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Auto-focus Control by Chromatic Filtering in Laser Welding

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Optical monitoring using the chromatic aberration of focusing optics is applied to auto-focus control in laser welding. The spectral transmittance of thermal radiation from a weld pool through an aperture depends on the wavelength of the spectral band and on the distance of the weld pool from the focusing optics. Its dependence has been used to monitor the focus shift in laser welding by measuring the spectral band signals filtered by the aperture. The difference between pulsed and continuous laser welding is analyzed. Furthermore, the dependence of the focus shift monitoring on the weld pool size variation is optimized to monitor the focus shift independently from the laser power change at the weld pool. The performance of the auto-focus control with chromatic filtering is presented for pulsed laser welding.

I. INTRODUCTION

The application of high power Nd:YAG lasers for precision welding in industry has been growing quite fast these days in diverse areas such as the automobile, electronics and aerospace industries. Nowadays, an Nd:YAG laser with as much as 6 kW of average power is available in the market and the fiber delivery of a Nd:YAG laser makes it useful for many remote applications. On the other hand, these diverse applications also require new developments for precise focus control. Many focus control techniques based upon capacitance measurements or upon thermal radiation measurement at several spectral bands [1] have been developed. However, focus control based on capacitance measurement is very sensitive to electrical noise and can't be applied to continuous laser welding due to the electrical interference generated during laser welding.

In laser welding, the power change of a laser generator itself can be monitored easily, but the laser power change at a weld pool is quite difficult to monitor. The laser power at a weld pool can be affected by the absorption of delivery optics. The laser power change at a weld pool can vary the size of a weld pool and also the spectral band signals from a weld pool. Therefore, a focus shift control method using the measurement of laser power change at a weld pool can't be used in industrial applications because it can't discriminate a power change and a focus shift. In other words, a focus shift control method should not depend on the size variation of a weld pool and the intensity variation of spectral band signals from a weld pool. In conclusion, for industrial applications, a focus shift monitoring independent of the laser power change at a weld pool is required.

The chromatic filtering of thermal radiation has been applied to the size variation monitoring of an extended thermal radiation source [2]. In this paper, chromatic filtering has been applied to focus shift monitoring and control in pulsed and continuous laser welding. In continuous laser welding, weld pool size is larger than focused laser spot size all the time except at the beginning of welding. However, in pulsed laser welding, weld pool size decrease between the laser pulses due to thermal conduction cooling. In both cases, the chromatic filtering of thermal radiation for focus shift monitoring and control has been optimized.

II. CHROMATIC FILTERING FOR FOCUS SHIFT MONITORING

The principle of chromatic filtering is shown in Fig. 1. In laser welding, a laser beam is focused on a workpiece by focusing optics. The focusing optics images

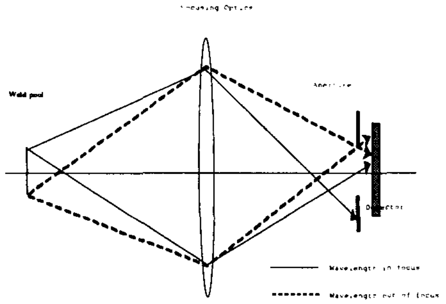

FIG. 1. Optical Layout for Chromatic Filtering

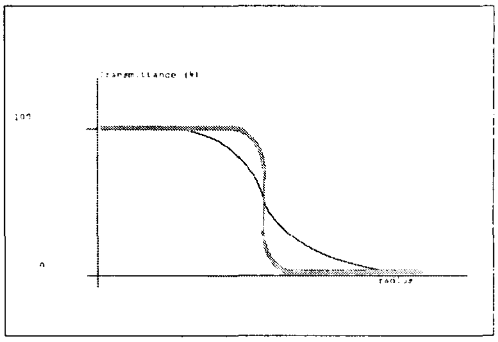

FIG. 3. Typical Transmittance Profiles

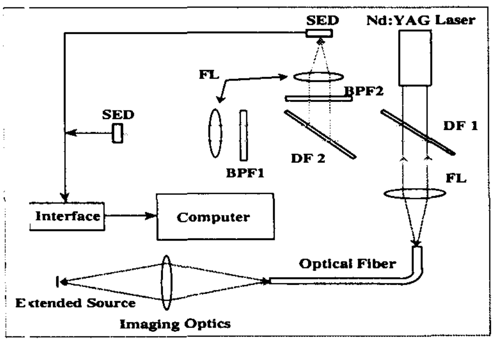

FIG. 2. Experimental Setup for Chromatic Filtering (SED : single-element detector,FL: focusing lens, DF1/DF2 : dichromatic filters, BPF1/BPF2 : band-pass filters)

