Title	Processing Mechanism of High Energy Density Beam (Report I) : Mechanism of Drilling
Author(s)	Arata, Yoshiaki; Miyamoto, Isamu
Citation	Transactions of JWRI. 1973, 2(2), p. 148-151
Version Type	VoR
URL	https://doi.org/10.18910/12881
rights	
Note	

Processing Mechanism of High Energy Density Beam (Report I)†
—Mechanism of Drilling—

Yoshiaki ARATA* and Isamu MIYAMOTO**

Abstract

A method obtaining transient distributions of two energy densities in the hole drilled by high energy density beams was proposed: $\widetilde{w}_v$ which passed through the plane perpendicular to the beam axis and $\widetilde{w}_s$ which was absorbed by the side wall of the hole. In a hole of acrylic resin drilled by CW CO_2 laser beam, maximum value of $\widetilde{w}_v$ reached 4~5 times that of the focal point of the lens system used due to a "wall-focusing effect". In the hole drilled by the electron beam, the wall-focusing effect was not recognized, and beam was rather scattered by the vapor. As the result, the CO_2 laser beam produced slender cylindrical hole and the electron beam produced fat hole. The method proposed here may be applied to measure the beam power.

1. Introduction

By irradiating high energy density beams such as laser and electron beams to materials, the irradiated part evaporates and drilling is achieved. In the course of penetrating to the bottom of the drilled hole from the surface, the beam is often scattered, absorbed by the vapor, or reflected from the wall of the hole. As the result, in many cases the shape of the hole is quite different from the contour of the beam formed through the lens. For example, the hole formed by laser is slender and almost straight even when the convergent angle of the lens used is not small. From such phonomena, it is assumed that the shape is affected by a kind of materials, beams properties and intensity, and so on, and at the same time that the beam energy density varies greatly under the presence of interactions between the beam and material.

In this paper, distributions of two mean energy densities in the hole are analyzed: $\widetilde{w}_v$ passed through the plane perpendicular to the beam axis and $\widetilde{w}_s$ absorbed by the side wall.

Since it is generally difficult to measure these energy densities directly, the authors proposed the method for obtaining transient energy densities by measuring change of the shape and size of the hole with the irradiation time. The relationship between the energy densities thus obtained and the hole's shape will be further discussed.

A transparent acrylic resin was used as a test material as it made the theoretical treatment and the observation of the hole's shape easy. The CW CO_2 laser and the electron beam were used and the properties of both were compared based on the results obtained.

2. Theory

After irradiation of laser beam on such materials as synthetic resin and ceramic, the irradiated part evaporates and then a slender hole is formed. Supposed that beam with intensity W is irradiated for time t and volume V is removed by evaporation, the following equation is obtained,

$$W \cdot t = (H + c\rho\theta_v)\,V + Q_h \quad \text{------------------------} \quad (1)$$

where H= latant heat of fusion and evaporation, c= specific heat of material, ρ= density, θ_v= evaporating temperature and Q_h = heat loss by heat conduction. When the beam power is very high or heat conductivity of material is very small, Q_h is negligible in comparison with $(H + c\rho Q_v)\,V$, and the removed volume V is proportional to the incident energy Wt.

Figure 1 illustrates schematically the drilled shape of hole formed by the focused beam. In this figure, two outlines in the plane containing the z-axis correspond to the irradiation time t and $t + dt$, and r and z represent radial and axial distances respectively. Assuming that the hole is symmetric with respect to the z-axis, the volume $V(z, t)$ from $z = Z$ to the bottom of the hole at time t is given by

† Received on Aug. 6, 1973
* Professor
** Research Instructor, Dept. of Welding Engineering, Faculty of Engeneering, Osaka University

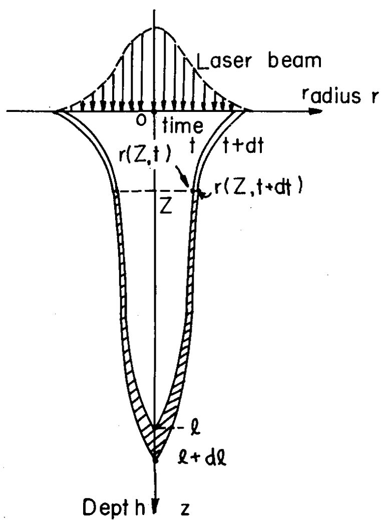

Fig. 1. Schematic diagram of holes drilled by the focused beam.

