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Real-time observation of laser cutting fronts by X-ray transmission

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ABSTRACT

In laser cutting, industry practitioners have long demanded higher cutting speeds and better quality cuts. There is thus much interest in the elucidation of related processing phenomena. Cutting quality is known to be affected by ejection behavior of generated melt, which itself is thought to be influenced by the profile of the laser cutting front. It would thus be desirable to directly observe the cutting front in real time, but this is not easily done in practice, mainly because laser cutting speeds are relatively high and visible light generally cannot pass through workpieces. In this study, we used an X-ray transmission system to perform fluoroscopic observation of cutting fronts in real time during actual processing. Further, we discuss the effect of the cutting parameters (cutting speed, etc.) on cutting front profile and melt ejection. We find that both the profile of the cutting front and the ejected melt behavior were stable when a sound cut was produced. We directly confirmed that the cutting front profile changed along with cutting speed.

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1. Introduction

Laser cutting is one of the most widely established laser-based processes, and also the oldest used in industry (Laser Society of Japan, 2006). Throughout its history, higher cutting speeds and better quality cuts have been demanded.

In the laser cutting of metal plates, a laser beam is shone onto the surface to form a kerf (slit or notch) by either melting or vaporizing that material. The resulting liquid, hereafter, called as melt, is a mixture consisting mainly of molten metal and oxidation products. Melt is usually removed by an assist gas blown in at a suitable pressure. To produce a high quality cut, it is best that the melt flows smoothly out from the bottom of the plate (Arai et al., 1994). Indeed, melt ejection is known to affect cutting quality.

As ejection behavior is thought to be influenced by the profile of the laser cutting front, it would be desirable to observe that front in real time. In practice, however, such observation can be exceedingly difficult, mainly because (a) cutting speeds are relatively high and (b) visible light generally cannot pass through workpieces.

Several studies of cutting fronts have been conducted. Arata et al. (1979) have discussed mechanism for the laser cutting mild steel with oxygen gas based on high speed color films of both vertical and lateral motions of the cutting front. Schober et al. (2012) have obliquely observed cutting fronts with a high-speed camera, utilizing that data to geometrically calculate the slant angle of the cutting front. In addition, the cutting front has been visualized by laser cutting of rose's alloy combined with glass (Yudin and Kovalev, 2009) or by the laser cutting of glass (Riveiro et al., 2011). Yamada et al. (2013) have conducted numerical simulations to analytically investigate the process of cutting front formation. However, there have been few reports of direct observation of cutting fronts during laser cutting. Moreover, since both the profile of the cutting front and the ejection behavior of the melt have not been observed at the same time, the relationship between the two has been unrevealed in practical cutting conditions. Here, our aim is to perform real-time observation of laser cutting fronts by means of an X-ray transmission system in order to gain direct and useful insights into related processing phenomena.

In laser welding, various processing phenomena, including the mechanism of porosity formation, have been revealed by two-dimensional real-time observation with a micro-focus X-ray transmission system (Kawahito et al., 2008). Arata et al. (1985) have studied fundamental phenomena in laser welding including beam hole shape by dynamic observation using a transmission X-ray system. More recently, three-dimensional real-time observation of welding and joining mechanisms has been made possible

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Table 1
Chemical composition of the steel used in this study, mass%.

C	Si	Mn	P	S
0.18	0.27	0.68	0.019	0.020

by the development of a high-brightness four-dimensional X-ray transmission visualization system (Kawahito and Katayama, 2011). Three-dimensional visualization of plastic flow during friction stir welding has also been performed (Morisada et al., 2011). However, to our knowledge, fluoroscopic observation of the laser front during laser cutting has not been reported.

In this study, we aimed to perform fluoroscopic observation of laser cutting fronts in real time by means of an X-ray transmission system. For this, we utilized mild steel, a widely used industrial material, together with oxygen assist gas. Also, the effect of cutting parameters (cutting speed, etc.) on cutting front profile and melt ejection behavior are discussed.

2. Experimental procedure

2.1. Material used

This study examined the laser cutting of a mild steel (JIS SGD3M rolled carbon steel for cold-finished steel bars) with an oxygen assist gas. The chemical composition of this steel is shown in Table 1.

