CONTROL OF LASER WELD KEYHOLE DYNAMICS BY POWER MODULATION

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ABSTRACT

The keyhole formed by high energy density laser-material interaction periodically collapses due to surface tension of the molten metal in partial penetration welds. The collapse sometimes traps a void at the bottom of the keyhole, and it remains as welding defects. This phenomenon is seen as one cause of the instability of the keyhole during laser beam welding. Thus, it seems likely that improving the stability of the keyhole can reduce voids and uniform the penetration depth. The goal of this work is to develop techniques for controlling laser weld keyhole dynamics to reduce weld defects such as voids and inconsistent penetration.

Statistical analysis of the penetration depth signals in glycerin determined that keyhole dynamics are chaotic. The chaotic nature of keyhole fluctuations and the ability of laser power modulation to control them have been demonstrated by high-speed video images of laser welds in glycerin. Additionally, an incident leading beam angle is applied to enhance the stability of the keyhole. The quasi-sinusoidal laser beam power of 400Hz frequency and 15° incident leading beam angle were determined to be the optimum parameters for the reduction of voids.

Finally, chaos analyses of uncontrolled signals and controlled signals were done to show the effectiveness of modulation on the keyhole dynamics. Three-dimensional phase plots for uncontrolled system and controlled system are produced to demonstrate that the chaotic keyhole dynamics is converted to regular periodic behavior by control methods: power modulation and incident leading beam angle.

KEYWORDS

Laser welding, keyhole, keyhole control, power modulation, chaos analysis

1. Introduction

The keyhole formed by high energy density laser-material interaction is one of the most important aspects in the laser welding process. The evaporation involved in laser material interaction induces a recoil pressure of evaporation depressed the molten metal and forms the keyhole (deep penetration mode) inside the molten material. There are a couple of welding defects induced by the plume and the keyhole, but porosity formation is the major problem that limits its application in the partial penetration laser welds. The reduction of porosity formation is an important issue in improving laser weld quality.

There are generally two mechanisms by which porosity is formed in deep partial penetration laser welds. Voids trapped by keyhole collapse usually form at the bottom of the keyhole, and are relatively large and irregular in shape [1]. The other mechanism is by hydrogen and oxygen or other gases dissolving in weld metal because of the high temperature and then becoming trapped due to the rapid solidification of the weld metal. These voids are relatively small and spherical in shape. The latter is not a critical problem in the process because it is relatively easy to reduce the voids by eliminating hydrogen and oxygen sources.

Voids formed by keyhole collapse are the key problem to be solved for the improvement of the weld quality because they are more likely to cause welding failure due to their size and irregular shape. The main cause of keyhole collapse is the instability of keyhole dynamics during the laser welding [1], [2].

Traditionally, welding engineers have avoided these types of defects by experimental process design. However, experimentation is expensive and there is a need for the capability to quantitatively design the process and/or implement process controls that yield more stable keyhole dynamics that avoid weld defects.

The observation of keyhole dynamics has become the important subject due to the close relationship between keyhole dynamic fluctuations and weld defects. The use of x-ray videography to record laser weld keyhole fluctuations appears to have been reported by Matsunawa and co-workers [2]. This is an important development because the ability to observe keyhole dynamics and defect formation is needed to model keyhole dynamics and such models are very useful. In other experimental work, the ability to reduce weld defect formation by pulsed laser power modulation has also been demonstrated and continues to be developed by other workers [2].

In the field of nonlinear dynamics, several control methods designed for chaotic systems have been published in the last decade. Cho *et al.* studied that the emission signals such as sound, light, and plasma charge from the laser weld fluctuate chaotically [3]. Unfortunately this work is focused on the keyhole rather than emission signals from the laser weld. Since keyhole fluctuations are linked to emission signals of the laser weld, this result suggests that keyhole fluctuations are also chaotic. In this paper, the characterization of keyhole dynamics is undertaken to apply the chaos control method. Among several control methods the sinusoidal variation of one parameter of the system presented by Chowdhury *et al* is potentially related to the current topic of this paper to control the chaotic keyhole dynamics system [4]. A three-dimensional phase plot is created to demonstrate that the chaotic system is converted to a periodic state by a control method applied in this paper.

2. Experimental procedure

A ROFIN-SINAR 850 5kW CO_2 Laser for high power laser generation, reflecting mirrors for beam delivery, and a parabolic focusing mirror for the beam focus with a 254mm focal length were used for this experiment. Glycerin in a semi-solidified state was used as a medium for performing the welding because of visualization of the keyhole due to its transparency. A KODAK (EKTAPRO HS) high speed coupled charge device (CCD) camera was utilized for recording the images of keyhole. In this experiment, the recording rate was 750 fps to observe the keyhole motion; the time interval between frames was 0.0013sec.

