Research on Q-Switched Nd:YAG Laser Engraving

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Abstract: In this paper, the engraving process with Q-Switched Nd:YAG laser is investigated. High power density is the pre-requisition to vapor materials, and high repetition rate makes the engraving process highly efficient. An acousto-optic Q-Switch is applied in the cavity of CW 200 W Nd:YAG laser to achieve the high peak power density and the high pulse repetition rate . Different shape craters are formed in a patterned structure on the material surface when the laser beam irradiates on it by controlling power density, pulse repetition rate, pulse quantity and pulse interval. In addition, assisting oxygen gas is used for not only improving combustion to deepen the craters but also removing the plasma that generated on the top of craters. Off-focus length classified as negative and positive has a substantial effect on crater diameters. According to the message of rotating angle positions from material to be engraved and the information of graph pixels from computer, a special graph is imparted to the material by integrating the Q-Switched Nd:YAG laser with the computer graph manipulation and the numerically controlled worktable. The crater diameter depends on laser beam divergence and laser focal length. The crater diameter changes from 50 μm to 300 μm , and the maximum of crater depth reaches one millimeter.

Key Words: Laser engraving, Q-Switched Nd:YAG laser, Crater, Power density, Repetition rate

1. INTRODUCTION

Many engraving methods, such as mechanical tool, electro-discharge, ion and electron beam and acid corrosion, have been developed to make a patterned structure on material surface in recent years[1,2,3,4]. The adoption of mechanical tool is limited by the hardness of the engraved material and the size of tool for achieving micro-engraving. For acid corrosion etching usually used in lithography, source illustration passes through a patterned photo-mask or reticule, then through a complex optical system that projects the patterned image onto the photo-resist coated target. After the photo-resist is developed, it acts as an acid etching mask in the fabrication of the patterned structure. Patterns generated by such an acid etching method is limited by the resolution and field size of the imaging systems. The pattern figure is not clear or definite because of the diffusion of acid. Acid etching process is complex and expensive. Ion, electron and laser engraving utilize high-energy beam to directly engrave patterns on the material surface.

The aim of this paper is to introduce Q-Switched Nd:YAG laser engraving theory and procedures. The influences of power density, pulse time, pulse repetition and assisting gas on craters and beads are mainly studied.

2. ENGRAVING THEORY

The laser engraving prescribed in this paper is to irradiate the material surface by means of Q-Switched Nd:YAG pulsed laser with high power density and high repetition rate, the melting and vaporization of laser acting part sequentially takes place. As a result, a crater is generated on the material surface, as illustrated in Fig.1. At the same time, assisting oxygen gas is used to remove the plasma on the top of crater and improve combustion for deepening the crater. Because the plasma atmosphere inhibits the absorption of laser irradiation, it is indispensable to adopt assisting gas with a certain pressure and flow.