Specimen dimensions were 4 × 120 × 4 mm (Fig. 1), set in consideration of the limited penetrative power of the X-rays. Two holes of 2.2 mm in diameter were drilled, one on each end of the specimen, for fastening to a jig. Another hole, this one also of 2 mm diameter, was drilled (not pierced) to provide a starting point for the laser cut. After surface degreasing with ethanol, the specimen was cut by laser in the longitudinal direction.

2.2. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 2.

Laser cutting equipment was used together with fluoroscopic observation equipment. The laser cutting equipment consisted of a 16-kW disk laser (wavelength: 1030 nm; beam parameter product: 8 mm·mrad; fiber diameter: 200 μm) and a cutting head. Both were arranged perpendicularly to the longitudinal axis of the specimen. The fluoroscopic observation equipment consisted of a micro-focus X-ray generator and an X-ray image intensifier, both of which are components of a high-brightness four-dimensional X-ray transmission system for the visualization of welding and joining processes.

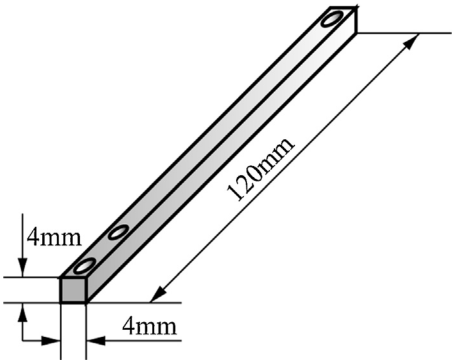

Fig. 1. Schematic diagram of specimen for X-ray fluoroscopic observation during laser cutting.

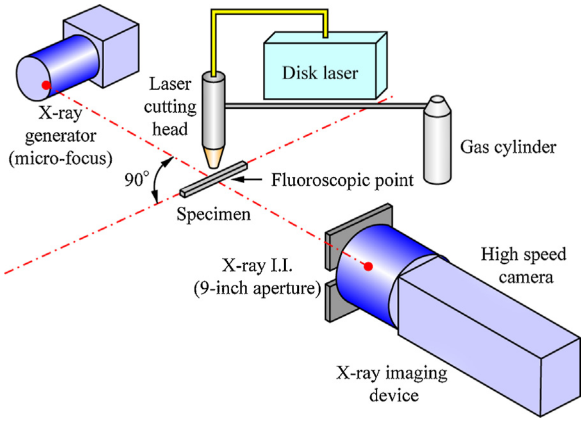

Fig. 2. Schematic diagram of experimental setup for fluoroscopic observation during laser cutting.

2.3. Experimental conditions

Laser cutting process parameters are shown in Table 2.

A continuous-wave disk laser was used with a lens focal length of 200 mm. Oxygen was used as an assist gas, with pressure varied from 0.25 to 1 MPa. Cutting speed was varied from 0.5 to 7 m/min. Kept constant were laser power, at 2 kW; defocusing distance, at −1 mm; nozzle gap, at 1 mm; and cut length, at 70 mm. The defocusing distance −1 mm means focus position is placed under the specimen surface. The laser beam and the oxygen gas were come through a convergent coaxial nozzle with 2 mm diameter.

A micro-focus X-ray generator was used for fluoroscopic observation of the laser cutting front from one side. The generator has a maximum resolution of 4 μm, a maximum voltage of 230 kV, a maximum current of 1 mA, and a frame rate of 1000 fps.

3. Experimental results and discussions

3.1. Laser cutting process window

Ahead of fluoroscopic observation, we prepared a process window over a range of cutting speeds and assist gas pressures. This window is shown in Fig. 3.

The resulting cuts can be classified by appearance as follows: self-burning; sound cut; dross adhesion; and gouging. When a part of the specimen was disappeared due to excessive melting, the cutting conditions were classified into the self-burning. The sound cut conditions mean achievement of the dross-free cutting. The conditions of the dross adhesion were distinguished by existence of the dross at the bottom surface of the specimen. In the gouging conditions, cutting was impossible. Sound cuts were generally obtained under cutting speeds of 2–3 m/min. Under these conditions, the resulting kerf width was approximately 0.5 mm on the specimen surface. In this study, real-time observations were mainly conducted under an assist gas pressure of 0.5 MPa.

Table 2
Process parameters for laser cutting.

Laser type	Disk laser (continuous wave)
Laser power	2 kW
Focal length of lens	200 mm
Defocusing distance	−1 mm
Cutting speed	0.5–7 m/min
Assist gas	O_2
Assist gas pressure	0.25–1 MPa
Nozzle gap	1 mm

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