an aperture limiting the size of the laser beam on the workpiece, and the size of focused laser beam is the image size of the aperture on the workpiece at the wavelength of the laser. The aperture can be the distal end of an optical fiber for delivery of the laser beam or any other aperture which limits the size of a weld pool. The thermal radiation is measured with signal-element detectors by adopting two dichromatic mirrors and band-pass filters as shown Fig. 2. The first dichromatic mirror(DF1) is used to separate the thermal radiation from the laser beam and the other dichromatic mirror(DF2) is used to split the spectral bands of the thermal radiation.

In laser welding, a weld pool is generated by the interaction of a focused laser beam and a workpiece. Due to the thermal conduction of the workpiece, the size of the weld pool is generally not the same as the size of the focused laser beam and varies with the power of the laser or with the focus shift of the focusing optics. Due to the chromatic aberration of the focusing optics, the transmittance of each spectral band of the thermal radiation from a weld pool varies with the size variation and with the focus position of a weld pool and the spectral band signals measured with single element detectors vary if the focus position of a weld pool varies. The transmittance of thermal radiation from a weld pool through focusing optics and through an aperture can be calculated as a function of position on the weld pool at each spectral band on the basis of optical design parameters of the focusing optics and the aperture. Furthermore, the spectral band signals follow the blackbody radiation law so that the dependence of the spectral band signals on the size variation and the focus shift of a weld pool can be estimated using the transmittance functions of the spectral bands. The focus shift monitoring is achieved by comparing the measured spectral band signals with the calculated values obtained from the transmittance functions.

The spectral band signals from single element detectors depend on the temperature of a weld pool and the wavelength of the spectral band. To measure the thermal radiation, the weld pool has to be imaged on an aperture and the transmitted spectral band signals are measured with single element detectors. The imaging optics consists of one or more lenses with some chromatic aberration, but with minimum spherical aberration. If an aperture is introduced in front of the detector as shown in Fig. 1 so that all the radiation passing the aperture is captured by the detector, the transmittance profile of the thermal radiation from the edge of a weld pool depends strongly on the wavelength, due to chromatic aberration as shown in Fig. 3. The aperture acts as a field-stop and it limits the area of a weld pool that can be seen through the imaging optics by a single element detector. In other words, due to the chromatic aberration of the imaging optics, the detector can obtain thermal radiation from a wider area of the weld pool, even if only a small portion is transmitted, at a wavelength with large chromatic aberration than at the wavelength close to the laser wavelength during laser welding.

To be more quantitative, a weld pool can be approximated to the first order as a uniform thermal radiation source at temperature TK [3]. Wien's law can be applicable in the visible range because λT is much smaller than 14380 μmK. If we measure the thermal radiation at one wavelength W_1 and at another wavelength W_2 quite far from W_1 to introduce a large chromatic aberration on the imaging optics, the spectral band thermal radiation signals measured at detectors can be described as follows:

The spectral band detector signals at wavelength W_1 and W_2 become

$$\begin{aligned} X &= C_1 \exp(-\frac{14380}{W_1 T}\int_0^{r_0} t_1 r dr) \\ &= C_1 \exp(-\frac{14380}{W_1 T} F(W_1, r_0)) \qquad (1) \end{aligned}$$

$$\begin{aligned} Y &= C_2 \exp(-\frac{14380}{W_2 T}\int_0^{r_0} t_2 r dr) \\ &= C_2 \exp(-\frac{14380}{W_2 T} F(W_2, r_0)) \qquad (2) \end{aligned}$$

where C_1 and C_2 are constants, W_1 and W_2 are the wavelengths in microns, t_1 and t_2 are the transmittance profiles at wavelength W_1 and W_2, T is the temperature of a weld pool in K and r_0 is the radius of a weld pool.