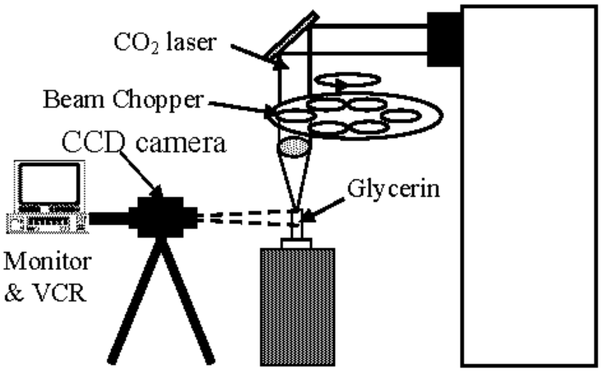

Fig. 1 Schematic of experiment apparatus for observation of keyhole behavior

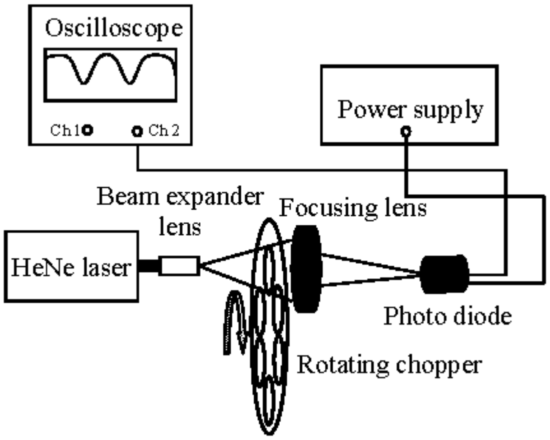

Fig. 2 Schematic of an experimental setup for measurement of laser beam power shape

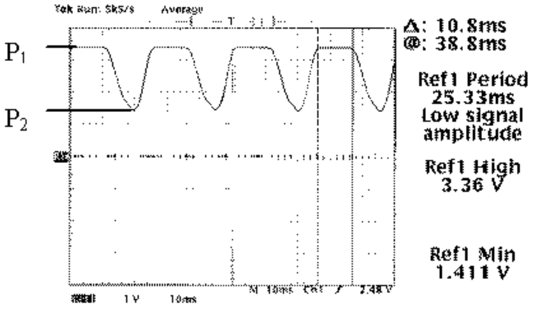

Fig.3 Sinusoidal shape of laser beam power and duty cycle of laser beam power

A schematic of the experimental setup is shown in figure 1. A linear motion system was used to move the material so the keyhole would remain fixed in the camera's field of view. The laser beam power shape was measured using the experimental setup shown in figure 2. The beam from HeNe laser was enlarged to the same diameter as the CO_2 laser beam by passing it through a beam expander lens and then the rotating chopper blocked a certain amount of beam with various frequencies to modulate the HeNe laser beam power. The modulated beam was focused onto the photo diode, which is an optical sensor to detect the intensity of light. The oscilloscope traces the signal of HeNe laser beam intensity from the photo diode detector shown in figure 3. According to figure 3, the minimum background power and duty cycle can be calculated to be 42% of peak power and 43% duty cycle. A duty cycle used for this investigation is similar to that in previous works [5], but the background power is different. The frequencies of power modulation were varied from 100Hz to 500Hz and the travel speed of the motion system was fixed at 25.4mm/sec.

Some researchers believe that the leading angle is better for reducing porosity than vertical or the trailing angle because bubbles can easily escape from the bottom of keyhole [2], [6]. Therefore the forward welding angle was used for this work and was varied from 0 to 25 degrees by 5 degrees increment.

3. Statistical analysis of uncontrolled signals

There are two methods, quadratic autocorrelation coefficient (QACC) and power spectral density (PSD), used to determine the characteristics of keyhole dynamics before applying the control method. First of all, the signals of the penetration depths in glycerin were normalized to remove extraneous effects, and then QACC and PSD plots were performed to determine whether or not the keyhole is chaotic.