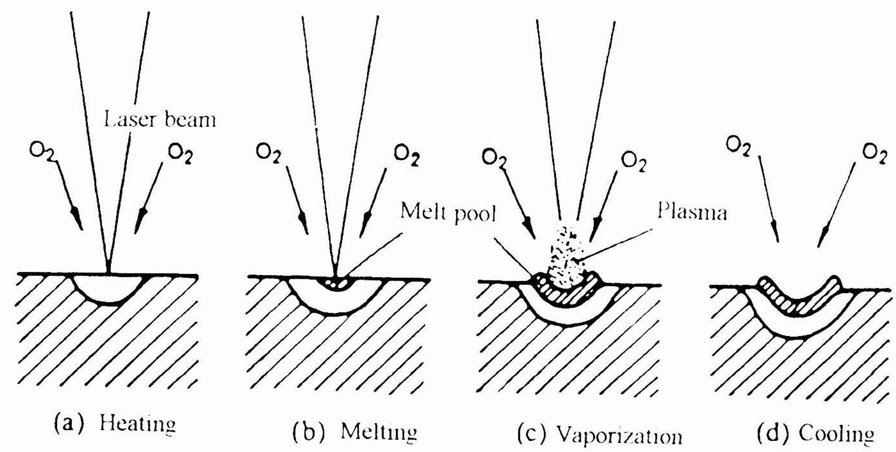


Fig.1 Formation mechanism of laser engraving crater

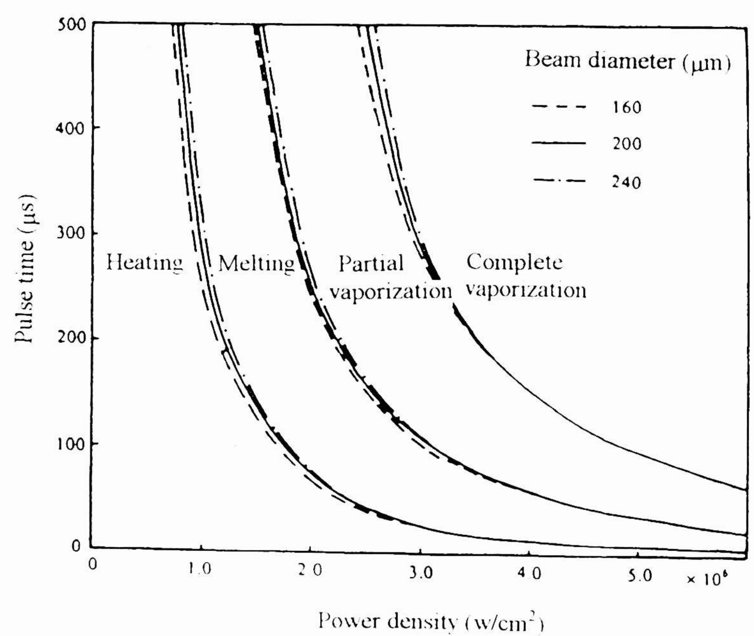


Fig.2 Relationship of power density and pulse time with state of material

Both high power density and high repetition rate play important roles during laser engraving. High power density is the pre-requisition to melt and vapor materials. Fig.2 shows the relationship of laser power density with the state of materials[5]. It is the key factor to select moderate power density to achieve different crater aspect and shape. The depth and diameter of crater are dependent on laser power density as well.

Furthermore, high repetition rate makes the engraving process high efficient and precise. In order to achieve high peak power density and high repetition rate of laser pulse, an acousto-optic Q-Switch is applied in the cavity of CW 200 W Nd:YAG laser controlling the gain of intracavity. When RF power is turned on, light is diffracted from the zeroth-order beam. This introduces a loss in the cavity, thereby quenching laser oscillation. During this time, energy is stored in the lasing medium. When RF power is turned off, the stored energy is released in a short, high-peak-power pulse. The hold-off of laser power depends on RF power of Q-Switch driver and gain characteristics of laser. Assuming that only the first order of light is considered, the amount of light I_1 in the first order, separated from the zeroth-order beam I_0 by twice the Bragg angle[6], is given by

$$\eta = I_1/I = \sin^2(\Delta\phi/2) \tag{1}$$

where η is the diffraction efficiency, $\Delta\phi$ is the phase excursion determined by the acoustic power level, material properties, and the geometry of the sound field. After η is selected according to the laser gain characteristics, RF power P' is correspondingly obtained from the following equation[6]

$$\Delta\phi = (\pi/\lambda)[2(L/H)M_2P']^{1/2} \tag{2}$$

where λ is the laser wavelength, L/H is the aspect ratio (length to height) of the sound field, M_2 is the material's acousto-optic figure of merit, and P' is the acoustic power.

The laser energy injection determining the crater shape mainly depends on pulse power density, mode, diameter of beam, pulse time and moving velocity of the processed material. The laser energy density E_0 in the beam center is expressed as the following relationship

$$E_0 = 1.60 \times \frac{P}{v r_0} \times f(v\tau/r_0) \tag{3}$$

where P is the laser output power, v is the processed material's moving velocity, r_0 is the focal radius, τ is the laser irradiation time, f is a function of v, τ, and r_0.

Craters with special shapes and distributions are formed in a patterned structure on the material surface when the laser beam irradiates on it by controlling power density, pulse repetition, pulse time, pulse quantity and pulse interval time for a given moving velocity.

3. EXPERIMENTAL

Fig.3 shows the schematic of Q-Switched Nd:YAG laser engraving. A CW 200 W Nd:YAG laser inserted with an acousto-optic Q-Switch system (including a Q-Switch and its driver with RF power of 100 W) is used as an engraving tool. The material to be engraved is supported by a numerically controlled worktable and be able to rotate and move longitudinally. In addition, a light conducting system connects laser with worktable.

