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Visualization of Molten Pools and Invisible Laser Beam Profiles Using an Ultraviolet CCD Camera

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***Abstract*:** A visualization technique using an ultraviolet CCD camera has been successfully applied to the non-contact monitoring of molten pools produced in material processing by high power CO_2 lasers. This technique is based on the principle that the temperature sensitivity of UV radiation emitted from molten pools is much higher than visible or infrared region. Additionally, the target area directly irradiated by a focused laser beam could be largely dominated by UV radiation because of its highly energetic condition. In this experiment, molten pools produced by a 100-W CO_2 laser were observed as 250-nm UV images by means of an UV-CCD imaging system. It has been attractively demonstrated that the developed technique could offer not only more realistic pictures of actual laser focused area without the secondary effects due to heat conduction around them, but also the intensity profiles of the incoming, invisible laser beam. The 3-D representation of laser beam intensity profile has been reconstructed through the contour maps of UV images captured at a laser irradiated target region, with showing a very small deviation of 5% from the ideal Gaussian distribution. The obtained results imply that this visualization method could be an alternative beam profiling technique to conventional acrylic burning method which has much larger deviations in beam profiling.

***Keywords*:** visualization, ultraviolet image, temperature sensitivity, molten pool, beam profile.

1. Introduction

Laser processing which currently utilizes such high power lasers as CO_2, YAG and excimers has been widely applied to various material processings (Garifo, 1992; Ogura et al., 1998). CO_2 lasers have been particularly used in general because of its low photon cost with high energy density (Bondelie, 1996; Watanabe, 1993). Most of lasers used in laser processings are operated in the invisible wavelengths of the infrared or ultraviolet (UV) regions with high energy densities. In order to achieve the well-controlled and precise laser processing on a real-time base, it is preferably required to monitor both the resultant molten pools and the intensity profiles of the incoming laser beam at a targeted point. Although the use of the charge-coupled-devices (CCD) could be helpful for this purpose, there exists inevitable difficulties that the direct exposure of such high power lasers is unrealistic because of the destruction of CCD and that their invisible wavelength regions are non- or very less-sensitive to the visible dynamic range of CCD. Another point of view has also to be considered on the ambiguous observation of laser-produced molten pools, since the visible CCD images largely include secondary heated regions which can be created as a result of heat conduction spreading outward from an actually laser-irradiated spot.

Infrared thermography is one of the most useful techniques for thermal surface measurement and has been applied to such various fields as medical applications, engineering, natural science and remote sensing (Burnay et al., 1988; Huang et al., 1997). These techniques have also been available not only for thermal surface phenomenon but also for thermal visualization of fluid flow or combustion (Carlomagno et al., 1998; Sato et al., 2000). Since such thermographical methods deal with heat-image capturing based on near-infrared radiation from relatively low temperature materials, the ambiguity of the captured images much more largely extends around the beam spot than the visible images. Some other monitoring methods have been interestingly reported on the observation of keyhole dynamics in laser welding using an X-ray method and on the visualization of excimer laser ablation using a high speed camera (Matsunawa and Katayama, 1998; Fushinobu et al., 1997).

On the other hand, visualization of laser beams to diagnose spatial profiles of laser beam can be conventionally classified into electronic and non-electronic methods (Rahul and Jochen, 2000). Electronic ones are known as the scanning knife-edge profilers and the scanning-slit devices which are fraught with a difficulty in their uses in laser focused conditions. Non-electronic methods of beam profiler mainly include acrylic mode burns, burn paper and fluorescent beam card, the accuracies of which are insufficient to perform laser processing control. Additionally, both schemes have to be used by placing them directly in the path of high intensity beams during operation.