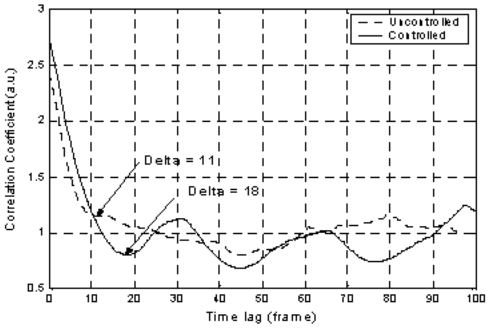

Fig. 4 Quadratic autocorrelation coefficients of uncontrolled and controlled signals

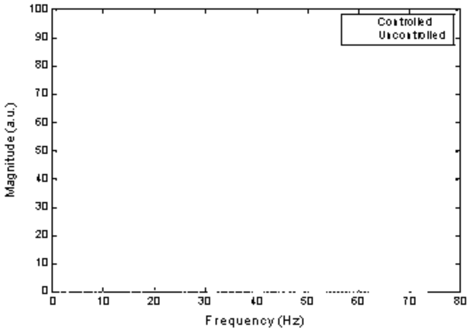

Fig. 5 Power spectral density of penetration depth signals of uncontrolled and controlled system

QACC for the uncontrolled signals from the penetration depth shown in figure 4 is the main evidence to determine that the system is chaotic because the steep slope of the curve at the beginning of the plot implies that "memory" of the system is quickly lost [7]. Also, quadratic autocorrelation coefficients were used to determine the time delay for three-dimensional phase plots.

The presence of a continuous component and a continuum of frequencies in PSD plot are the typical characteristics for chaotic dynamics [8]. In figure 5, the power spectral density of penetration depth signals is seen as more evidence of the chaotic behavior of keyhole dynamics. According to PSD plot, the frequency of the keyhole is not constant but rather continuous, indicating that the keyhole is a chaotic system. The high peak at the specific frequency represents the frequency of keyhole collapse, and the low peaks indicate the frequencies of keyhole fluctuation without keyhole collapse. A couple of high peaks appear in the low frequency range for the uncontrolled penetration depth signals. This is the clear evidence not to use the frequency in the low frequency range to stabilize the keyhole for power modulation.

4. Keyhole Control

4.1 Effects of frequency and incident beam angle on porosity formation

The frequency of the modulated laser beam and the incident leading beam angle were varied to determine the optimum parameters for the best keyhole stability. The frequency of keyhole collapse is considered to determine the frequency range for power modulation. According to figure 5, the keyhole collapses occurred in the lower range of frequency, so the frequency in this control method was applied above the keyhole collapse frequency. The volume of voids generated by keyhole collapse was plotted to show the effect of parameter changes shown in figure 6. The data was produced from the measurement of pore volume from

600 frames of keyhole images. When the keyhole is unstable and collapses often, the volume of void is large, but it is small when the keyhole is stable. Therefore, the volume of voids is strongly related to the stability of the keyhole.

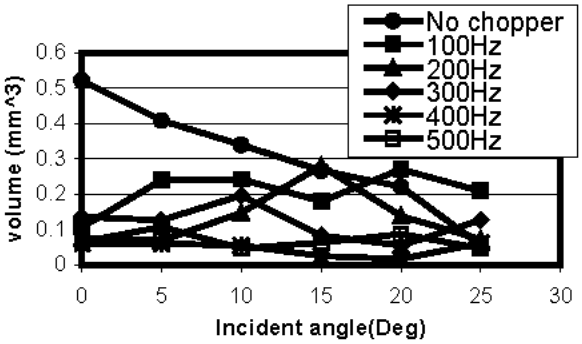

Fig.6 Volume of Pores with Various Beam Incident Angle and Frequencies

According to figure 6, power modulation, the quasi-sinusoidal waveform, is the dominant factor to reduce voids formation because the volume of void at all frequencies was slightly changing with various incident angles. Another point should be discussed which are the existence of background power and the laser power shape to explain the phenomenon of improving keyhole dynamics in this experiment. The background power, which gradually decreases and increases after passing the peak point, actually helps to maintain the keyhole in the state shown in figure 3. Fujinaga *et al.* also mentioned that the rapid increase of laser power produced the spatter in the molten metal due to the high intense vibration, and the rapid decrease of laser power causes porosity formation by keyhole collapse [5]. In this experiment, the gradual increase and decrease of laser power prevents the sudden change of keyhole dynamics, which is aiding the stability of the keyhole.

To determine the effect of the incident beam angle, the incident beam angle without power modulation (CW beam) was changed to check the volume of voids. The increase of the incident beam angle decreases the volume of voids based on the data shown in figure 6. However, the leading angle is not the dominant factor reducing the volume of voids because the pore volume is slightly changing with various incident angles, but it does improve the reduction of bottom porosity formation. From keyhole images in figure 9, it is clear that entrapped bubbles escaped more easily from the keyhole because it is somewhat enlarged by the leading angle compared to the keyhole images with the normal incident beam angle.