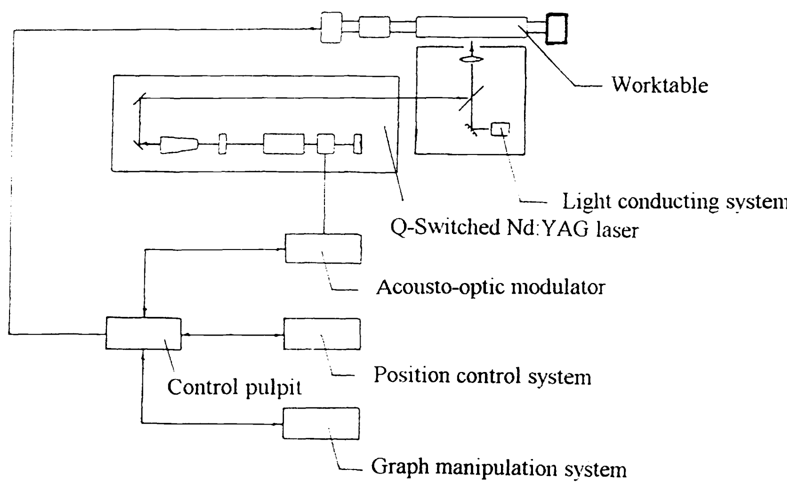


Fig.3 Schematic of Q-Switched Nd:YAG laser engraving

This process has the characteristics of disperse trace of dot by dot and micro-graving with modification. The position information and the graph pixel message are input into the control pulpit with a computer. All signals processed by the computer with a special software are transferred to Q-Switched Nd:YAG laser and numerically controlled worktable. The wanted pattern is engraved on the material surface by manipulating laser parameters and moving information of material. During engraving, assisting oxygen gas with pressure of 0.4-0.6 MPa and flow velocity of 5-30 l/min was applied at blowing angle of 60 degree. Laser pulse repetition ranges from 5 to 30 KHz. Pulse time changes from 0.2 to 1.0 μm. Focal diameter is obtained at the range of 50 to 300 μm by adjusting focal length and beam divergence. The effects of power density, pulse time, off-focus length, and flow velocity and pressure of assisting gas on the shape, depth and diameter of crater are investigated in this paper.

4. RESULTS

By controlling power density, pulse repetition rate, pulse quantity and pulse interval time of Q-Switched Nd:YAG laser, specially patterned craters were fabricated on material surface at a given moving velocity , as demonstrated in Fig.4. The topography and surface roughness of materials can be precisely made through adjusting crater aspct ratio (diameter to depth) and interval distance. Four typical crater shapes were formed by changing the relevant engraving parameters. Fig. 5 illustrates the crater shapes without bead, with circle bead, with one side bead, and with multi-layer bead respectively. The crater shape is mainly dependent on the blowing angle of assisting gas, the laser pulse quantity integrated with the moving speed of materials.

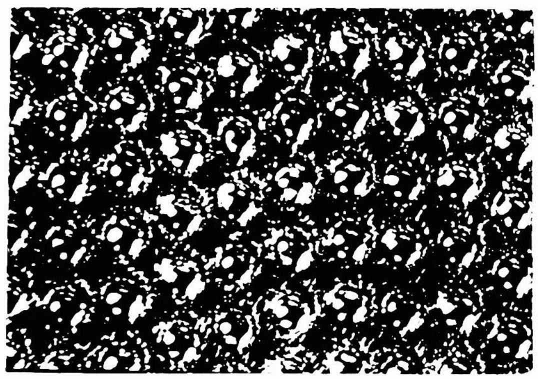


Fig.4 Q-Switched Nd:YAG laser engraving crater pattern

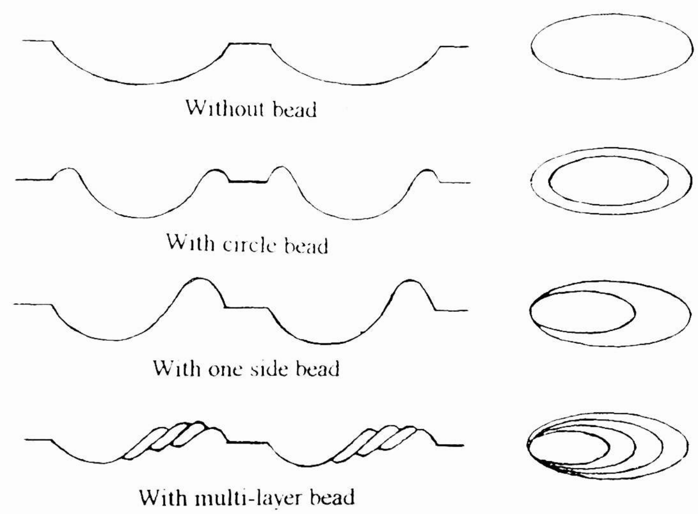


Fig.5 Schematic of engraved typical crater shapes

The variation of crater diameter with energy density (multiplication of power density by pulse time) is shown in Fig.6. It is seen that the diameter of crater increases with the energy density. Fig.7 presents the relationships of crater depth and bead height with energy density. The crater depth and bead height all increase with energy density. This can be explained by the effect of total amount of laser energy upon the melt pool volume resulting from power density and pulse time. The bead surrounding the crater is formed by blowing a part of melting volume onto the plateau.