As to the monitoring of the focus shift of a weld pool, the dependence of spectral band signals on the focus shift of a weld pool can be used. However, the ratio of two spectral band signals is preferred to the difference of two spectral band signals because the ratio does not depend on the intensity variation of the spectral band signals caused by the power variation of a laser. Furthermore, if the change in the ratio of two spectral band signals is monitored by division rather than by subtraction, then the result does not depend on the variations in the gains of single element detectors. These advantages can be obtained by comparing the difference in the natural logarithm of the ratio of two spectral band signals.

From Eqs. (1) and (2), a focus shift signal which is the natural logarithm of the ratio of two spectral band signals , X over Y, can be expressed as

$$\begin{aligned} \ln(X/Y) &= \ln(C_1/C_2) + \frac{14380}{T}(\frac{1}{W_2} - \frac{1}{W_1}) \\ &+ [\ln(F(W_1, r_0)) - \ln(F(W_2, r_0))] \qquad (3) \end{aligned}$$

The third term in Eq. (3) shows the focus shift dependence. Therefore, the variation in $\ln(X/Y)$ obtained from the measured spectral band signals, X and Y, can be used for focus shift monitoring and the sensitivity of the focus shift monitoring can be estimated from the focus shift dependence of the third term in Eq. (3). It is also known that the temperature fluctuation induced by laser power variation is small [4], but laser power variation induces a size variation of a weld pool in laser welding. Therefore, the weld pool size dependence of a focus shift function of $[\ln(F(W_1, r_0)) - \ln(F(W_2, r_0))]$ in the third term in Eq. (3) has to be minimized. Then, the focus shift dependence of the third term in Eq. (3) can be used for the monitoring of the focus shift of a weld pool independently from the size variation of a weld pool. It means that the differentiation of $[\ln(F(W_1, r_2)) - \ln(F(W_2, r_0))]$ with r_0 should be zero at the weld pool radius of interest.

$$\begin{aligned} & d(\ln(F(W_1, r_0)) - \ln(F(W_2, r_0)))/dr_0 \\ &= r_0[t_1(r_0)/F(W_1, r_0) - t_2(r_0)/F(W_2, r_0)] \qquad (4) \end{aligned}$$

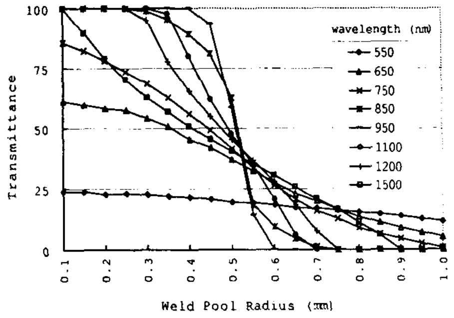

FIG. 4. Transmittance Function of two SF11 Plano-Convex 100 mm F/3.8 Lenses

One obvious solution can be obtained because $d(\ln(F(W_1, r_0)) - \ln(F(W_2, r_0)))/dr_0$ in Eq. (4) can be zero if the shape of $t_1(r_0)$ is the same as the shape of $t_2(r_0)$. In other words, we have to choose the two wavelengths of the spectral bands so that the transmittances of the spectral bands at the two wavelengths are as close as possible. This condition can be satisfied by selecting one wavelength shorter and the other wavelength longer than the laser wavelength. Furthermore, the wavelengths should be far enough from the laser wavelength to introduce large chromatic aberration. For an optical system comprised of two SF11 plano-convex 100 mm F/3.8 lenses, the transmittances at 650 nm and 1500 nm are nearly the same as shown in Fig. 4. The optical system with two SF11 lenses has enough chromatic aberration for chromatic filtering and has small spherical aberration for good imaging. Fig. 5 shows the focus shift dependence of $[\ln(F(W_1, r_0)) - \ln(F(W_2, r_0))]$ for several focus shifts wherein W_1 and W_2 are 1500 nm and 650 nm respectively and a weld pool of 1 mm diameter and an aperture of 1 mm diameter are assumed. It shows that the monitoring of the focus shift of a weld pool is not affected by the size variation induced by laser power