According to the results from two keyhole control methods, power modulation and incident beam angle, the quasi-sinusoidal laser beam power of 400Hz frequency and 15° incident beam angle were determined to be the optimum parameters for the reduction of voids based on the data shown in figure 6.

4.2 Effects of frequency and incident beam angle on keyhole penetration uniformity

In the previous section, 400W laser power was used to determine the optimum parameters for the frequency and the incident beam angle due to the consistent conditions for each case. To compare the penetration profile between modulated and non-modulated case with the same penetration depth, the power for the modulated case was increased to 750W to compensate for the loss of laser beam power blocking by the beam chopper and the less penetration by the incident beam angle.

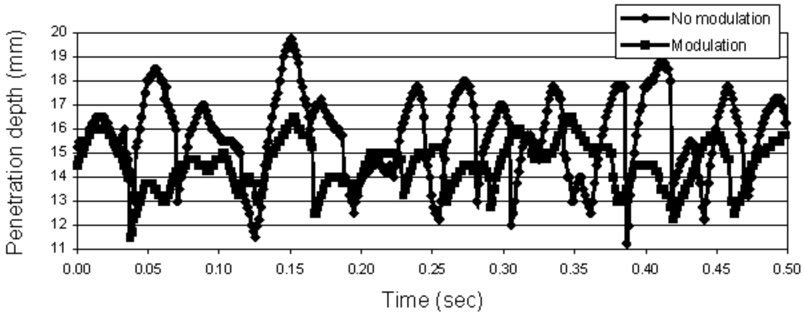

Fig.7 Comparison of penetration depth between no modulation (400W) and modulation (750W and 15° angle)

The penetration profile for modulated case (SW, 400Hz, P_1=750W, 15° incident beam angle) is more uniform than the one for non-modulated case (CW, P=400W, 0° incident beam angle) presented in figure 7. The modulation decreases the void volume (figure 6) as mentioned in section 4.1, and it also produces a more uniform penetration depth.

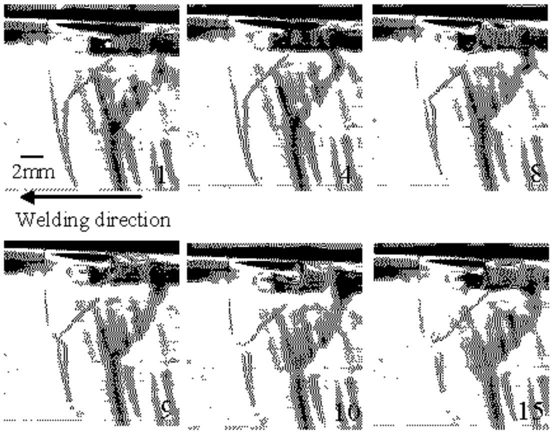

Fig.8 Keyhole motion and porosity formation observed by CCD camera at no modulation

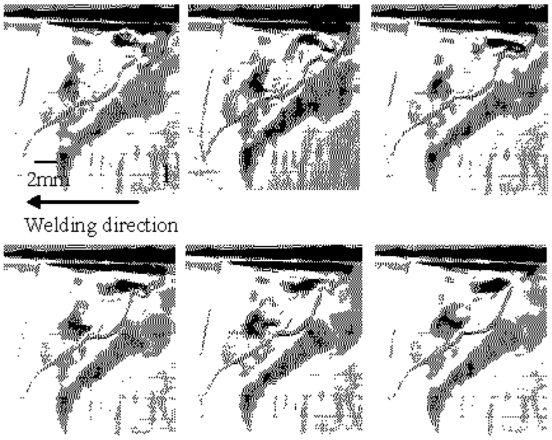

Fig.9 Keyhole motion observed by CCD camera at modulation

The images of keyhole dynamics are shown in figure 8 (no modulation, normal incidence) and figure 9 (modulation, 15° incidence). The number at the right bottom on the image represents how many frames passed from the initial frame. The moment of keyhole collapse and porosity formation behind the keyhole are shown to illustrate keyhole dynamics for non-modulation case in figure 8. The keyhole motion captured by high speed CCD camera is shown to verify the effect of modulation in figure 9.

