

# Laser Weld Keyhole Dynamics and Control

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## I. INTRODUCTION

Porosity formation is a major problem that limits application of the partial penetration laser welding process. Thus, reduction of voids trapped by keyhole collapse is an important issue in improving laser weld quality. The main cause of keyhole collapse is the instability of keyhole dynamics during the laser welding process. Therefore, process controls that modify the keyhole dynamics are needed to reduce the likelihood of formation of these defects.

In this work, the dynamics of laser weld keyholes are studied by numerical simulation with results validated by experiments. A non-feedback nonlinear system control method is then applied to assess its ability to stabilize the keyhole dynamics, with a goal of preventing keyhole collapse and defect formation.

## II. EXPERIMENTAL PROCEDURE

Keyhole dynamics model predictions are compared to keyhole motion measured experimentally by exposing a weld sample with a micro-focus x-ray and capturing images with a high-speed video camera as shown in Figure 1. In subsequent work, a CO<sub>2</sub> laser is used to produce keyholes in glycerin, a clear substance selected so that the keyhole is easily visualized. The ability of laser power modulation via a rotating shutter to stabilize the laser keyholes is demonstrated. A schematic of the experimental setup is shown in Figure 2. The peak power was 400W, and the minimum power was 42% of peak power. The frequencies of power modulation were varied from 100Hz to 500Hz and the travel speed of the motion system was fixed at 1in/sec.

## III. RESULTS AND DISCUSSION

Figure 3 shows the real time x-ray images of the keyhole formation during 500W CO<sub>2</sub> spot welding of plain carbon steel. The keyhole was collapsed in the second image, and a pore was trapped at the bottom of the keyhole after 0.22 ms since the complete keyhole formed. This was the first pore seen since the laser beam impinged on the edge of the sample. In the fifth image a protrusion appeared on the walls of the keyhole. This is the beginning point of the keyhole collapse. Finally, the bridge was completely built and the pore was trapped at the bottom of the keyhole in the sixth image. The complete keyhole was found 1.75ms after the laser beam impinged on the plain carbon steel. After 1.97ms, the first keyhole collapse was observed and then the keyhole reopened by the continuous

laser beam irradiation after 0.22ms. The period of the periodical collapse time is about 0.88ms.

The simulated keyhole surface profile and flow velocities distributions corresponding to a 500W laser power are shown in Figure 4. The recoil pressure is significant and a keyhole exists after 6 ms. The keyhole becomes unstable and it collapses at 9.2ms. At 9.6 ms, the keyhole is once again opened by the recoil pressure.

For the control study, the quasi-sinusoidal power modulation frequency and the incident beam angle were varied to determine the optimum parameters for the best keyhole stability. The volume of voids remaining in the glycerin behind the keyhole is plotted in Fig. 5. When the keyhole is unstable and collapses often, the void volume is large, but it is small when the keyhole is stable. 400Hz sinusoidal power frequency and 15° incident beam angle were determined to be the optimum parameters for the stability of keyhole.

#### **IV. CONCLUSIONS**

The keyhole formation was monitored and instability of the keyhole was observed by the analysis of x-ray images. Additionally the dynamic behavior of the keyhole was simulated and it was compared to the experimental results. Surface tension caused collapse of the keyhole walls. In the experiments, the time for the complete collapse of keyhole after the protrusion appeared was about 0.2ms. This number showed reasonable correlation between the experiment and the simulation.

400Hz frequency of power modulation and 15° incident leading beam angle were found out to be optimum parameters that drastically reduced the volume of voids and produced the most uniform keyhole penetration in glycerin keyholes.