$$V(Z,\ t)=\pi \int_{z}^{l(t)} r^2(z,\ t)\ dz \quad (2)$$

where $l(t)$ is depth of the hole due to the beam irradiation of time t. Energy amount dJ (joules) which passes through the $z=Z$ plane from time t to $t+dt$ is proportional to the hatched volume in **Fig. 1** as follows:

$$dJ=K\{V(Z,\ t+dt)-V(Z,\ t)\}=K\cdot dV(Z,\ t), \quad (3)$$

where $K=H+c\rho\theta_v$.

Therefore the beam power (watts) passing through $z=Z$ plane at time t is given by

$$W(Z,\ t)=\frac{dJ}{dt}=2\pi K \int_{z}^{l(t)} r(z,\ t)\ \frac{\partial}{\partial t}\ r(z,\ t)\ dz \quad (4)$$

and the average energy density $\widetilde{w}_v\ (Z,\ t)$ in the plane perpendicular to the z-axis is given

$$\widetilde{w}_v=\frac{W(Z,\ t)}{\pi r^2(Z,\ t)}$$

$$=\frac{2K}{r^2(Z,\ t)} \int_{z}^{l(t)} r(z,\ t)\ \frac{\partial}{\partial t}\ r(z,\ t)\ dz \quad (5)$$

The propertional constant $K=H+c\rho\theta_v$ and $r(Z,\ t)$ are necessary to know $\widetilde{w}_v\ (Z,\ t)$.

On the other hand, the beam energy $\widetilde{w}_s$ absorbed by the side wall in unit area at $z=Z$ is given by

$$\widetilde{w}_s=-\frac{1}{2\pi r}\cdot\frac{\partial W}{\partial z}=K\frac{\partial}{\partial t}\ r(z,\ t) \quad (6)$$

3. Relation between Removed Volume and Heat Quantity

The length and bore of CW CO_2 laser tube[1] used in this test were 12 m and 74 mm. The laser beam coupled out from 15 mm diam hole was focused by a concave spherical mirror of radius 310 mm which gave a convergent angle of about 0.1 rad. The incident angle of off-axial beam to the mirror was so small (about 5°) that influence of the astigmatism could be neglected[2]. The radial energy density distribution profile at focal point of this optical system may be approximated by a Gaussian curve with e^{-1} diameter 0.5 mm[2].

Figure 2 shows the relationship between the drilled volume of the acrylic resin and the incident heat quantity in the test using the laser with the power level 360 w and 100 W for various times from 0.01 sec 0.32 sec. The test pieces were shielded with argon gas in order to prevent combustion. As is clea from the figure the removed volume is fairly proportional to the incident heat quantity, and hence effect of heat conduction is negligible. The constant $(H+c\rho\theta_v)$ was about 9 joules/mm^3.

It is often difficult to measure a laser power. Especially the absolute value of transient laser power is apt to be incorrect, though accurate output wave of the laser power can be obtained. However the absolute value of the power is easily obtained by measuring the removed volume so that power measurement with quick response may be possible.

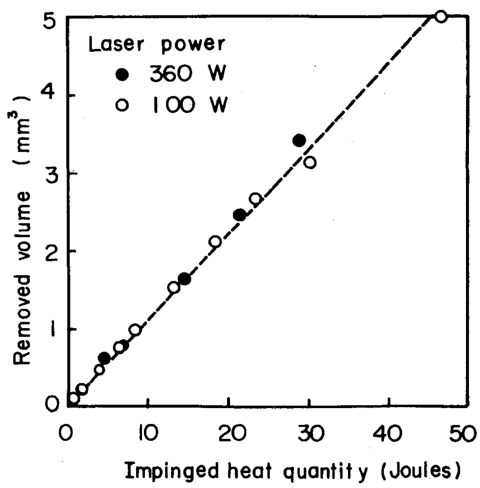

Fig. 2. Relationship between the removed volume of acrylic resin and heat quantity of the incident beam.