In this paper, an UV-CCD camera imaging system has been introduced to visualize the temperature distribution of highly energetic molten pool. Based on an approximate blackbody radiation assumed on continuous-wave (CW) laser-produced molten pools observed in this experiment, it is described that the temperature sensitivity in UV region is significantly higher than in visible or infrared regions. UV imaging at the wavelength of 250-nm has been made as a function of the elapsed time from the onset of the irradiation by a high power CO_2 laser beam which was focused on a firebrick. These results have been carefully compared with the visible imaging at the wavelength of 550-nm, the temperature sensitivity of which would be lower than the UV imaging, as will be discussed in the next section. The experiment successfully shows that the obtained UV images more realistically visualize the temperature distribution of molten pools in the close vicinity of focused laser beam spots than the visible images. A 3-dimensional (3-D) representation of intensity profile for focused laser beam has been reconstructed by combining the obtained UV images at a laser spot area with a sufficiently small deviation of 5% from an ideal Gaussian profile. The experimental results support a feasible discussion that the proposed UV imaging technique could be a promising way of visualizing not only molten pools but also incoming laser beam profiles.

2. Theoretical Consideration of UV-CCD Imaging

Light emission from high temperature molten pool produced by a high power laser beam generally consists of many of line spectra and continuum spectrum which might be very complicated in its mechanism. Although the detailed emission mechanism could include non-thermal equilibrium processes in terms of time and space, it can be reasonably considered that time-integrated images taken by a CCD well reflect the emission spectrum for approximate blackbody radiation particularly under the condition where CW laser exposure is performed with a constant power onto relatively small heat-conductive materials. This situation is very similar to a filament highly heated by electricity. Figure 1 shows a conceivable model for a molten pool which consists of a core area directly heated by focused laser beam and a secondary heated area around the core produced as a result of heat conduction. It can be obviously mentioned that emission from the directly irradiated core is much more dominated by ultraviolet wavelength region because of its higher temperature than other areas. With the temperature decreasing toward the outside of the core, visible and infrared emission comes to be dominant rather than UV emission. The outer area around the molten pool indicated in Fig. 1 is heated up to lower temperatures below a melting point

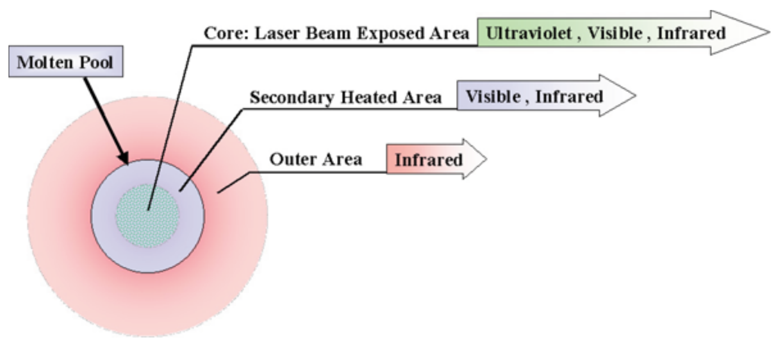


Fig. 1. Spectrum at target zone.

which could be infrared dominant. Accordingly, UV images could show more realistic picture of the laser irradiated core-area which is called a laser spot. The spatial intensity distribution of UV images is indicative of the laser beam intensity profile if the temperature sensitivity of the UV intensity is appropriately assured, as described in the following discussion.

Assuming the thermal equilibrium of the molten pool in a limited time period (1/30 s) of CCD framing, the spectrum characteristics from molten pools can be approximated to blackbody radiation at a given temperature $T(k)$. The emitted power density W_λ ($W \cdot cm^{-2} \cdot \mu m^{-1}$) of an ideal blackbody at a given wavelength is given by the well known Planck formula;

$$W_\lambda = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{\exp(hc/\lambda kT) - 1} \tag{1}$$

where h, c, k and λ are Planck's constant, the speed of light in free space, Boltzmann's constant and the wavelength, respectively. It is well known as Wien's Displacement Law that the peak of wavelength in the blackbody spectrum shifts to progressively shorter wavelength region as the temperature is increased.

Figure 2 shows the variations of light intensity calculated from Eq. (1) as a function of blackbody temperature T for the UV (250 nm) and visible (550 nm) wavelengths. This shows that the image with visible light would include broader temperature area than with the UV one. This means that the visible imaging has a difficulty in distinguishing a laser spot area from the other heated area in a fixed optical configuration with a limited CCD dynamic range.