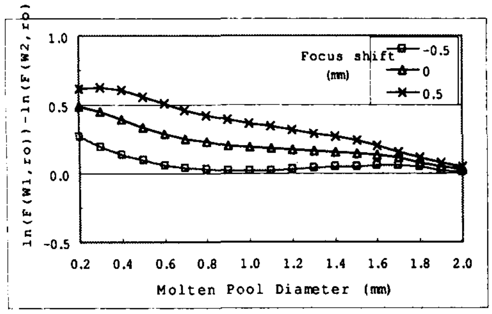

FIG 5. Focus Shift Dependence of [$\ln(F(W1,r0)) - \ln(F(W2,r0))$] for 100 mm lenses (W1 : 1500 nm, W2 : 650 nm)

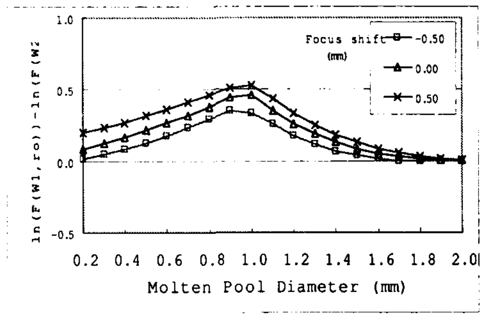

FIG 6. Focus Shift Dependence of [$\ln(F(W1,r0)) - \ln(F(W2,r0))$] for 30 mm lenses (W1 : 950 nm, W2 : 550 nm)

variation for a weld pool size range from the focused laser spot size of 1 mm up to 1.5 times the focused laser spot size which covers the size variation of interest in industrial laser welding applications.

As shown in Fig. 5, the sensitivity of a focus shift signal $\ln(X/Y)$, which is the same as the focus shift sensitivity of the focus shift function of $\ln(F(W_1, r_0)) - \ln(F(W_2, r_0))$, is higher than 0.2 per mm focus shift for a weld pool size range from the focused laser spot size of 1 mm up to 1.5 times the focused laser spot size. This sensitivity of the focus shift signal is used in determining the amount of focus error for the focus control of a weld pool. For the monitoring of focus shift of a weld pool, a weld pool size of 1.3 mm is assumed. The minimum detectable focus shift is determined with the focus shift function in focus which has a focus shift sensitivity higher than 0.2 per mm focus shift. The minimum detectable focus shift is ± 0.1 mm for a noise level of or less than ± 0.02 in a focus shift signal which can be easily obtained for detector circuits with digitization with 12 bits accuracy and with signal to noise ratio higher than a couple of hundred. The temperature dependence of a focus shift signal in Eq. (3) shows that the induced error in a focus shift signal for a temperature variation of 50 K at a weld pool temperature of 2000 K is about 0.15 and introduces a focus shift error of about 0.75 mm. It is known that the temperature variation of a weld pool for a size variation of up to ± 0.2 mm is generally less than 50 K in laser welding. The induced error on the focus shift from the size variation of up to ± 0.2 mm is less than ± 0.2 mm. Therefore, the focus shift signal of $\ln(X/Y)$ can be used to control the focus shift of a weld pool within ± 0.7 mm independently of the weld pool size variation of 1.3 ± 0.2 mm, which is good enough for industrial laser welding applications. The focus shift monitoring by focus shift signal of $\ln(X/Y)$ can be applied both for continuous and pulsed laser welding if the spectral band signals are measured during a laser pulse when the size of the weld pool is larger than the focused laser spot size.

III. FOCUS SHIFT MONITORING IN A PULSED LASER WELDING

In pulsed laser welding, the weld pool size increases at the beginning of a laser pulse and decreases at the end of a laser pulse. The weld pool size varies quite fast and much more than in continuous laser welding. Furthermore, the duty cycle of the laser pulse is quite low and the weld pool size is comparable to the focused laser spot size in a pulsed laser welding. Therefore, we had better satisfy Eq. (4) at the weld pool size near the focused laser spot size. There is an easy way to satisfy it.

