Weld Defect Prevention for Fillet Welded Joints on Steel Plates Coated with Shop Primer using Hot-wire Laser Welding*

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Shop primer is a predominant cause of pits and blowholes during fillet welding using a conventional CO₂ arc welding process. The hot-wire laser welding process for fillet welds employs a reflected laser beam incident on a molten pool for melting the base metal, and produces a weld bead with an extremely low dilution of base metal. In this study, weld-defect prevention in hot-wire laser welding as applied to steel plates coated with shop primer was investigated by examining the vaporization of the shop primer at the molten pool front and beneath the stiffener at the root region. A melting technique employing a reflected laser beam incident on the molten pool surface can efficiently remove the shop primer at the molten pool front during welding. The quantity of several gases and metallic vapors emitted during decomposition of the shop primer at a root was reduced markedly during hot-wire laser welding under extremely low base metal dilution. The above features of the hot-wire laser welding process achieved sound fillet welds without pits and blowholes.

Key Words: Shop primer, Pit and blowhole, Hot-wire Laser welding, Fillet welding, PSPC

1. Introduction

In many industries where fabricating periods are long, such as shipbuilding and bridge construction, shop primers are generally used to protect steel plates from rusting. Zinc is the primary element of shop primers, and its melting point (907 °C) is much lower than that of steel. Nevertheless, shop primer can be a predominant cause of pits and blowholes during fillet welding (Fig. 1) because it decomposes into several gases and metallic vapors during CO₂ arc welding. In the ship building industry, the Performance Standard for Protective Coatings (PSPC) for dedicated seawater ballast tanks on all new ships and double-sided skin spaces of bulk carriers was adopted by the IMO (International Maritime Organization) in 2006. Following acceptance of this standard, production costs increased for the welding stage as sputters, pits and sharp toe shapes must be removed or repaired before the painting stage. A novel welding process that not only has high efficiency and high welding speed but also prevents defects from forming has been wanting.

Hot-wire laser welding of fillet welds has been investigated by the authors. This process has many features, e.g. a low heat input, low deformation, high efficiency and flexibility in weld-bead formation. In addition, this process can produce a weld bead with the extremely low dilution of base metal because an appropriate reflected laser beam on the molten pool surface can slightly fuse the base metal. It is generally considered that pits and blowholes in fillet welds of steel plates coated with shop primer are caused by several gases and metallic vapors during the decomposition of the primer originating from regions around the root of the fillet weld and the molten pool front. Therefore, it can be expected that these features of the hot-wire laser welding process can prevent defect formation on steel plates coated with shop primer during fillet welding.

In this study, the processes involved in providing weld defect prevention using hot-wire laser welding were investigated in two aspects. First, the vaporization of the shop primer near the molten pool front during hot-wire laser welding was examined in-situ using a high-speed camera. Second, the vaporization of the shop primer beneath the stiffener at the root region was examined by analyzing various cross-sections of the weld bead.

2. Materials and experimental procedure

NK-K36A steel plates and JIS YGW11 filler wire were used as test materials. The chemical compositions of the test materials and shop primer are listed in Table 1; the primary element of the shop primer is clearly Zn. Figure 2 shows a schematic illustration of the experimental setup. A diode laser oscillator and a hot-wire
power source were used for fillet welding. A high-speed camera was used for in-situ observations during welding. The welding conditions are listed in Table 2. The optimum welding conditions such as a laser power of 4 kW, welding speed of 0.3 m/min and a laser spot diameter of 7.5 mm (defocused laser) were used to obtain a sound bead without defects. Under these conditions, in-situ observations were performed to investigate the effects of melting in the molten pool front on shop primer vaporization during welding. To investigate the effect of a dilution and penetration at a root of a fillet weld on the defect formation, a range of welding conditions were used including laser power from 4 to 6 kW, as well as welding speeds of 0.5 m/min and a laser spot diameter of 4 mm (just focused).

3. Results and discussion

3.1 Removal of shop primer by reflected laser beam in the molten pool front

Figure 3 presents a magnified high-speed image at the molten pool front during welding using the optimum conditions employing a relatively large laser spot diameter. The dashed line indicates the root position of the fillet joint. The black region with low brightness (A in Fig. 3) and white region with high brightness (B in Fig. 3) were observed in the molten pool front continuously in the high-speed movie during welding. The average width of the black region was about 1.2 mm.

Figure 4 shows the results from an EDX analysis, SEM, and macro-images at the welded bead front in the same region. Red lines on the SEM and macro-images mark the EDX analysis location. Zn, the main element of shop primer, is detected in the base metal. In contrast, the region where shop primer was removed completely can be seen just in front of the weld bead; its width is about 1.2 mm. Moreover, shop primer decreases gradually at the front of the region where shop primer was removed. In addition, the SEM image shows entirely different surface appearances in these regions compared with that in an original base metal surface.