According to non-modulated case in figure 8, a deep penetration keyhole is generated at the first frame. At that moment, the recoil pressure of the glycerin evaporation balances with the surface tension of glycerin to maintain the keyhole. There are several forces acting on the keyhole, but surface tension appears to be the driving force of the keyhole collapse [1]. When the balance between recoil pressure and surface tension breaks down, the surface tension begins necking the keyhole at the fourth frame. The neck of keyhole becomes narrower in the ninth frame and finally collapses at the tenth frame. The penetration depth of the keyhole drastically drops after the keyhole collapses at the tenth frame. The separated lower part from the keyhole remains behind in the resolidifying glycerin as a bubble. The bubble shape changes from an irregular shape to a sphere due to surface tension because the surface tension dominates over the hydrostatic pressure difference from top to bottom in bubble. Presumably, the shape of voids in partial penetration weld in steel is irregular because there is less time to change to a sphere due to the more rapid solidification. In the fifteenth frame the laser beam starts reopening the keyhole, and at a latter time the keyhole collapses again. This cyclical phenomenon of keyhole dynamics causes the instability of keyhole dynamics, which is the main reason of repetitive void formation.

The keyhole drastically fluctuates with large variation in keyhole penetration depth because the keyhole depth becomes less due to the separation of its lower portion when the keyhole collapses. The beginning point of fluctuating the keyhole penetration is the ninth frame in figure 8. The keyhole collapse causes an abrupt decrease in penetration depth and the number of keyhole collapses can be measured from the penetration depth profile (figure 7) by counting the number of the big step decreases in penetration depth. Figure 9 shows keyhole images of power modulation and leading incident angle to illustrate more uniform keyhole dynamics and penetration that is achieved by controlling the welding process.

5. Chaos analyses of uncontrolled and controlled system

The first step of chaos analysis in this work is to remove the noise from the original penetration depth signals. The usual low-pass filtering is not performed to clean the high level noise because conventional filtering method removes a part of the important information at the high frequency range and power spectra of chaotic processes are broadband in figure 5 [7]. Therefore, the noise reduction technique that is appropriate for the non-linear dynamic system is used to accomplish the noise reduction from the original signals. Three-dimensional phase plots of the cleansed signals, which are signals excluding the high dimensional noise, were produced by using time intervals, 11 frames for uncontrolled system and 18 frames for controlled system, from the interpretation of quadratic autocorrelation coefficients in figure 4.

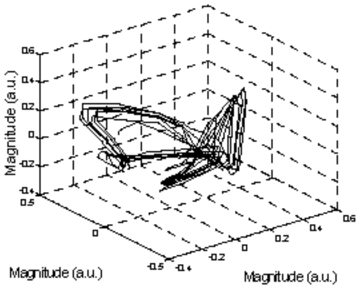

Fig.10 3D Phase plot of the cleaned penetration depth signals for no modulation case

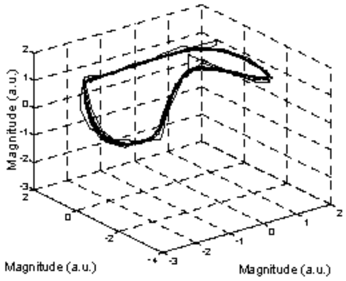

Fig.11 3D Phase plot of the cleaned penetration depth signals for modulation case

A three-dimensional phase plot is usually used to present characteristics of a chaotic system. The structure of the three-dimensional phase plot depends on the signal characteristics, so the structure for uncontrolled chaotic signals is similar to infinite orbits and the three-dimensional phase plot for controlled signals contains one closed orbit structure. In figure 10 the three-dimensional phase plot of uncontrolled signals is reconstructed using the time-delay approach, which creates infinite unclosed loops reached a point beyond the periodic orbit. It is not completely regular but it has a general pattern, which is distinguished from the phase trajectories for raw signals (no cleaned signals) that appears as complicated tangles because the noise level is so high. The three-dimensional phase plot for controlled signals is presented in figure 11, this graph shows the distinguished structure that contains a closed orbit and points are sitting on its orbit. Compared to the phase plot of uncontrolled signals shown in figure 10, the phase plot for controlled signals demonstrates less chaotic behaviors, which means that the system was successfully controlled by power modulation and leading incident beam angle. The ordered phase plot represents stable keyhole dynamics and the relation between the phase plot and the stability of keyhole is significant.

6. Conclusions

Power modulation (400Hz quasi-sinusoidal wave) and incident beam angle (15°) of the laser beam were used to be able to stabilize the keyhole in glycerin, preventing the formation of large voids caused by keyhole collapse. Consequently, the frequency of power modulation became the dominant parameter to decrease porosity formation, and the incident leading beam angle was added to enhance the stability of the keyhole. Three-dimensional phase plots for uncontrolled signals and controlled signals demonstrated that the keyhole dynamics were successfully controlled from a chaotic regime to a regular one by control methods used in this paper.

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