If we define

$$H(r) = [F(W_2, r)/F(W_1, r)] * [t_1/t_2] \qquad (5)$$

then, the effect of power variation on the focus shift monitoring is minimized when $H(r) = 1$. The meaning of $H(r)$ is the ratio of the ratio in the two transmittances of the wavelengths W_1 and W_2 at a radius r to the ratio of the two integrated transmittances up to the radius r. Because $H(0) = 1$ and $H(r_{max}) = 0$ wherein r_{max} is the maximum radius of a weld pool detectable at the wavelength W_1, there is always a solution satisfying $H(r') = 1$ such that $0 < r' < r_{max}$. The ratio in the two transmittances of the wavelengths W_1 and W_2 at a radius r is generally larger than the ratio of the two integrated transmittances up to the radius r except near r_{max}. Therefore, if wavelength W_1 is chosen near the laser wavelength and the other wavelength W_2 is chosen quite far from the laser wavelength, the radius r' satisfying $H(r') = 1$ is a little bit smaller than r_{max}. Therefore, in pulsed laser welding, we have to choose a wavelength W_1 near the laser wavelength but far enough from the laser wavelength

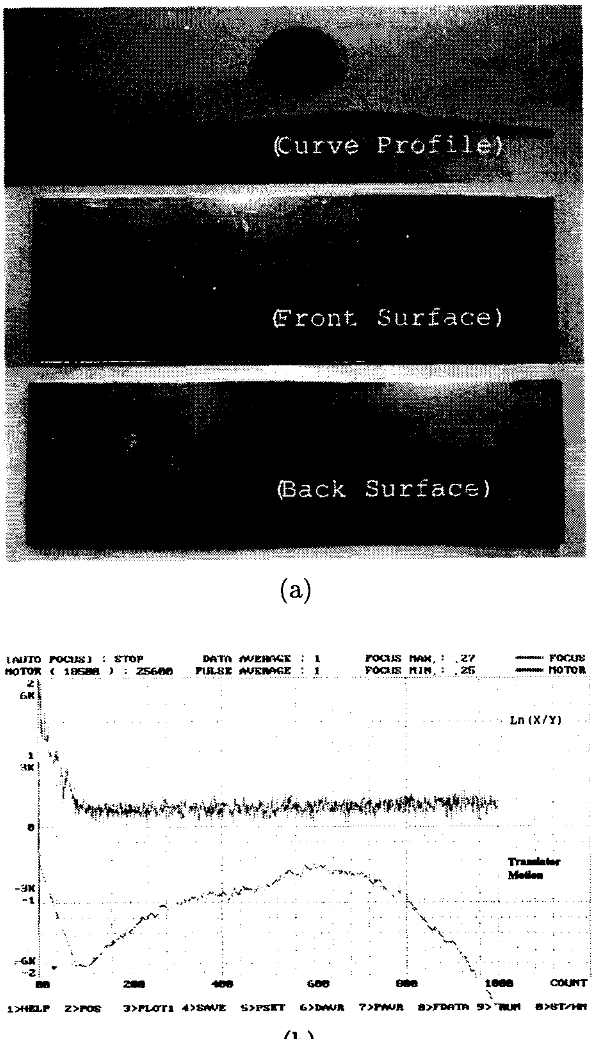

FIG. 7. (a) Weld Bead/ Burn Pattern for Robot Control (b) $\ln(X/Y)$ & Translator Motion

to be separated with a band-pass filter and another wavelength W_2 far from the laser wavelength. Then, the same focus shift signal $\ln(X/Y)$ can be used for the focus shift monitoring only if the spectral band signals are measured when the weld pool radius is reduced down to r'. In other words, we have to adjust the delay time in sampling the spectral band signals and wait after the end of a laser pulse until the weld pool radius becomes r'. Usually, the weld pool size becomes the same as the focused laser spot size at the end of a laser pulse. Therefore, the spectral band signals can be measured just after the end of a laser pulse for focus shift monitoring.

