Weld Defect Formation Phenomena during High Frequency Electric Resistance Welding

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Abstract

In this study, welding phenomena involved in formation of penetrators during high frequency electric resistance welding were investigated. High speed cinematography of the process revealed that a molten bridge between neighboring skelp edges forms at apex point and travels along narrow gap toward to welding point at a speed ranging from 100 to 400 m/min. The bridge while moving along the narrow gap swept away oxide containing molten metal from the gap, providing oxide-free surface for a forge-welding at upsetting stand. Frequency of the bridge formation, travel distance and speed of the bridge were affected by the heat input rate into strip. The travel distance and its standard deviation were found to have a strong relationship with the weld defect density. Based on the observation, a new mechanism of the penetrator formation during HF ERW process is proposed.

1. Introduction

High frequency electric resistance welding (HF ERW) process has been used extensively in manufacturing straight seam steel pipes. In this process, strip is formed into a circular shape in a continuous roll-forming mill, the seam is brought together under a small amount of pressure at a upsetting roll stand, and a high frequency current concentrated to adjoining edges of the strip coalescences the edges to produce a continuous forged weld. High-frequency current in metal conductors tends to flow at the surface of the material at relatively shallow depth, which is commonly called the skin effect. For example, the skin depth of current penetration in steel at 800°C is about 0.8mm at 450kHz[1]. As the concentrated high-frequency current heats only a small volume of the metal just where the weld is to take place, the process is extremely energy efficient, and welding speeds can be as high as 200 m/min. These characteristics make the process very economical. In addition, as the molten metal containing oxides and impurities on faying surface of the edges is squeezed-out from the joint interface during the forge welding, the weld is relatively free of weld defects, especially the defects associated with weld solidification. The steel pipes produced utilizing the HF ERW process, therefore, have been extensively used in critical applications requiring stringent weld qualities, such as line and drilling pipes.

In order to produce a high-quality weld during HF ERW process, welding variables should be adjusted such that two edges are at welding temperature when they reach the welding point. The variables include welding speed, heat input rate, thickness of the strip, 'vee' angle at the welding point, length of the high-frequency current path, and forging pressure. If the temperature of the edges is lower than the welding temperature, oxides on the edge surfaces may not be squeezed-out, leading to a defect, so-called cold weld. On the other hand, if the strip edge surface becomes molten excessively due to high heat input rate, weld defect so-called penetrator was reported to occur[2]. In addition to these weld defects, defects such as paste weld and hook crack that are mainly related with chemical compositions and non-metallic inclusions in the strip are also observed in the HF ERW weldment.

Among the defects, penetrator is a more frequently observed one and affects mechanical properties of the weld more critically. Penetrator is a mixture of iron-, manganese-, silicone-, and/or aluminum-oxide in iron matrix. When the weld containing the penetrator is under stress, the defect may cause brittle fracture in the weld. Several studies have been conducted to investigate the mechanism of the penetrator formation. In their classical studies on HF ERW, Haga et al [2,3] classified welding phenomena of HF ERW by three types depending on the characteristics of narrow gap developed near welding point. The narrow gap is a region near welding point, where the gap between strip edges is very narrow. The gap forms when the rate of exclusion of molten metal from the edges of strip due to electromagnetic repulsive force is same as the approaching speed of the strip edges that is solely determined by the strip speed and vee angle. According to the classification, in type I, the narrow gap is very short in length under insufficient welding heat input rate and in type II, the gap maintains a relatively constant length under a moderate heat input rate. As the heat input rate is increased further, length of the gap is increased also but its length changes significantly with time, which was classified as type III welding phenomenon. Change in the length of gap was attributed to change in impedance of the current path in the strip and led to variation in welding point. Penetrator formation has been observed mainly in this type of welding condition and refilling of molten metal containing oxides and impurities into the gap during the changes in gap length has been attributed as main mechanism of penetrator formation in the weld.

Penetrator, however, was observed even under the type II welding conditions[4]. In addition, several researchers indicated that sparking or flashing occurs at the apex point during HF ERW process[5], but detailed studies on the phenomenon have not reported. Thus in this study, mechanism of the penetrator formation was investigated in more details in combination with the flashing at apex point. At an instant of flashing, electromagnetic pinch force should decrease significantly at the narrow gap since a significant fraction of current is diverted through the flash at apex point. This might result in a significant effect on the flow of molten metal into the gap. Thus, in this study, HF ERW process was investigated using a high-speed video camera as well as high-speed cinematography. Based on these observations, a new formation mechanism of penetrator was proposed in conjunction with the flashing at the apex point.