4. Beam Intensity in Hole

(1) CO_2 laser beam

Figure 3 shows cross sections of hole in the plane containing beam axis z, which has been formed by irradiating 100w CW CO_2 laser beam focused on the acrylic resin. In this figure, the shape of hole is drawn such that radial distance r is 10 times axial distance z. Shape of each hole, which is much slender considerably differes from the contour of the convergent angle 0.1 rad. This shows that the incident beam was affected by scattering by acrylic vapor or reflection from the side wall of the hole.

As shown in **Fig. 5,** the mean energy density $\widetilde{w}_v$ in the plane perpendicular to the z-axis increased with increasing z for each irradiation time, and maximum value of $\widetilde{w}_v$ reached 3~4 times that of focal

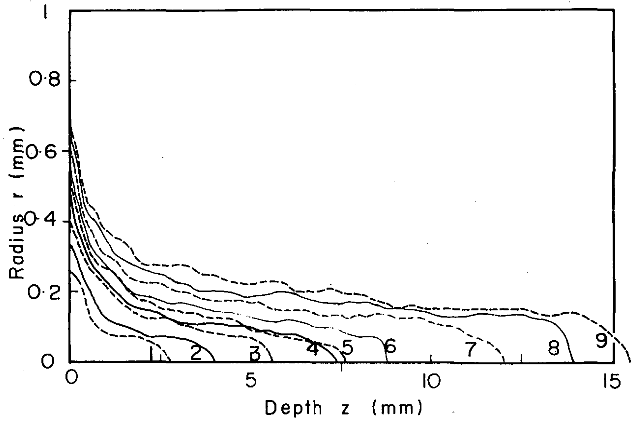

Fig. 3. The shape of holes drilled by the focused laser beam with power level of 100 W. Irradiation time (msec); (1) 10, (2) 20, (3) 30, (4) 50, (5) 70, (6) 90, (7) 140, (8) 190, (9) 250.

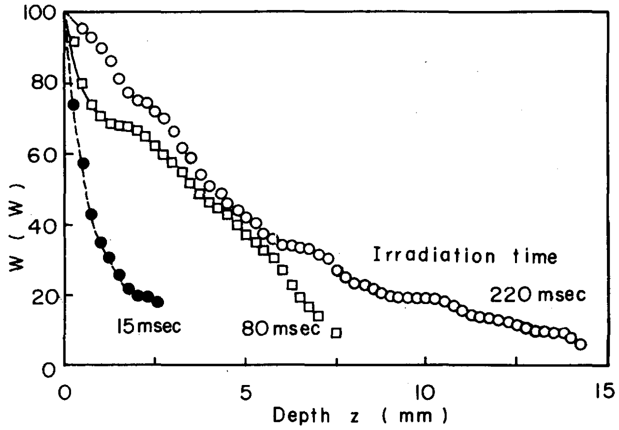

Fig. 4. Relationship between z and power W in the hole for laser beam.

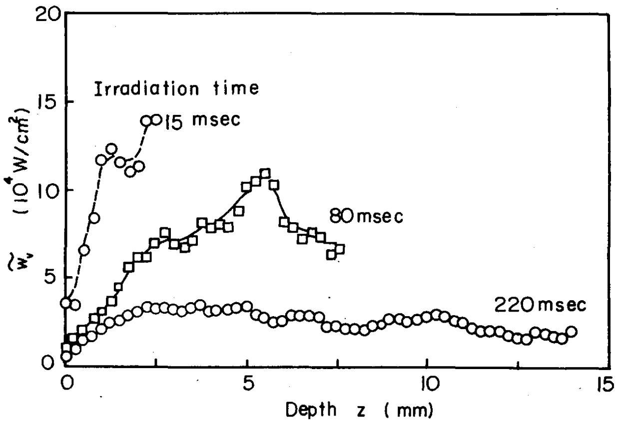

Fig. 5. Relationship between z and $\widetilde{w}_v$ for laser beam.

