Journal of Manufacturing Processes 33 (2018) 144–149

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

# Effects of groove parameters on space constraint of narrow gap laser-arc hybrid welding

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ARTICLE INFO

*Keywords:*
Space constraint
Narrow gap
Hybrid welding
Groove
Melting energy

ABSTRACT

Obvious space constraint effect (SCE) related to energy transfer was found in narrow gap laser-arc hybrid welding (NGHW). It was significantly affected by changing the width of rectangle groove ($W_G$) and the angle of Y-shape groove ($\alpha_G$), and the central crack and sidewall notch occurred on weld cross-section when $W_G \le 4$ mm or $\alpha_G \le 60°$. The SCE was quantitatively characterized by the dimensionless parameter of melting energy increment ($\psi$), which is the increment of melting efficiency of NGHW to the hybrid welding without narrow gap. The larger the $\psi$, the stronger the SCE. The $\psi$ of rectangle groove was up to 30% when the $W_G$ was at 6 mm, while the maximum of the $\psi$ of Y-shape groove was only 7% when the $\alpha_G$ was at 60°. According to the calculated $\psi$ and the defect occurring tendency, the optimized groove of NGHW was confirmed as the rectangle groove with 6 mm-width, and was verified by a 25 mm-thick joint. Besides, the effects of SCE on the energy transfer in narrow gap were discussed according to the behaviors of arc column and laser-induced plasma.

## 1. Introduction

Narrow gap laser-arc hybrid welding (NGHW) has been paid a lot of attentions in thick plate fabrications because of low heat input and high welding efficiency [1–3]. In order to stabilize arc burning, the groove of narrow gap arc welding is generally wide to 10–18 mm or larger, resulting in the occurrence of lack of fusion (LOF) at sidewalls [4–6]. NGHW could stabilize the arc burning via laser-arc interaction, and then save the material consumption by employing narrower groove [7–9]. For example, Li et al. welded 30 mm-thick plate by one pass laser welding and seven-pass NGHW with the groove width of 5.49 mm [10].Choi et al. joined 15mm-thick A572 Gr50 steel by six-pass NGHW with a rectangle groove width of 3.2 mm [11]. Hayashi et al. obtained a sound 22 mm-thick carbon steel weld with excellent mechanical properties by NGHW with the gap of 4 mm [12]. Our previous work achieved a 40mm-thick mild steel weld by nine-pass NGHW with the groove width of 6 mm, in which the ultimate tensile strength and the toughness of the weld was 49% and 60% higher than base metal, respectively [13]. The stability of NGHW were also quantitatively studied by approximate entropy in our previous study [14], demonstrating the stabilization of space constraint effect (SCE) caused by narrow gap. The SCE had significantly influences on the stability of NGHW by affecting the behaviors of arc column, droplet transfer, laser induced plasma, laser keyhole, and melt flow [15–17].

Above-mentioned studies indicated the strong SCE within the narrow gap of NGHW, but no attention has been paid on the effects of groove parameters so far. In order to deepen the understanding, the effects of groove parameters on the SCE of NGHW were discussed by the behaviors of arc column and laser-induced plasma, and were quantitatively characterized by melting energy increment.

## 2. Experimental

Hot rolled and annealed Q235 mild steel plates with the thickness of 25 mm was used as base metal (BM). ER70S-6 with the diameter of 1.0 mm was used as filler wire. The chemical compositions of the BM and filler wire are presented in Table 1. Before welding, the narrow gap (NG) was machined, and the oxidized film was removed. The shielding gas was a mixed gas with 80% Ar and 20% $CO_2$ in volume at the flow rate of 20 l/min.

An IPG YLR-6000 fiber laser with the maximum power of 6 kW was employed. The focus spot was approximately 0.4 mm. A Fronius TPS-4000 welder was used in pulsed mode. The schematic diagram of experimental set-up is shown in Fig. 1, where the hybrid welding was carried out in arc leading mode. The parameters used were laser power 4.5 kW, arc current 210 A, welding speed 0.5 m/min, laser-arc distance 3 mm, defocus distance −2 mm, the angle of arc torch to workpiece surface 55–60°, and wire extension 10–12 mm. The dimensional design of the groove used is shown in Fig. 2. For simplification, the width of rectangle groove and the angle of Y-shape groove were named as $W_G$

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https://doi.org/10.1016/j.jmapro.2018.05.006
Received 10 January 2018; Received in revised form 19 April 2018; Accepted 6 May 2018

**Table 1**
Chemical compositions of BM and filler wire.

| Materials | Compositions (wt. %) | | | | | | |
|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Others | Fe |
| BM | 0.12 | 0.15 | 0.44 | 0.015 | 0.008 | ≤0.3 | Bal. |
| Filler wire | 0.08 | 0.92 | 1.52 | 0.020 | 0.015 | ≤0.5 | Bal. |

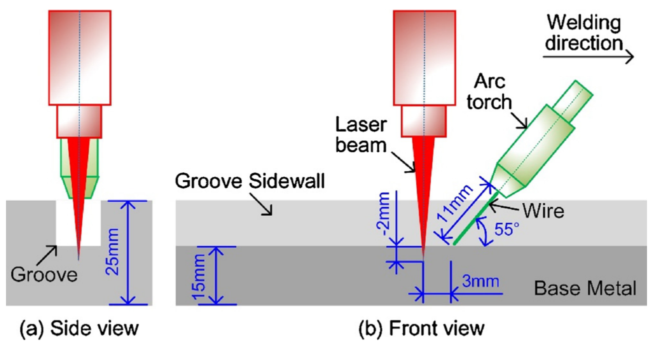


**Fig. 1.** Schematic diagram of experimental set-up, (a) side view, (b) front view.

and $\alpha_G$, respectively. After welding, the welds were cut at the middle, and etched with a solution of 2% nital for 10 s. The cross-sectional shape was observed by optical metallographic microscope.

