Welding characteristics of S45C medium carbon steel in laser welding process using a high power CW Nd:YAG laser

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Laser welding process is widely used in the industrial area due to its numerous advantages: a small heat affected zone (HAZ), deep penetration, high welding speed, and small distortion after welding [1–3]. The weldability of the laser welding process is dependent on welding conditions such as the combination of the laser and workpiece, the laser power, the welding speed of the laser, and the focal position of the laser beam [4, 5]. In order to weld metallic materials, CO_2 and Nd:YAG lasers with a high power have been generally employed [1].

In terms of weldability for metallic materials, Nd:YAG welding has various advantages, such as a high energy absorption rate due to a low reflectivity, a high welding speed, and a low residual stress compared to CO_2 laser welding, so the application of Nd:YAG laser to weld metallic materials is steadily being increased [6, 7].

S45C medium carbon steel has been widely used in industrial applications, such as crank shafts, gears, main spindles of machine tools, connecting rods, etc., because of its distinguished mechanical property. In the conventional arc welding of S45C plates without heat treatments, it is possible for welding defects to take place, such as a void or a hotcrack, due to a high carbon composition of S45C [8–10].

The objective of this research work is to investigate the welding characteristics of a S45C medium carbon steel plate in a laser welding process using a high power Nd:YAG laser with a continuous wave (CW). In order to obtain optimum welding conditions, the influence of process parameters, such as laser power and welding speed, on the depth of penetration, the width of bead, and the occurrence of defects, was studied by experiments.

Laser welding experiments were performed using a 2-axis computerized automatic laser welding system. A CW Nd:YAG laser with a 2.8 kWatt of the maximum power was employed. (LASMA 1054, TRUMPH) The wavelength, focal length, and focal number of the focusing lens for the laser head were 1.06 μm, 200 mm, and 3.3, respectively. Argon gas was employed as shielding gas.

Table I summarizes the chemical composition of the specimen. The thickness of specimen (t) was 4.5 mm. The length and width of the specimen were 100 and 50 mm, respectively. The specimen was welded in the longitudinal direction using a bead-on-plate welding with a CW Nd:YAG laser. The power and welding speed of laser were set to be 600–2000 Watt and 600–6000 mm/min, respectively. The microstructure of the welded specimen was observed by using an optical microscope (Eclipse L150). The aspect ratio of bead for the welded specimen was calculated from the ratio of sizes between the depth of penetration and width of the bead.

Fig. 1 shows the influence of laser power on the depth of penetration and the aspect ratio of the bead.

When the laser power is greater than 1320 Watt, the increment of the depth of penetration is larger than that of the width. This is because the keyholing phenomenon, in which a hole of the workpiece is opened up so that laser energy can penetrate deep into the workpiece and be absorbed there, is initiated at 1320 Watt of laser power. In addition, it is seen that the aspect ratio is greater than 1.0 at 1500 Watt. Comparing the bead shape and the microstructure of 1200 Watt with those of 1600 Watt, it is found that the deep penetration welding, induced by the keyholing phenomenon, occurs at 1600 W of laser power, as shown in Fig. 2.

When the laser power is less than 1320 Watt, it is seen that the aspect ratio of 1200 mm/min for welding speed is larger than that of 800 mm/min, although the effective incident energy of the 800 mm/min is larger than that of 1200 mm/min. This may be ascribed to

TABLE I Chemical composition of S45C (wt%)

Fe	C	Si	Mn	P	S
98.48	0.45	0.25	0.75	0.03	0.04

the fact that conduction is a dominant phenomenon to transfer the absorbed energy into the material, since the keyholing phenomenon is not initiated. Hence, a greater amount of the absorbed energy is transferred in the radial direction of the surface than in the thickness direction, and the increment of the width for the bead is subsequently larger than the increment of the depth of the penetration. Consequently, the aspect ratio in a high welding speed is greater than that of a low welding speed.

From the results of the experiment, it has been shown that the laser power should be higher than 1500 Watts, irrespective of welding speed, in order to obtain deep penetration with the keyhole in which the depth of penetration is larger than the width of the bead.