2. Experimental Procedures

HF ERW was conducted using a pipe mill (SeAh Steel Co. LTD, Pohang, Korea) and an ERW simulator (POSCO, Pohang, Korea). Welding speed was in a range from 10 to 40 m/min and strip thickness was 9.5 mm. Heat input rate was changed in a range such that the three types of welding phenomena could be realized. The welding phenomena were observed using high-speed cinematography and high-speed video camera(NAC Inc., Tokyo, Japan). The framing range was from 1,000 to 10,000 pictures per second (pps) with the high-speed camera and from 1,000 to 2,000 pps with the video camera. In order to enhance the observation of the flashing at the apex point, neutral density, red color, and polarizing filters were attached to the camera lenses.

Area fraction of weld defects was measured along the bond line for a length of 50cm using an optical microscopy combined with an image analyzer. The fraction was measured by machining the weldment by 1/4 of the strip thickness following by micro-polishing. More detailed analysis for the bond line microstructure were made by scanning electron microscope (SEM)(Model : Hitachi, Japan) /energy dispersive spectroscopy(EDS)(model : Kevex, USA).

3. Results and Discussion

3.1 Flashing and Bridge Formation

Fig. 1 shows a high-speed cinematographic image of skelp edges just prior to welding point during HF ERW. The edges were molten well ahead of welding point and the molten metal was repelled from the surface of the strip edges to form spherical beads on surface of the skelp. Near the welding point, size of the bead was increased due to the increased amount of the repelled molten metal and the narrow gap was developed near the welding point as indicated Haga et al[3,4]. The length of the gap was measured from the images of the high-speed cinematography as a function of heat input rate (Fig. 2). The welding speed was kept at 18 m/min. As the heat input rate was changed from 200 to 240 kW, the narrow gap length was increased linearly from 10 to 40 mm.

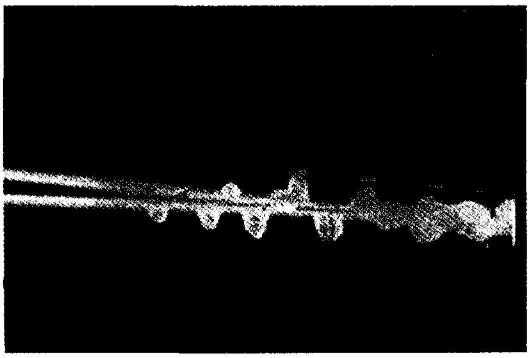


Fig. 1 Typical melting behavior of skelp edges during the HF ERW.

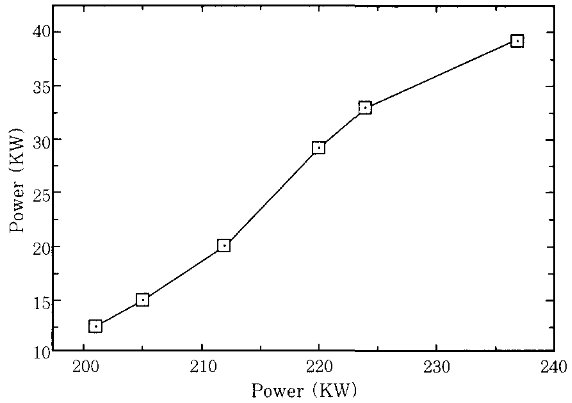
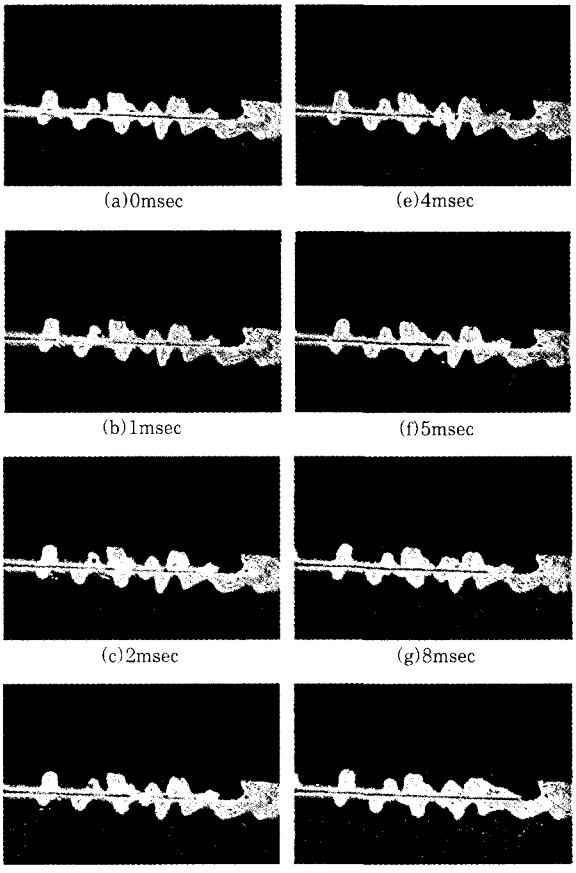


Fig. 2 Narrow gap length as a function of heat input rate. Welding speed was 18 m/min and strip thickness 9.5mm.