The temperature sensitivity U_T can be defined as the change of relative light intensity to an unit temperature change at a given wavelength, as can be written in the following;

$$U_T = (1/W_\lambda)(dW_\lambda/dT) \tag{2}$$

Figure 3 shows the temperature sensitivities as a function of the temperature T at the wavelengths of 250 and 550 nm. It can be obviously found that the temperature sensitivity for the UV light is two times higher than for the visible light. This implied that the intensity distribution of laser beam could be more explicitly represented by observing the UV light than the visible one.

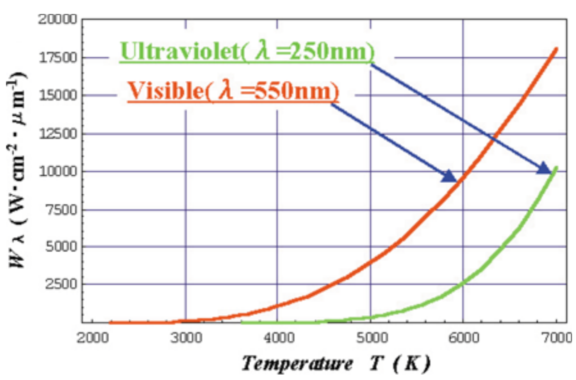


Fig. 2. Variation of light intensity for λ = 250 and 550 nm as a function of T.

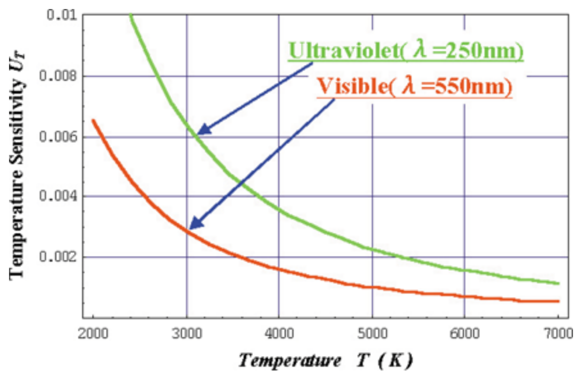


Fig. 3. Temperature Sensitivity for λ = 250 and 550 nm.

3. Experimental Apparatus

Figure 4 represents the experimental arrangement which consists of i) an RF (radio frequency) excited slab carbon dioxide (CO_2) laser as a high power laser beam source, ii) a set of focusing optics and iii) a CCD monitoring system with an image controller assisted by a personal computer (PC). The RF excited, slab CO_2 laser developed in our laboratory (Watanabe, 1993) has some attractive features which are the capability of producing a moderate power level of 100-200 W, the compact size for its power level, the excellent beam quality and the good operational controllability. This laser system consists of an RF power supply which is capable of producing a maximum RF power of 2 kW at 100 MHz, an laser head made of an aluminum housing, a gas handling system to pump out air before use and supply a mixed gas of CO_2, N_2 and He at a ratio of 1:1:3 into the laser head, a water-cooling system and a PC with control electronics. High power laser beam produced by the slab CO_2 laser was focused onto a firebrick through a focusing optics made of ZnSe. Molten pools produced by the laser beam irradiation on the brick have been observed using an UV CCD camera (HAMAMATSU Photonics Co.) at a viewing angle of 15 degree to the incidence of laser beam. The molten pool to be observed and the CCD camera are distanced with an approximately 60-cm path in which a glass plate was placed in order to adjust the emission brightness to a CCD saturation level. An UV lens was combined with the CCD camera, whose focal length and F-number were 50.4 mm and < 3.5, respectively. The used CCD camera consists of an image intensifier (I.I.) and a charge coupled device (CCD), whose wavelength sensitivity is extended in the range of 180-850 nm. A band pass filter centered at 252.2 nm with a bandwidth of 11.4 nm (FWHM) was used to pick up only UV images. In comparison with the UV images, a band pass filter centered at 551.7 nm with a bandwidth of 9.8 nm (FWHM) was also used for visible images. The laser power was monitored by a combination of a ZnSe beam splitter and a laser power meter (JLP-300 of JAPAN LASER Co.). Image capturing was performed every 6 seconds from the onset of laser irradiation, and was followed by the data storage and analysis through the PC/controller combination.