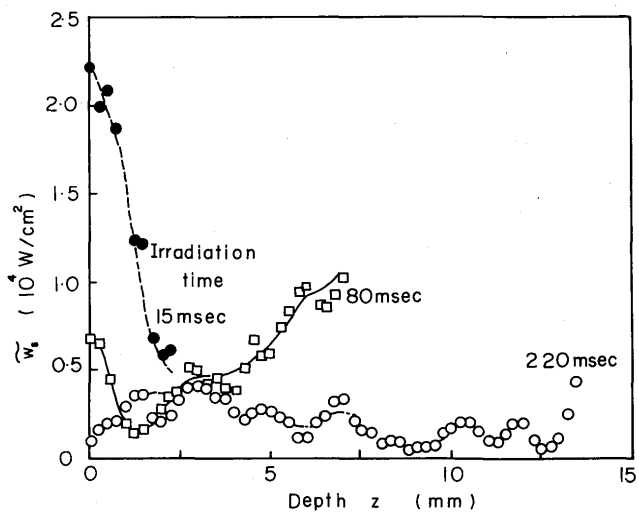

Fig. 6. Relationship between z and $\widetilde{w}_s$ for laser beam.

point. For longer irradiation time, $\widetilde{w}_v$ became almost constant except for vicinity of the top and bottom of the hole. The presence of a certain re-focusing action in the hole is predicted from the fact that $\widetilde{w}_v$ increases with z in spite of obvious degradation in W as shown in **Fig. 4.** The re-focusing effect seems to be produced by the beam reflection from the side wall, and is named "wall-focusing" effect by the authors. The beam energy may be effectively transfered toward the bottom of the hole because the reflectivity of the side wall is high, and as a result a slender and cylindrical hole is formed. Therefore a much slender hole may be obtained by use of an optical system with smaller convergent angle which has a large incident angle to the side wall.

On the other hand energy density $\widetilde{w}_v$ absorbed by the side wall of which a scattering of data is somewhat larger, was very high near surface, and decreased rapidly with increasing z for short irradiating time as shown in **Fig. 6.** This indicates that the removal of acrylic resin by evaporation almost occurred near the surface. As the irradiation time increased, the value of $\widetilde{w}_s$ near surface decreased, and increased near the bottom of the hole. Then in the middle part of the hole, $\widetilde{w}_s$ became almost constant. There was tendency that the length of the constant $\widetilde{w}_s$ region increased and at the same time that the value of $\widetilde{w}_s$ decreased, with increasing the irradiation time. These facts show that the beam energy was transfered to the bottom of the hole with smaller energy loss and drilling action occured mainly near the bottom providing slender and cylindrical hole.

The affect of the scattering by the vapor seems to be negligible, because $\widetilde{w}_v$ and $\widetilde{w}_s$ have a same tendency when much higher CO_2 laser beam has been used.

(2) Electron Beam

Electron beam with accelerating voltage 150 KV and beam current 0.5 mA has irradiated to acrylic resin for various times, and the results obtained are indicated in **Figs. 7~10.** As shown in **Fig. 7,** the depth of the drilled hole was considerably smaller than that of CO_2 laser beam. When the beam current increased to 10 mA, the depth was only two times that of 0.5 mA at the most. One of remarkable features of the electron beam drilling was that the hole was fat on the whole and was pot-like shape near the bottom especially with longer irradiating time. This fact indicates that scattering of the electron by the vapor of arcylic resin influences the shape of the hole.

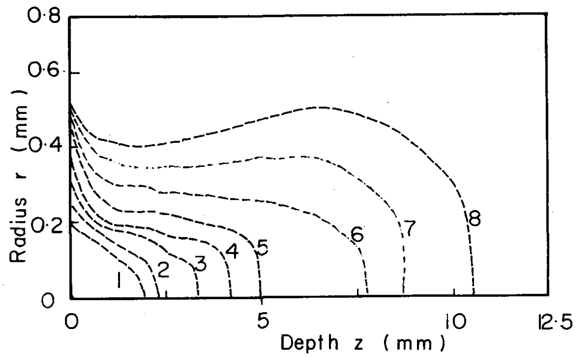

Fig. 7. The shape of holes drilled by the electron beam of 150 KV-0.5 mA. Irradiation time (msec): (1) 15, (2) 30, (3) 50, (4) 65, (5) 180, (6) 270, (7) 650, (8) 900.