(a)0msec (e)4msec

(b)1msec (f)5msec

(c)2msec (g)8msec

(d)3msec (h)12msec

Fig. 3 Sequential images of flashing and bridge movement during HF ERW

An interesting phenomenon noted in Fig. 1 is flashing at apex point. The flashing was not discernable when the filters were not employed for the high-speed cinematography. The flashing occurred very consistently at a given welding condition and resulted in a formation of a bridge at the apex point. Just before the flashing, images near the apex point became slightly obscured, probably due to Fe vapor formed due to the joule heating. The flashing occurred in the whole range of heat input rate tested in this study and its frequency was in a range 0.1 to 5 kHz. At low heat input rate, the rate of flashing was measured to be relatively high. As the heat input rate is increased further, the arcing rate was decreased and then increased again.

Just after the flashing, a bridge formed between the strip edges was resulted and traveled along the narrow gap at a speed much higher than the welding speed of the strip. Fig. 3 shows sequential images of the flashing and bridge movement during HF ERW. The images were filmed at a rate of 10,000 pps. As illustrated in the figure, the flashing occurred at the apex point. Just after the flashing (one frame later, i.e., less than 0.1 msec), a bridge between the two edges of the strip was formed. As the time progressed, the bridge traveled towards to the welding point at a much faster speed than that of the strip. The speed of bridges was estimated by measuring the time elapsed to travel the narrow gap and was found to be also affected by the heat input rate (Fig. 4). At the heat input rate is increased from 201 to 237 KW, its speed increased from 159 to 375 m/min, peaking at an intermediate heat input rate. At higher heat input rates, the flashing was observed not only at the apex point but also in the narrow gap. The speed of the bridge became decreased when the flashing starts to occur in the narrow gap.

As the bridge travels along the narrow gap, molten metal forming a skin of strip edge was also swept along with the bridge towards the welding point. As the bridge traveled at such a high speed, it resulted in violent ripples on molten beads upon colliding at welding point. These observations indicate that not only the repulsive electromagnetic force but also the sweeping action of the bridge expels the molten metal away from the narrow gap, providing oxide free surface for the forge weld.

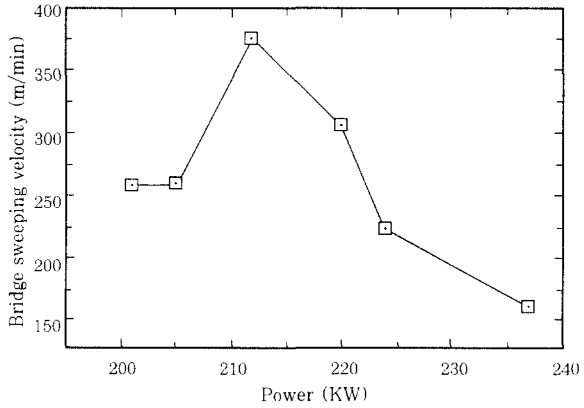


Fig. 4 Sweeping speed of bridge as a function of heat input rate.

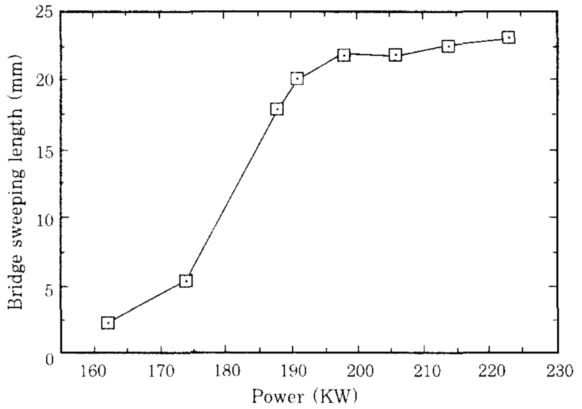


Fig. 5 Sweeping distance of bridges as a function of heat input rate.