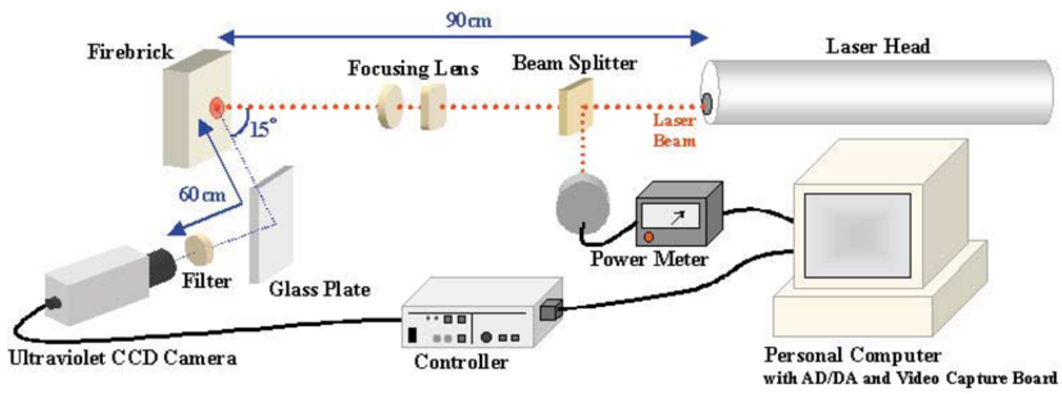


Fig. 4. Experimental arrangement.

4. Image Processing Procedure

Images of molten pool taken by the used UV CCD camera system were properly processed along with the procedures shown in Fig. 5. The PICT-form target images were transformed to RAW-data form which consisted with only the brightness data for each pixel of CCD imager in order to make it easy to correct and analyze the observed images. Some correction processes were made on the RAW data in terms of the necessary CCD-noise reduction and the view angle compensation for the distortion caused by the capturing angle of 15 degrees. These corrected images based on the brightness data were finally transformed to brightness data matrices with the x-y coordinates so as to generate intensity contour maps and to reconstruct 3-D representation with showing a larger coverage for the CCD dynamic range.

The intensity contour map presented by coloring according to the above brightness values could be a real-time scheme to monitor the central part of molten pool during the laser processing although this work was carried out through the off-line image processing. It is well known that there inevitably exists a limited dynamic range in the CCD intensity sensitivity to cover the entire intensity distribution produced by highly energetic molten pools. In order to avoid such a saturation problem, a gain control scheme was employed in this work in which two images were captured with different gain levels of the CCD camera. A brightness distribution map taken by a low gain was added to a saturation area in a high gain image so that the intensities for the two images fits in each other at the edge of saturation area. This procedure has successfully demonstrated a whole intensity profile for a given laser irradiation due to its larger dynamic range coverage. With this device, the whole area directly exposed by incoming laser beam was reconstructed as a 3-D representation. To verify how this reconstructed profile is close to the actual incoming laser beam, the obtained 3D-UV profile was compared with the result of a typical acrylic burn method using acrylic blocks.

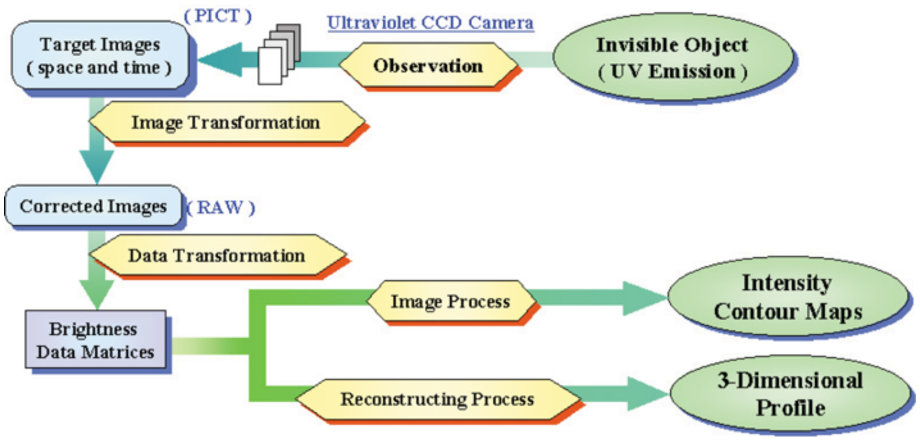


Fig. 5. Image correction and analysis procedure.

