a short time after the pulse duration finished. The angle of deformation is α as shown in *Fig. 14*(a). It depends on the temperature gradient in the thickness direction and the geometry constraint of the specimen.
- Cooling phase
  After laser beam switches off, the temperature on the upper surface is falling very quickly. Material contracts so that part of accumulative material recovers and compressive stress decreases. With the development of cooling process, due to heat conductance, the lower layer of the specimen expands continually and makes it elongate. So the deformation away from laser beam reduces gradually. As far as the material possesses phase transformation property, the martensitic transformation can cause volume expansion so that the deformation away from the laser beam increases. Therefore, the angle β of deformation is the result of thermal deformation and transformation deformation cooperation.

Thus, it can be seen that the final deformation angle of the specimen can be expressed by $\gamma = \beta - \alpha$. When $\beta > \alpha$, the specimen deforms towards the laser beam as shown in *Fig. 14*(b_1). When $\beta < \alpha$, the specimen deforms away from the laser beam as shown in *Fig. 14*(b_2).

Acknowledgements

The authors gratefully acknowledge support for this study from the Department of Mechanical Engineering Technology and the Department of Materials Science and Engineering. They also thank Dr. Antal Sklánitz and Dr. Zoltán Dudás for their assistance during the experiments.

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