It is generally known that the laser beam reflects from the molten pool surface because of the high optical reflectivity of liquid metals, especially when the laser beam irradiation is of low energy density. Clearly the molten pool front and the shop primer on the plate surface are heated up rapidly to melting point and boiling point by the reflected laser beam. The Zn in the shop primer melts and vaporizes in the molten pool front, the white region in the high-speed image, and hence thins the shop primer down rapidly in this region. Ultimately, the shop primer is vaporized and removed completely from the region, the black region in the high-speed image immediately in front of the molten pool.

![Fig. 2 Schematic illustration of experimental setup.](image)

![Fig. 3 Magnified high-speed image during welding.](image)

![Fig. 4 SEM and EDX analysis result on weld bead front.](image)
3.2 Effect of penetration at root on defect formation

In conventional CO₂ arc welding, it has been reported that a high heat input and perfect contact conditions have increased pits and blowholes in fillet welds\(^5\). It is suspected that penetration at the root of the fillet welded joint affects pit and blowhole formation as the shop primer on the main plate surface beneath the stiffener plate must melt and vaporize during welding. The gas and metallic vapor byproducts find a path through to the molten pool that lead of the creation of pits and blowholes in the weld bead.

Figure 5 shows examples of bead shapes created under CO₂ arc welding and hot-wire laser welding. Extremely small penetrations and a heat-affected zone at the root region, that is, beneath the stiffener, are produced under hot-wire laser welding compared with CO₂ arc welding. It is believed that the above features of hot-wire laser welding have the potential to mitigate defect formation at the root region. For this reason, the effect of penetration at the root region of a fillet joint on pit and blowhole formation was investigated using a relatively small laser spot size (just-focused condition) and changes in laser power to vary the penetration depth.

Cross-sectional images were taken at laser power of 4, 5, and 6 kW under a just-focused condition (Fig. 6). A deeper penetration at the root is observed with increasing laser power when a relatively smaller spot size (4 mm) was used. Notably large blowholes are also observed when a high laser power was employed (5 and 6 kW); that is, when deep penetration at the root was created.

Figure 7 gives the observed and EDX analyzed location along the fillet weld. SEM and EDX analyses were performed on the main plate surface beneath the stiffener in a straight bead section after the stiffener was cut off from the welded joint. Figure 8 shows the EDX analysis result and SEM image on the analyzed region for the 4 kW laser power and a relatively small spot size (4 mm). A macro-image around the analyzed region appears as an inset in Fig. 8. Red lines on the SEM and macro images represent the EDX analysis location, and Zn quantities from the shop primer were obtained in the EDX analysis. The penetrated region and heat-affected region are observed beneath the stiffener in the SEM image (Fig. 8). From the EDX analysis, the shop primer is seen to be completely removed in the penetrated region and decreases gradually in the heat-affected region. The total width where shop primer is removed (penetration depth and heat-affected region) was 2.65 mm for the 4 kW laser power and small spot size (4 mm).

The width of shop primer removed and the penetration depth beneath the stiffener plate at the root of the fillet welded joint were measured under three laser power conditions of 4, 5 and 6 kW using a spot size of 4 mm, and under a laser power condition...
of 4 kW using a spot size of 7.5 mm (Fig. 9). Increases in the area of shop primer removed and the penetration depth are clearly observed with increasing laser power for the small spot size. In contrast, when a relatively larger spot size was used, no changes in both area and penetration depth were observed. It is believed that decomposition of the shop primer into gases and metallic vapors do not occur at the root for larger spot sizes.

It is clear that penetration at the root of the fillet welded joint affects markedly pit and blowhole formation because the amount of gases and metallic vapors initiating from shop primer decomposition should increase with increasing penetration depth. Moreover, the proposed hot-wire laser welding process using a relatively large laser spot size can markedly decrease pits and blowholes as this process produces extremely small penetration.

4. Conclusions

In this study, the weld defect prevention process using hot-wire laser welding was investigated for a fillet joint. The following features of hot-wire laser welding produced sound welds without pits and blowholes.

1. A melting technique employing a reflected laser beam on the molten pool surface removes the shop primer efficiently in the molten pool front during hot-wire laser welding.

2. The amount of gases and metallic vapors arising from decomposition of the shop primer at the root is reduced markedly during hot-wire laser welding with extremely low base-metal dilution.

Acknowledgments

This research was supported by the Hiroshima Prefectural Institute of Industrial Science and Technology in the research project.

References