Fig. 3 shows the influence of welding speed on the depth of penetration and the aspect ratio. In addition, it

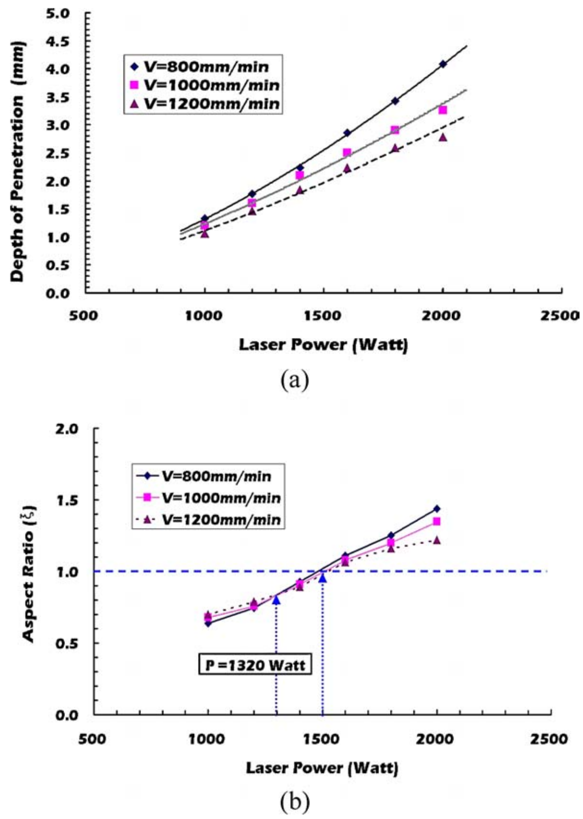


Figure 1 Influence of laser power on the depth of penetration and the aspect ratio: (a) depth of penetration and (b) aspect ratio.

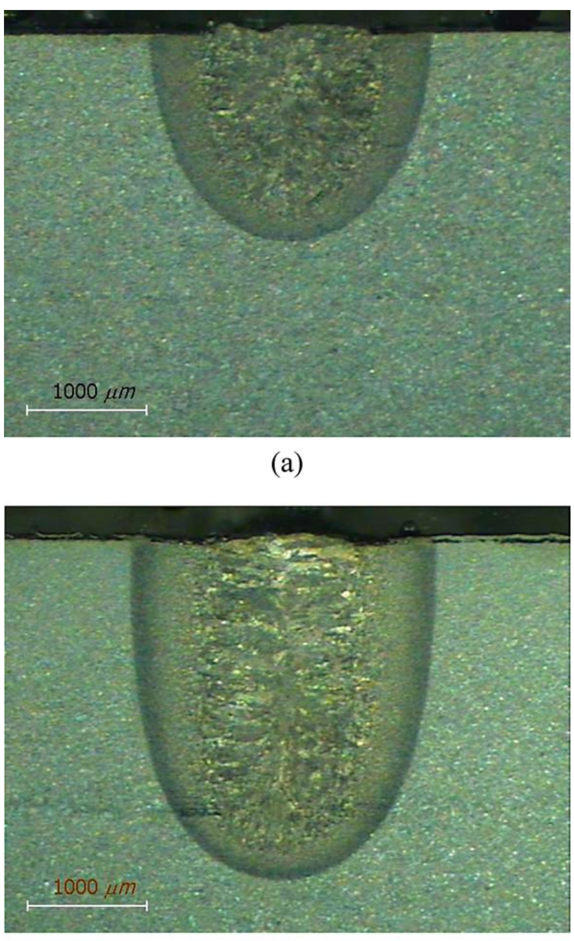


Figure 2 Microstructure in the vicinity of the welded area: (a) laser power = 1200 Watt, welding speed = 800 mm/min and (b) laser power = 1600 Watt, welding speed = 800 mm/min.

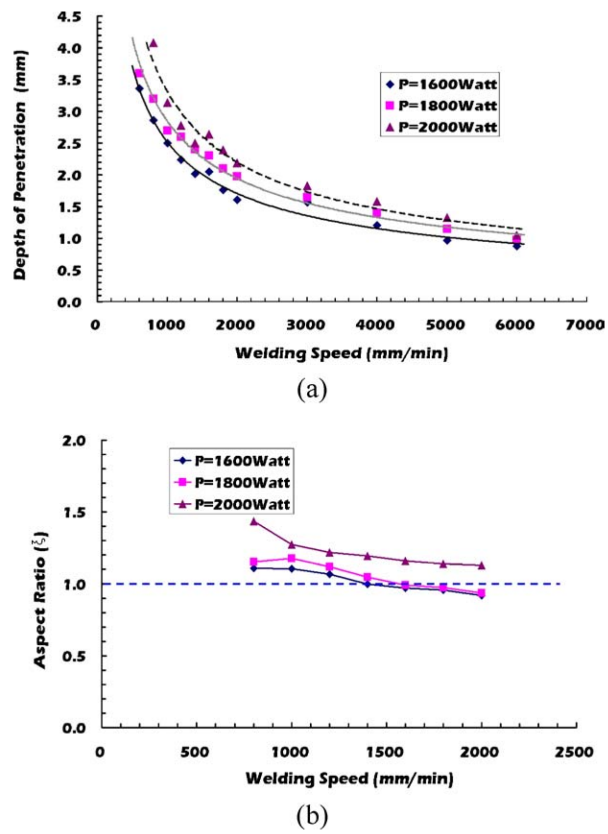


Figure 3 Influence of welding speed on the depth of penetration and the aspect ratio: (a) depth of penetration and (b) aspect ratio.

