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The effect of electromagnetic forces on the penetrator formation during high-frequency electric resistance welding

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ABSTRACT

During high-frequency electric resistance welding (HF-ERW), the electromagnetic force induced by the high-frequency electric current was studied to improve the understanding of penetrator formation mechanism. ERW melting zone behavior is investigated by the cinematography and the three-dimensional numerical analysis of electromagnetic field around molten metal bridge. Based on the results, the penetrator formation is mainly influenced by the narrow gap shape, the variation of electromagnetic forces along the narrow gap, the molten metal bridge traveling speed, and the second bridge formation frequency. Electromagnetic force acting on the molten metal bridge is rapidly decreasing as the bridge is traveling away from the apex point. The 'comet' shape narrow gap produced by the variation of Lorentz forces makes the bridge pushing pressure decrease. Due to the decrease of electromagnetic force and pushing pressure, the sweeping speed of molten metal bridge slows down until the bridge reaches the welding point. Previous molten metal bridge traveling is arrested when the next bridge is formed before the previous bridge arrives at the welding point. Thus, the molten metal and oxide are refilled into the narrow gap due to the capillary force and then remained as a penetrator. According to the analysis of penetrator formation mechanism, the new penetrator formation model is proposed.

1. Introduction

Numerous straight seamed small and medium size diameter pipes are manufactured by the high-frequency electric resistance welding (HF-ERW) process. As frequency increases, the current tends to flow near edge of strips due to skin effect and proximity effect (Saito et al., 1986), generating the high current density along the strip edges. Thus, this concentrated current adjacent strip surfaces generated joule heat that produces the molten metal that forged at the upsetting roll stand. In this process, there are two types of weld defects such as cold weld defect and penetrator defect (Watanabe et al., 1986; Kyogoku et al., 1983). The cold weld defect as an oxide inclusion in the form of continuous thin film at the weld bond line has been observed in the low heat input power range because the amount of melting on strip edges is not sufficient enough to make the sound bonding. To prevent the incomplete bonding, high heat input power should be applied to get the sufficient melting on strip edges. When the large heat input is applied on the strip edges, a pancake type oxide inclusion is observed that is called penetrator defect although the weld surface looked sound weld. Also, the size of penetrator in a range of a few millimeters to centimeters is critical to determine the mechanical properties of the pipe weldment.There

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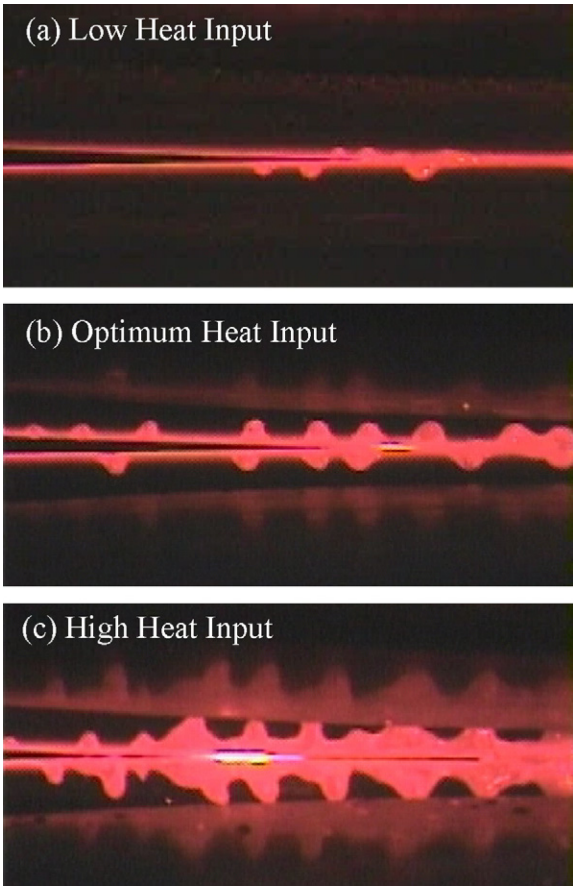