5. Results and Discussions

Figures 6 and 7 show the visible (550 nm) and UV (250 nm) contour maps for the observed images, respectively, with representing the distribution of light intensity emitted from a molten pool and its surrounding area produced by the slab CO_2 laser exposure. Although visualized images with a spatial resolution of 6.65 pixel/mm were taken every 6 seconds after the onset of laser irradiation in the experiments, the resultant contour maps in Figs. 6 and 7 are represented every 12 seconds. In these figures the color indication changes from red to orange, yellow, green, blue and to purple, as the light intensity increases. In the case of visible images as shown in Fig. 6, the central areas on contour maps show no detailed intensity distribution. A series of experiment performed with various imaging conditions obviously showed that this is because of the narrow dynamic range and the low temperature sensitivity due to the visible range imaging. As can be seen in Fig. 6, the contour maps inevitably include peripheral portions spreading much far away from laser focused areas. This means that visible images are indicative of low temperature area caused by secondary heat conduction around the laser spot zone. Although this area can be eliminated by means of an attenuation filter so that only a central area can be imaged, the intensity spatial distribution would be heavily vague because of the low temperature sensitivity. The visible imaging had a difficulty in capturing the detailed structure of the central zone of molten pools which is directly irradiated by laser beam. In contrast to the visible case, the UV imaging as shown in Fig. 7 clearly shows the more detailed structure of central area in their contour mapping. It is clearly indicated in the set of time-sequent images of Fig. 7 that the location of the highest peak of the laser beam is slightly fluctuated with time. Although such fluctuation can be observed, any of the UV images could be more informative than the visible case, associated with the incoming beam intensity distribution on the basis of the time-averaged viewpoint. In the early stages of heating process for

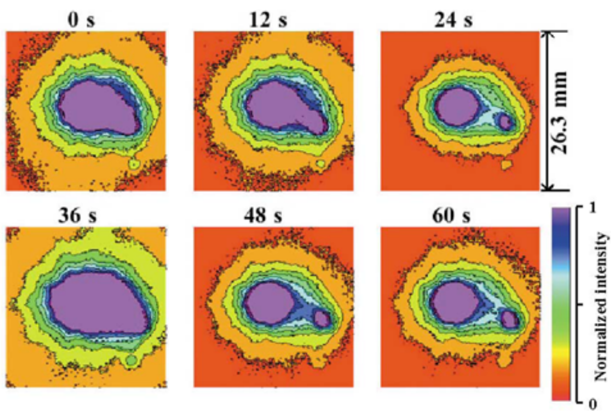


Fig. 6. Light intensity contour-maps of focused laser beam (visible l = 550 nm).

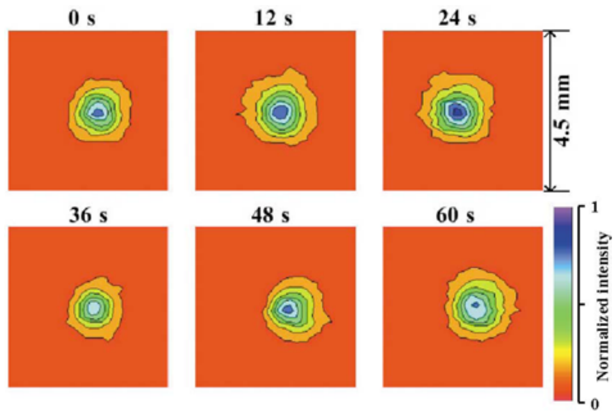
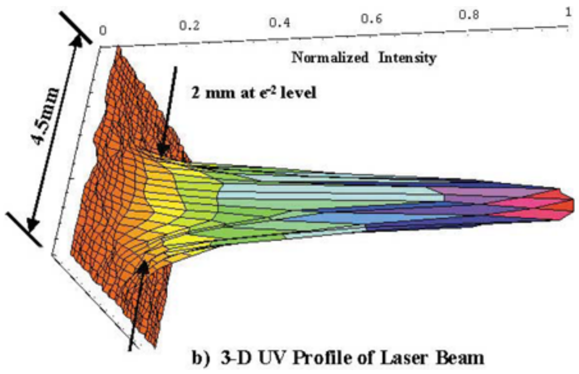