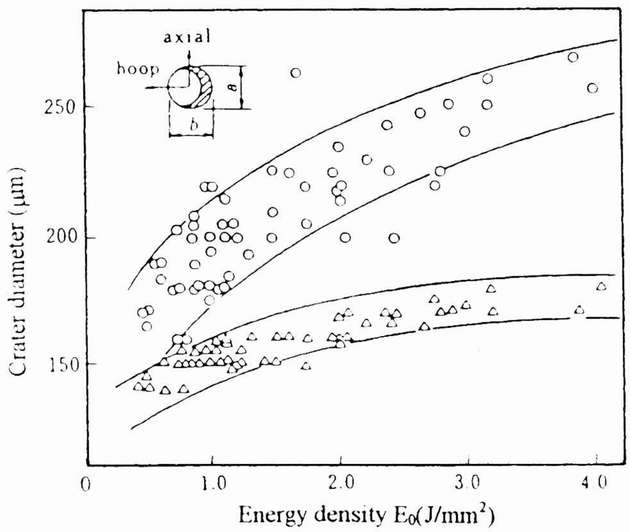


Fig.6 Relationship of crater diameter with energy density

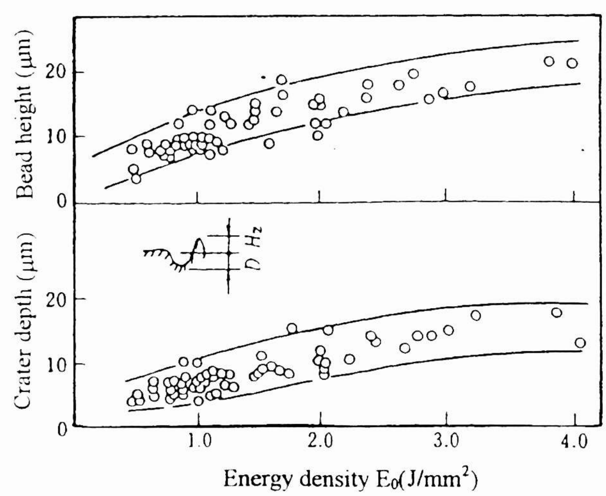


Fig.7 Influence of energy density on crater depth and bead height

Fig.8 illustrates the influence of off-focus length on crater diameter. The off-focus length is classified as negative and positive types. We can see that the crater diameter resulting from positive off-focus length increases greater than that from negative one. Furthermore, Fig.9 and Fig.10 show the effects of pressure and flow velocity of assisting oxygen gas on the depth and diameter of crater. The pressure of assisting oxygen gas mainly influences the crater diameter, and the crater depth and bead height get their maximum when the flow velocity has the range of 20-25 l/min.