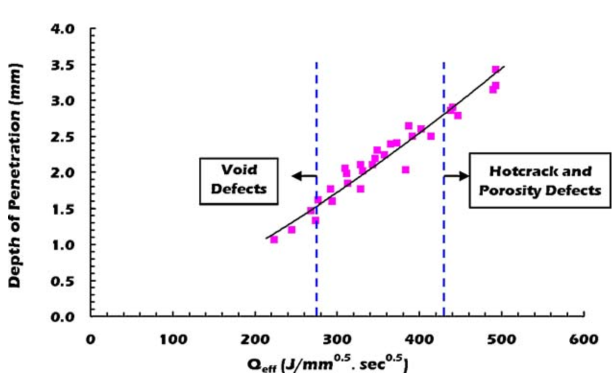
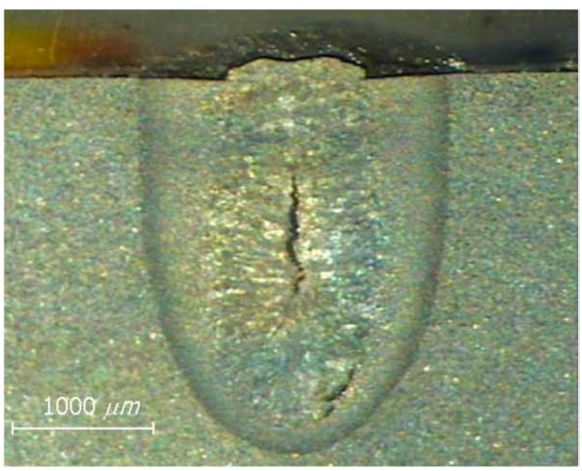


Figure 4 The relationship between the effective heat input and the depth of penetration.

(a)

(b)



(c)

Figure 5 Microstructure in the vicinity of the welded area: (a) effective heat input = 268 $J/mm^{0.5} \cdot sec^{0.5}$, (b) effective heat input = 392 $J/mm^{0.5} \cdot sec^{0.5}$, and (c) effective heat input = 465 $J/mm^{0.5} \cdot sec^{0.5}$.

is seen that the depth of penetration and the aspect ratio are in inverse proportion to the welding speed.

Based on the above experimental results, the effective heat input (Q_{eff}) was introduced to consider the influence of laser power (P) and welding speed (V) together, as shown in Equation 1.

$$Q_{eff} = \frac{P}{\sqrt{V}} \qquad (1)$$

Fig. 4 shows the relationship between the depth of penetration and the effective heat input. In order to obtain the optimal welding condition without defects, teardown inspection and the nondestructive inspection were carried out. In the nondestructive inspection, scanning acoustic tomography (SAT) was employed. The inspection showed that void defects occur when the effective heat input is less than 35 $J/mm^{0.5} \cdot sec^{0.5}$, and hotcrack and porosity defects occur when the effective heat input is greater than 56 $J/mm^{0.5} \cdot sec^{0.5}$. In addition, it is found that a percentage of the plasma plume above the surface of the workpiece was suddenly increased to 60% when the hotcrack and porosity defects were initiated. The plasma plume was measured by an infrared thermal vision camera. Fig. 5 illustrates the microstructure in the vicinity of the welded area at different the effective heat inputs. Figs 4 and 5 show that the Nd:YAG laser welding of S45C medium carbon steel can produce defect-free joints, as the effective heat input ranges from 275 $J/mm^{0.5} \cdot sec^{0.5}$ to 435 $J/mm^{0.5} \cdot sec^{0.5}$.

In conclusion, the influence of process parameters, such as laser power and welding speed on the depth of penetration, the aspect ratio of the bead and the initiation of defects in the bead for the case of the welding of S45C medium carbon steel, using a high power CW Nd:YAG laser, could be investigated by several experiments. Through the investigation of the effect of laser power on the depth of penetration and the aspect ratio of the bead, it has been shown that the laser power should be higher than 1500 Watts to obtain deep penetration with a keyhole, in which the depth of penetration is larger than the width of the bead, irrespective of welding speed. From the results of the experiment, the effective heat input was introduced to estimate the depth of penetration for each welding condition. In addition, the relationship between the effective heat input and the depth of penetration was obtained from the regression of experimental data. For successful welding without defects, it could be confirmed through this process, that the optimal welding region of the effective heat input for S45C medium carbon steel with the high power CW Nd:YAG laser should be ranged from 275 $J/mm^{0.5} \cdot sec^{0.5}$ to 435 $J/mm^{0.5} \cdot sec^{0.5}$.

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Received 4 March and accepted 21 April 2004