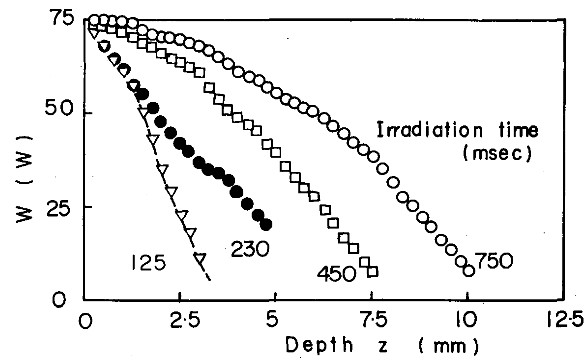

Fig. 8. Relationship between z and power W in the hole for electron beam.

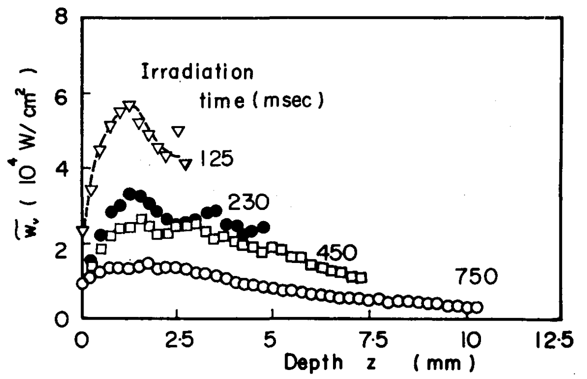

Fig. 9. Relationship between z and $\widetilde{w}_v$ for electron beam.

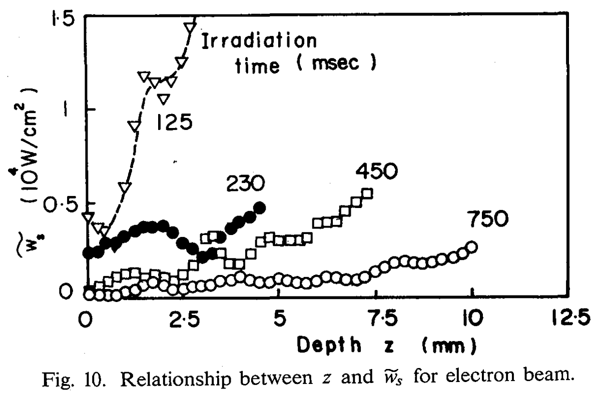

Fig. 10. Relationship between z and $\widetilde{w}_s$ for electron beam.

These do not contradict with $\widetilde{w}_v$-z curves shown in **Fig. 9** where $\widetilde{w}_v$ has a peak around $z=1\sim2$ mm and decreases monotonically in larger z. From this treatment it is not clear whether energy density on the z-axis increased or not near the surface from the increase in $\widetilde{w}_v$ with the degree shown in **Fig. 9,** because $\widetilde{w}_v$ is mean energy density. After all, the increase in the energy density on the z-axis seems to be not large even if $\widetilde{w}_v$ increases near at surface. As shown in **Fig. 10,** $\widetilde{w}_s$ increased gradually with increasing z even for longer irradiating time.

From these facts it may be concluded that in electron beam drilling of acrylic resin, the effect of beam scattering by the vapor is much more important than that of wall-focusing.

5. Conclusion

In CO_2 laser drilling of acrylic resin, it was clarified that energy of the laser beam was effectively transfered toward the bottom of the hole by the reflection from the side wall, and that the beam was re-focused due to "wall-focusing effect". Therefore in CO_2 laser drilling, a slender and cylindrical hole can be obtained. On the other hand, electron beam was scattered by the vapor of the acrylic resin in the hole, and rather fat hole was obtained in electron beam drilling.

The analyzing method described here may also be applied in measuring beam power.

In this work acrylic resin was used because the measuring and analysis were easy, but the re-focusing and scattering phenomena in the hole seemed to be different according to the material used. It is, however, expected that the method indicated here is useful in analysing interaction between beam and material.

In this experiment, the data sometimes scattered and hence gave even negative values of $\widetilde{w}_s$, which were not shown in this paper. The authors consider that a more precise test is necessary.

References

1) Y. Arata and I. Miyamoto, "Metal Heating by Laser Beam", Trans. Japan Weld. Soc., Vol. 3 (1972), No. 1.

2) Y. Arata and I. Miyamoto, "Beam Focusing Characteristics of CO_2 Laser", Trans. Japan Weld. Soc., Vol. 3 (1972), No. 1.