Fig. 7. Light intensity contour-maps of focused laser beam (ultraviolet l = 250 nm).

the time period of 0 to 12 seconds, it can be seen that the irradiated area comes to a thermal equilibrium. The pictures obtained after 24 seconds seem to be more stabilized in their intensity distribution than the early stages. These evidences could be sufficiently accepted to confirm the advantage that the spatial and temporal transition of the light intensity distribution for the laser irradiated area can be more exactly monitored using the UV images rather than using the visible images.

Taking a careful look at these contour maps, it is known that the light intensity distribution of molten pools conceivably corresponds to the power distribution of incoming laser beam. Construction of 3-D laser beam profile was attempted from two brightness data matrices which were obtained with changing the UV CCD gain level. The typical result is represented in Fig. 8(b). Figures 8(a) and(b) show beam patterns taken by a conventional burning pattern method on an acrylic block and a laser beam profile which is constructed from UV images and displayed by three dimensional way, respectively. A laser beam profile which has information of X-Y coordinate and its intensity as shown in Fig. 8(b) has been generally called as 3-D profile in laser processing field. The height from the reference plane in Fig. 8(b) is in accordance with the color changing from red to orange, yellow, green, blue and purple as the UV intensity distribution increases which should be approximately related to the intensity distribution of the incoming laser. It is noted that the 3-D profile for the focused beam is thicker than the burning pattern of the conventional method. This noticed us that it is difficult to completely eliminate the effect of secondary heated zone even with the use of UV images. This 3-D profile, however, contains more exact visualized information which includes the power intensity distribution of irradiating laser beam rather than that of a conventional way of beam profiling such as the acrylic block burning. Power distribution of a focused laser beam obtained by the acrylic burn method is inherently fraught with the ambiguity in its measuring procedure, since a depth and thickness of burn pattern depend on the laser exposure time. On the other hand, the 3-D power distribution obtained in Fig. 8(b) could be more reasonably reflected by only a transverse mode of laser beam with a possible real-time monitoring, since no explosive flaming process is involved.

a) Burning Beam Patterns on Acrylic Block



b) 3-D UV Profile of Laser Beam

Fig. 8. Profiles of focused laser beam.

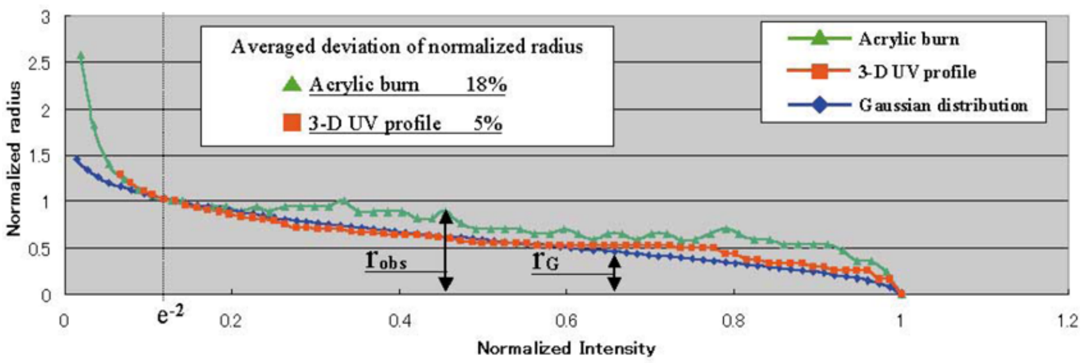


Fig. 9. Comparison with Gaussian distribution (focused laser beam).