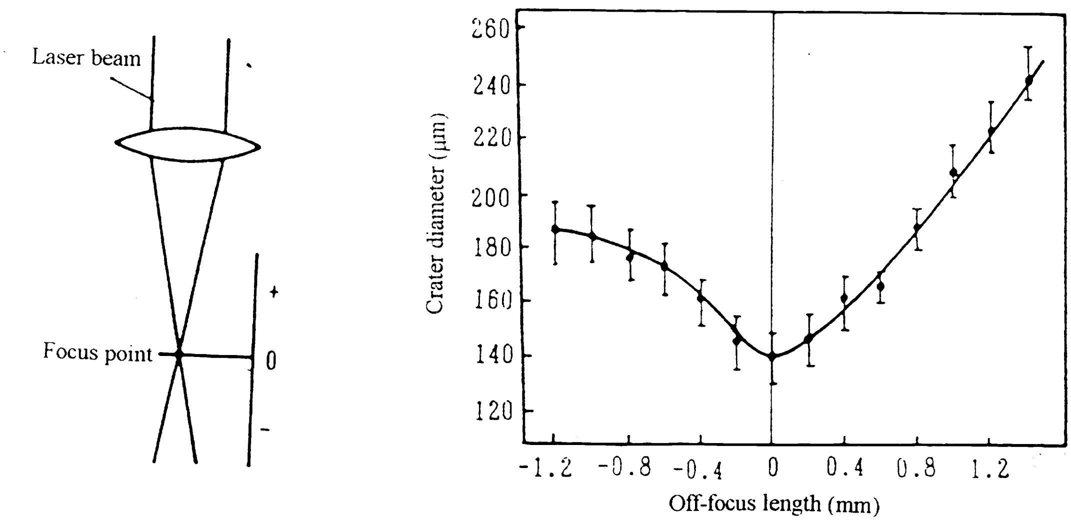
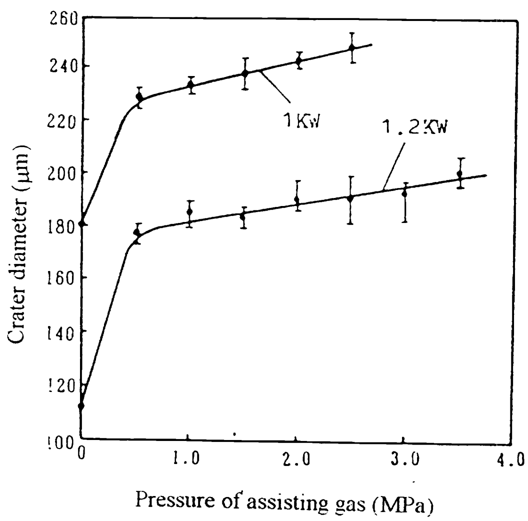


Fig.8 Effect of off-focus length on crater diameter



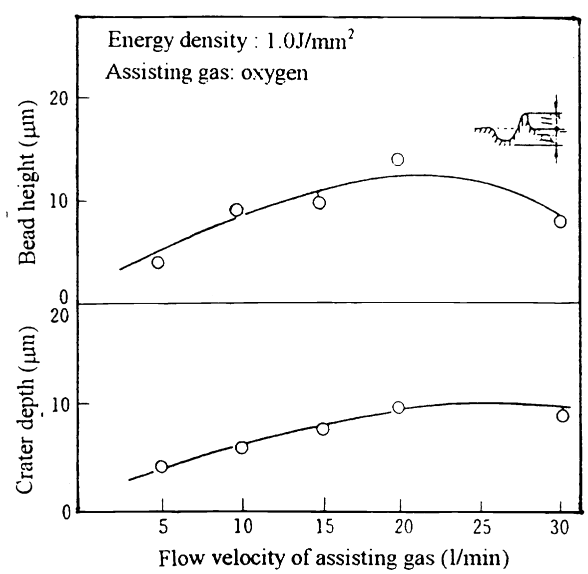


Fig.9 Influence of assisting gas pressure on crater diameter Fig.10 Effect of gas flow velocity on crater diameter and bead depth

The crater diameter substantially depends on laser beam divergence and focal length. By manipulating relevant laser process, the crater diameter changes from 50 up to 300 μm for achieving various dot density, and the maximum of crater depth reaches 1.0 mm.

This offers a wide selection for material surface topography and surface roughness. The dot density engraved by Q-Switched Nd:YAG laser is achieved from 3×3dots/mm^2 to 20×20dots/mm^2. The advantages of Q-Switched Nd:YAG laser engraving process lie in the excellent homogeneity, extraordinary high flxibility, good reproducibility, very easy characterisation, and long service life with a stable pattern.

5. CONCLUSIONS

During Q-Switched Nd:YAG laser engraving, both high power density and high repetition rate have important effects on the final engraved topography. High power density is the pre-requisition to vapor the material, and high repetition rate makes engraving process precise and highly efficient. An acousto-optic Q-Switch is applied in the cavity of CW 200 W Nd:YAG laser to achieve the high peak power density and the high pulse repetition rate . Different shape craters are formed in a patterned structure on the material surface when the laser beam irradiates on it by controlling power density, pulse repetition rate, pulse quantity and pulse interval. In addition, assisting oxygen gas is used for not only improving combustion to deepen the craters but also removing the plasma that generated on the top of craters. Off-focus length classified as negative and positive has a substantial effect on crater diameters. According to the message of rotating angle positions from material to be engraved and the information of graph pixels from computer, a special graph is imparted to the material by integrating the Q-Switched Nd:YAG laser with the computer graph manipulation and the numerically controlled worktable. The crater diameter depends on laser beam divergence and laser focal length. The crater diameter changes from 50 μm to 300 μm , and the maximum of crater depth reaches one millimeter.

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