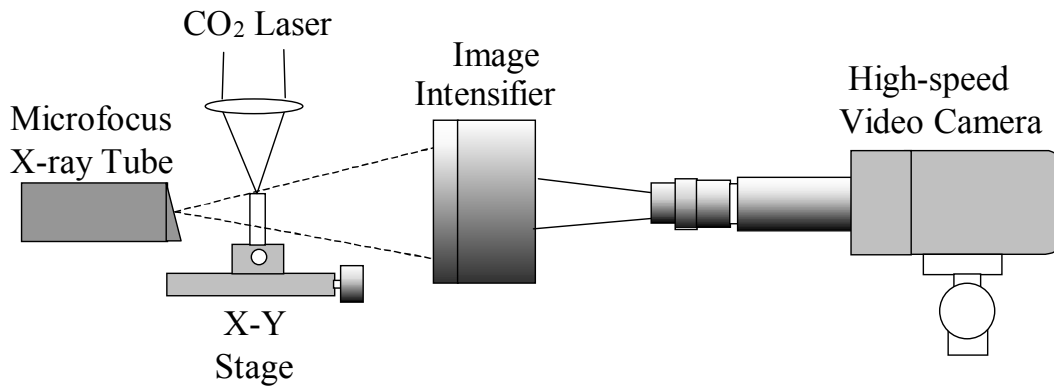


Figure 1: Microradiographic setup for observation of keyhole behavior

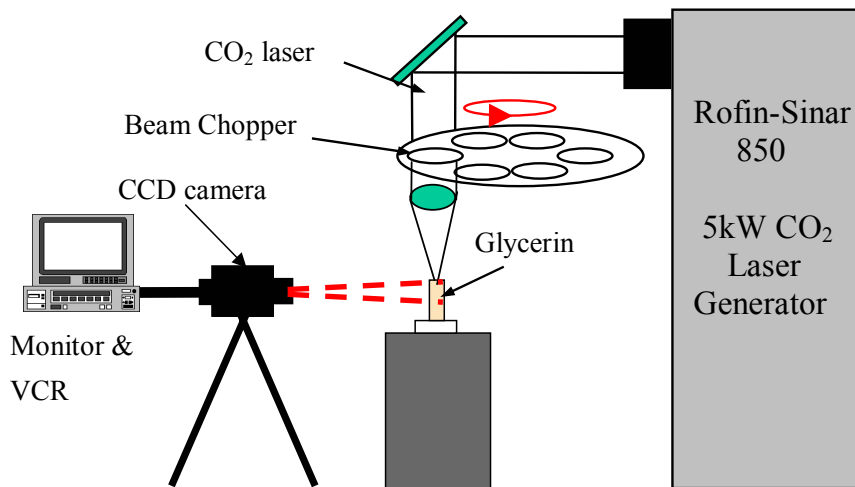


Fig.2 Schematic of experimental setup for keyhole modulation and observation



(1) 1.75ms



(2) (1.75+0.22)ms



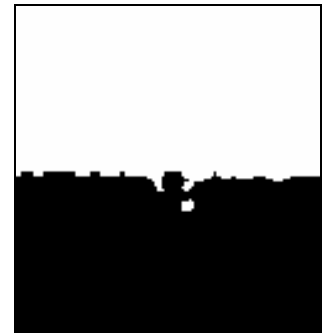
(3) (1.75+0.44)ms



(4) (1.75+0.66)ms



(5) (1.75+0.88)ms



(6) (1.75+1.1)ms

Figure 3: Keyhole behavior observed by X-ray image system

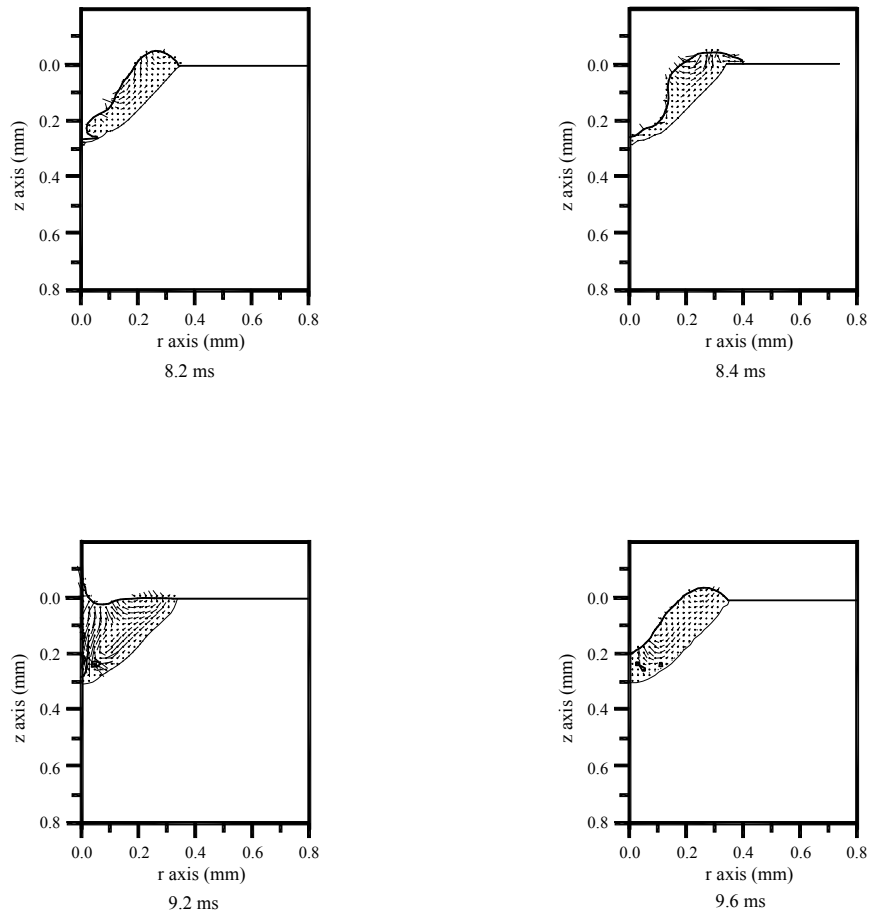


Fig.4 Predicted surface profile and flow patterns for 500W laser power

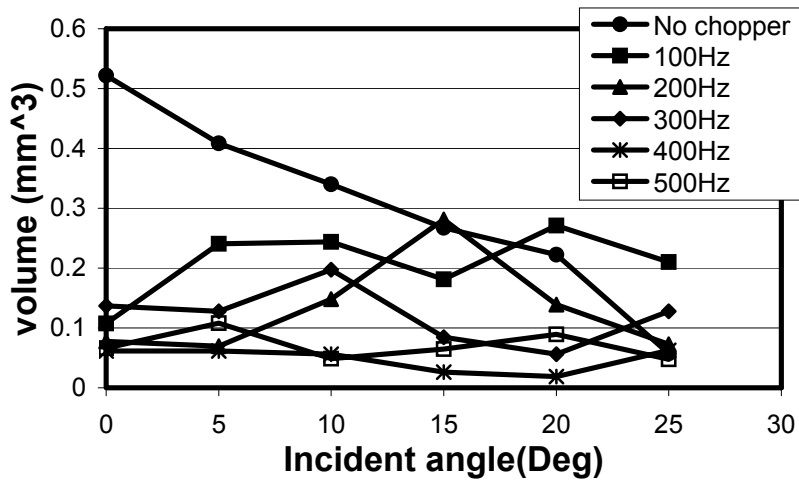


Fig. 5 Volume of voids with various beam incident angles and frequencies