Fig. 1 – ERW melting zone appearance by high-speed video camera.

were many reports for the optimization of heat input power for various strip conditions and pipe size. Haga et al. (1980, 1981) proposed three kinds of welding phenomena according to the heat input power range, and reported the penetrator defect was formed at the third type weld where much high heat input power applied. Especially, the surface tension was found out to be the major driving force to refill the molten metal and oxide into narrow gap when the bridge was formed at apex point. Those refilled oxides became the penetrator when the squeeze force is insufficient.

To get the defect free ERW joint, it is necessary to understand the ERW mechanism in terms of high-frequency electric current. In the previous report (Choi et al., 1999, 2004), the authors proposed a new mechanism for the penetrator formation during the HF-ERW process. The results showed that the flashing occurred between strip edges around the apex point resulted in the formation of molten metal bridge that always traveled toward the welding point with very high speed. This moving bridge swept molten metal mixed with oxides from the narrow gap due to the driving force generated by asymmetric distribution of electromagnetic field around the bridge. The occurrence of penetrator was highly dependent on the sweeping speed and sweeping distance. For the detailed understanding of new ERW mechanism, a quantitative analysis for the effect of electromagnetic force on the narrow gap formation and molten metal bridge traveling was needed.

In this article, the ERW melting zone behavior is investigated by using three-dimensional numerical analysis of electromagnetic field around molten metal bridge to demonstrate a penetrator formation mechanism at the ERW joints in detail. Also, the high-speed cinematography of the narrow gap was used to show the rapid moving behavior of molten metal bridge. Based on the results, the factors affecting the penetrator formation, such as narrow gap formation mechanism and bridge traveling behavior, are studied and the new model for the penetrator formation is proposed.

2. Narrow gap formation mechanism

According to the heat input power during ERW process, three types of narrow gaps formed between an apex point and a welding point in Fig. 1 are observed by high-speed video camera. In the case of low heat input power shown in Fig. 1(a), a cold weld defect was formed due to insufficient melting of strip edges. Fig. 1(b) shows the melting zone at the optimum heat input power that produces sound bonding without severe defects. The melting zone with high heat input power as displayed in Fig. 1(c) is usually containing the penetrator defect. Fig. 2 shows the penetrator which is the oxide inclusion left in the bond line appeared even on the surface. Particularly, when the penetrator is located within the bond line, the penetrator will deteriorate the mechanical properties of weld joint although the weld surface looked non-defects bonding.

Penetrator formation which usually occurred at the excessively high heat input power conditions is affected by the narrow gap shape. Narrow gap shape variation according to

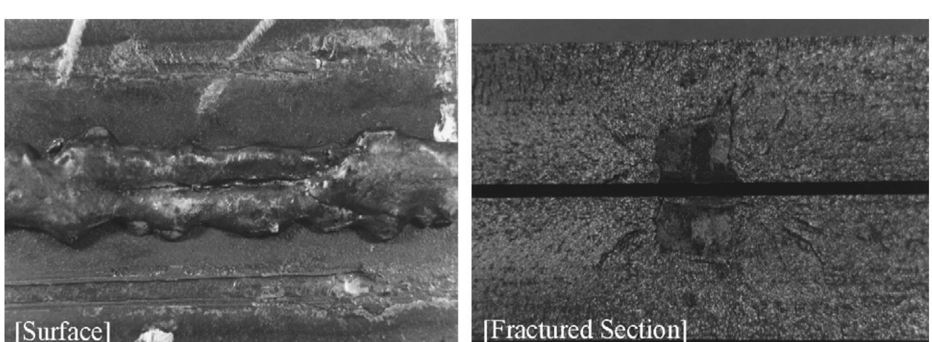

Fig. 2 – Appearances of refilled molten metal causing penetrator.