## 3. Results and discussion

### 3.1. Space constraint effect

As shown in Figs. 3 and 4, the weld penetration depth ($H_p$) of rectangle groove increases from 7 to 8.2 mm as the $W_G$ increases from 2 to 4 mm, but decreases to 6.1 mm as it continuously increases to 10 mm. The weld width ($W_D$) of rectangle groove increases from 3.1 to 7.2 mm as the $W_G$ increases from 2 to 10 mm. The effects of the $\alpha_G$ on the $H_p$ and the $W_D$ of Y-shape groove present the same variation. Obviously, the change of $H_p$ and $W_D$ was caused by narrow gap.

It can be noticed that the defects of sidewall notch and crack appear when $W_G \leq 4$ mm or $\alpha_G \leq 60°$, as shown in Fig. 3. It indicates that too narrow gap cannot maintain the stability because of the easy arc striking at sidewalls. Besides, the $W_D$ of rectangle groove is smaller than the $W_G$ as the $W_G$ increases to 8 mm or wider, suggesting that the rectangle groove cannot be fully filled by one pass and the defect of lack of fusion may occur in next pass. Therefore, the suggested $W_G$ for stable process is at the range from 4 to 8 mm, which is obviously lower than that of narrow gap arc welding, usually 10 to 18 mm [18,19]. During NGHW, since laser keyhole has a fixed position and the metallic vapor erupted from it has high conductivity, the arc plasma can be fixed and compressed by laser beam according to the minimum voltage principle, which suppresses the arc root wandering or the arc generation at sidewalls [20,21]. This laser-arc interaction stabilizes the arc column, and is benefit for the narrowing of groove.

### 3.2. Effects of SCE on energy transfer

Since the nature of the SCE is the variation of energy transfer, which is achieved by affecting the behaviors of arc column and laser-induced plasma, the effects of narrow gap on them are discussed to establish the quantitative characterization method of the SCE in NGHW.

#### 3.2.1. Effect of SCE on arc column

In the narrow gap of NGHW, the shielding gas is accelerated, which strengthens the cooling of the arc column in comparison of the hybrid welding without narrow gap (OpenHW). According to the minimum voltage principle, the arc column would be contracted in order to reduce the energy consumption, as shown in Fig. 5. It concentrates the arc energy, and increases the energy transfer efficiency.

On the other hand, according to the law of Biot-Savart [22,23], electromagnetism induction phenomenon generates between a point in the space and the wire. The magnetic induction intensity B is formulated as follows:

$$B = \int_l \frac{\mu_0 I}{4\pi} \frac{dl\,\overrightarrow{e_R}}{R^2} \tag{1}$$

where, $\mu_0$ is vacuum permeability, I is the current of wire, dl is unit wire length, $e_R$ is unit current vector, R is distance between the wire and the point in the space.

Assuming that wire length is infinite, Eq. 1 can be simplified as follows:

$$B = \frac{\mu_0 I}{2\pi R} \tag{2}$$

Eq. 2 indicates that the B is inversely proportional to the R when the I is constant. For NGHW, as shown in Fig. 6b, induced magnetic field generates surrounding the arc column. Eq. 2 suggests that the B at the sidewalls increase with the decrease of groove width because the R is equal to $W_G/2$. As a result, the sidewall material would be magnetized since it is ferromagnetic. It induces another magnetic field and strengthens the induced magnetic field caused by live wire [10,24,25]. The smaller the groove width, the greater the magnetization degree of

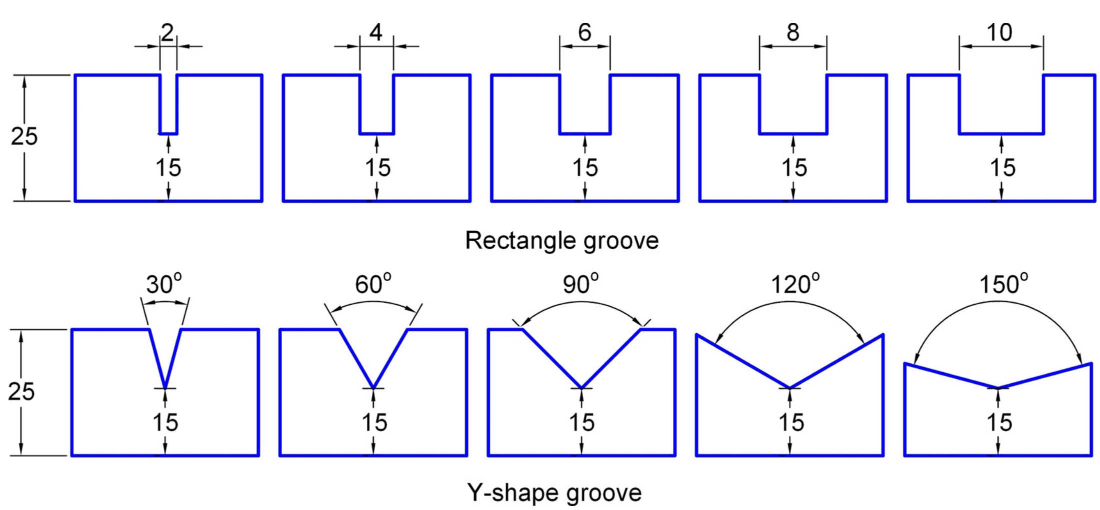


**Fig. 2.** Dimension of rectangle and Y-shape grooves.