Fig. 6 shows the focus shift dependence of $[\ln(F(W_1, r_0)) - \ln(F(W_2, r_0))]$ for focusing lenses comprised of two SF11 plano-convex 30 mm F/3.8 lenses at several focus shifts wherein W_1 and W_2 are 950 nm and 550 nm respectively and a weld pool of 1 mm diameter and an aperture of 1 mm diameter are assumed. It shows that the monitoring of the focus shift of a weld pool is not affected by the size variation induced by laser power variation for a weld pool size near the focused laser spot size of 1 mm. However, the sensitivity of focus shift monitoring is reduced due to the short focal length of the focusing lenses.

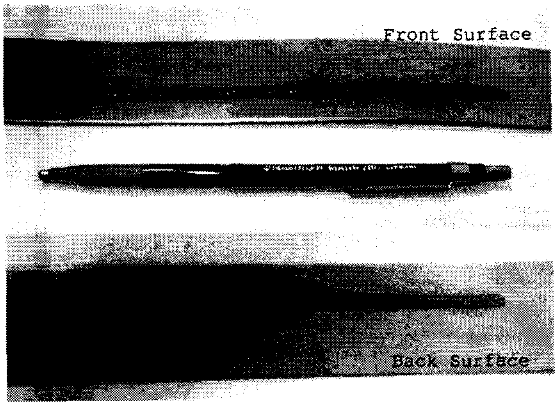

FIG. 8. Weld Bead/ Burn Pattern for Robot Control

IV. EXPERIMENTS IN PULSED LASER WELDING

During the following laser welding experiments, an RSY-1000 Rofin-Sinar pulsed Nd:YAG laser beam with maximum average power of 1 kW was delivered through a 1mm fiber and imaged to 1 mm spot size with focusing optics comprised of two SF11 plano-convex lenses of f/30 mm and F/3.8. Three detectors were used to detect laser pulses for synchronization and to measure the two spectral band signals at 550 nm and 950 nm. The spectral signals were sampled in series at up to 100 kHz in 12 bits and up to 200 sampling points for each pulse, but the start of sampling could be delayed from the start of the laser pulse by adjusting the delay time with 0.1 msec steps. A focus shift control system was developed to control the position of the focusing lens head by maintaining the measured value of the focus shift signal, $\ln(X/Y)$, within the target range. If a measured $\ln(X/Y)$ deviates from the target range, a linear translator attached to the focusing optics moves the focusing lens head back within the target range using the information on the sensitivity of $\ln(X/Y)$.

Chromatic filtering has been applied to the focus control in laser welding with CNC position control on a curved surface with a sudden laser power drop of 20 % in the middle of the laser welding. As shown in Fig. 7(a), the weld bead pattern is uniform and the burn pattern of the backside shows the sudden power drop in the middle of the laser welding. Fig. 7 (b) shows the focus shift signal $\ln(X/Y)$ and the motion of the linear translator during the laser welding. At the beginning of the laser welding, the focus shift signal $\ln(X/Y)$ was out of the target range and the linear translator moved the focusing lens head toward the focus position. Then, the focusing lens head was controlled to stay within the target range. Fig. 8 shows the weld bead pattern and backside burn pattern for a focus control with a robot arm. The robot arm was taught the coordinates of points to follow and moved along a straight line for a segment between two points. The combination of the segments is not a straight line. It shows the uniform laser welding even if the robot arm did not follow a straight motion. The non-straight motion of the robot arm is also compensated by the chromatic focus shift control.

V. SUMMARY AND CONCLUSIONS

In summary, we have demonstrated an innovative chromatic filtering method to monitor the focus shift of a weld pool with single element detectors. Focus shift monitoring is optimized bythe selection of spectral band wavelengths and is not affected by size variation from laser power changes. It can monitor the focus shift independently of laser power changes of as much as 20 %, which is large enough for industrial laser welding applications. The sensitivity of focus shift monitoring is good enough for precision laser welding. It is also demonstrated that the focus shift signal based on chromatic filtering can be used for a curved surface with a steep slope. In conclusion, a simple and robust focus shift control system based on chromatic filtering has been developed for precision laser welding and it can be easily adopted for either a CNC control system or a robot arm control system.

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