The sweeping action of the bridge along the narrow gap was found to occur in the whole range of the welding heat input rate, but differing in its frequency and distance depending on the rate. Fig. 5 shows the distance of the sweeping motion as a function of heat input rate. The distance of the bridge sweep was less than 2 mm when the heat input rate is 162 KW. As the heat input rate was increased to 223 KW, the distance was increased to 25mm. As the heat input rate was increased further, the distance decreased again. The decrease in sweep distance occurred also when the flashing followed by the bridge formation occurred not only in the narrow gap zone but also at the apex point. The formation of the bridges in the narrow gap zone should have affected the sweep action of the bridges.

3.2 Mechanism of Flashing and Bridge Vovement During HF ERW

From this study, it was noted that the arcing at the apex point and the bridge movement along the narrow gap occur during most of HF ERW process and that should bear a significant relationship with the quality of its weldments. The flashing during the HF ERW occurred in two different types: one with a strong flash followed by expulsion of metal bridge and the other with a soft flash followed by the formation of bridge. The former arcing was observed when the protrusions such as metal particles on the skelp edges meet together forming a short circuit and influenced by the preparation of the skelp edges rather than by welding conditions. The latter was observed to occur even when the edges are not touched together and was the main flashing phenomenon. As described in previous section, the frequency of the arcing was affected by the welding conditions such as welding speed, heat input rates, and apex angle.

Flashing between free standing electrodes, between the skelp edges in this case, is ruled by Paschen discharge phenomenon, of which break-down voltage, V, is given by equation 1) [6]:

$$V = B \cdot \frac{pd}{k + \log pd} \quad \text{equation} \qquad (1)$$

where p is the pressure, d is the distance between electrodes, B and k are constants. The break-down voltage is a function of "p · d" value and reaches 360 volts when the value is around 5 under air atmosphere[6]. The voltage was predicted to decrease by a factor of 0.8 when the frequency is increased from 10^1 to 10^3 kHz. This estimated break-down voltage is somewhat higher than the voltage applied between the strip during HF ERW process, which is between 70 to 120 volts. In addition, the break-down voltage should decrease when the atmosphere contains more easily ionizable species such as metallic vapors. Therefore, the flashing observed at the apex point might be caused by the Paschen discharge between free standing skelp edges.

Upon the flashing between skelp edges, a significant fraction of welding current is expected to be diverted through the arc column. The diversion should reduce the current flowing around the narrow gap and decrease the electromagnetic repulsive force on the liquid metal on the skelp edges. Under this condition, repelled molten metal may reflow into the narrow gap, which should provide a favorable condition for the bridge formation. In addition, uneven pressure distribution near the arc column of the flash may also promote the formation of the bridge.

Once, the bridge was formed near the flashing point, it traveled always towards the welding point at a much faster speed than that of the strip, suggesting a presence of strong external driving force for the movement. It is believed that the force is due asymmetric distribution of magnetic flux around the bridge. When a significant fraction of welding current is diverted to the bridge, magnetic fluxes due to the currents flowing in skelp edges and in bridge are of same direction in the left-hand side of bridge, but those are opposite in the narrow gap as illustrated in Fig. 6 As the electromagnetic pinch force on the bridge is given by vector product of current density in the bridge and magnetic flux, the pinch force on the left-side of the bridge should be larger than that on the right-hand side of the bridge. Although a further study is still needed to quantify the driving force, a rough estimation of the force indicated that the electromagnetic force is large enough to drive the bridge movement at a speed observed in this study[7].

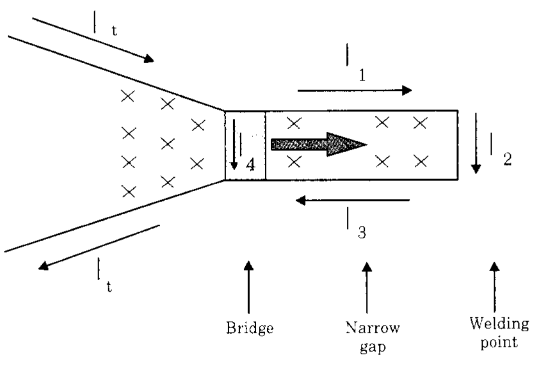


Fig. 6 Schematic illustration of magnetic flux density distribution around a bridge.