A more quantitative comparison has been made in Fig. 9 to speculate the validity of this 3D-UV profile. Figure 9 shows the normalized shapes of the 3D-UV profile, the acrylic burn method, and an ideal Gaussian distribution. Normalization was made in terms of the peak intensities and the beam spot size defined as a radius at $1/e^2$ of peak power. The horizontal axis indicates the normalized intensity value which corresponds to the power intensity level of laser beam. The red, blue, and green plots in Fig. 9 indicate the 3D-UV profile, the Gaussian distribution, and the acrylic burn method, respectively. In the 3D-UV profile, data plots smaller than 0.1 of the normalized intensity were eliminated since this intensity level was dominated by electronic noise due to the used CCD. In the conventional acrylic burn method, a large deviation from the ideal Gaussian distribution can be particularly found at the bottom of beam shape because of a blow-up effect more likely caused by the explosive flaming of acrylic components. Another deviation is largely observed in the vicinity of the peak intensity. This might be one of the evidences that explosive combustion takes place at the top of hole drilled by laser beam, accompanied with the outward pressure. From these comparisons, the distribution of 3D-UV profile is more close to ideal Gaussian distribution than that of conventional acrylic burn method. Quantitative deviations for the acrylic burn method and the 3D-UV profile were given as $((r_{obs}-r_G) \times 100)/r_G$ %, where r_G and r_{obs} are the normalized radius of Gaussian distribution and that from the observed results shown in Fig. 9, respectively. Average deviations for the normalized radiuses in Fig. 9 were calculated over the normalized intensity from 1 down to $1/e^2$. It is favorably found that the averaged deviation of 3D-UV profile is greatly reduced to 5% from 18% of the acrylic burn method. Allowing the difference in the size of beam spot inevitably caused by the heat conduction effect, the obtained accuracy of the normalized 3D-UV profile could be attractively sufficient to evaluate whether the quality of focused incoming beam is fit to the Gaussian profile of single mode or not. This implies that the proposed UV method could be an alternative tool in monitoring beam profiles especially in the focused beam condition which many of conventional method have avoided to deal with.

Although this work was performed with the scheme of off-line image processing, real-time image processing will be realized with improving the PC capability and with preparing dedicated software. A simple estimation based on the use of a commercially available PC of 400 MHz clock speed demonstrates that the contour map and the reconstructed 3D-UV profile could be up-dated every 0.3 s and 4.0 s, respectively. It can be concluded that the visualization based on UV images would be a new tool for the in-process monitoring not only of laser produced molten pools but also their incoming laser profile which is currently indispensable to establish well-controlled laser material processing.

6. Conclusions

The UV-CCD camera imaging system introduced in this study has successfully visualized the temperature distribution of highly energetic molten pools produced by a focused laser irradiation. Based on an approximate blackbody radiation assumed on CW laser-produced molten pools observed in this experiment, it has been discussed that the temperature sensitivity in UV region is significantly higher than in visible or infrared regions. Additionally, the target area directly irradiated by a focused laser beam could be largely dominated by UV radiation because of its highly energetic condition. UV imaging at the wavelength of 250 nm has been made as a function of the elapsed time from the onset of the irradiation by a high power CO_2 laser beam which was focused on a firebrick, with being compared with the visible imaging at 550 nm. The experiments apparently show in the contour maps that the obtained UV images more explicitly display the temperature distribution of molten pools in the close vicinity of focused laser beam spots than the visible images. A sufficiently small deviation of 5% from an ideal Gaussian profile has been obtained at a 3D-UV profile of focused laser beam which has been reconstructed through the obtained UV images at a laser spot area. The visualization technique investigated in this study can provide us with many of visual and quantitative data about the molten pools and invisible laser beams. The experimental results support a feasible discussion that the proposed UV imaging technique could be a promising way of visualizing not only molten pools but also incoming laser beam profiles. Since the contour map and the 3D-UV profile could be updated every 0.30 s and 4.00 s, respectively, this method would be easily applied to the in-process monitoring of molten pools and profiling of focused laser beam which requires a real-time or quasi-real time mode of operation for non-contact observation.

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