3.3 Relationship Between the Bridge Movement and Weld Defect in HF ERW

Since the bridge sweeps the molten metal containing oxides out of the narrow gap and faying interface, the disruption of the sweeping action is expected to result in inclusions of oxide particles in the weldment. The sweeping motion of the bridges, however, was observed to be affected by heat input rate. Fig. 7 shows standard deviation of the travelling distance and traveling distance of bridge along narrow gap. At low heat input rates, the deviation is very small and almost constant, which means that once the bridge is formed, it sweeps through the narrow gap completely to the welding point. As the heat input rate is increased further, the deviation became increased. In other words, a significant fraction of the sweeping bridges do not reach the welding point at the high heat input rates. This should be due to the diversion of welding current to the newly formed bridge. As the bridge is stopped on the way to the welding point in the narrow gap, narrow gap between the bridge and the welding point was observed to be refilled with the molten metal repelled from the narrow gap (Fig. 8). Refilling of the narrow gap was observed to occur very rapidly, less than 2~5msec.

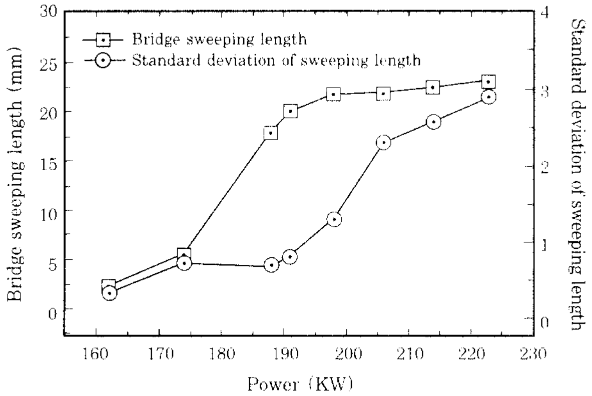
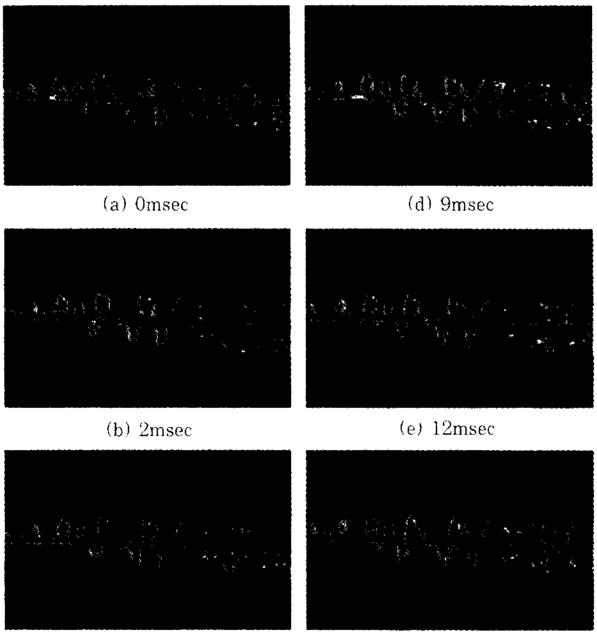


Fig. 7 Sweeping length and standard deviation of bridge traveling along narrow gap measured as a function of heat input rate.



(a) 0msec (d) 9msec

(b) 2msec (e) 12msec

(c) 5msec (f) 15msec

Fig. 8 Refilling of molten metal into narrow gap after flashing.

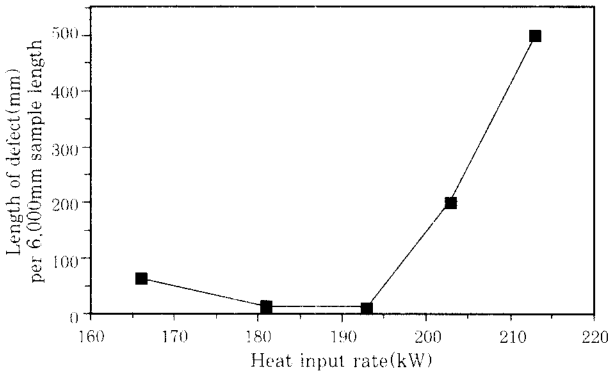


Fig. 9 Effect of heat input rate on the fraction of oxide inclusions in weld.

Fig. 9 shows a relationship between heat input rate and fraction of oxides inclusions in welds. When compared with Fig. 9, the lowest defects density was noted when the standard deviation of the bridge movement is minimum. These results indicate that the weld defect density in the weld of HF ERW process is strongly related with the sweeping action of the bridge. Fig. 10 show a cross section of the weld defect containing the penetrator, which is analyzed to include silicon-, manganese-, and iron-oxide.

4. Conclusions

The weld defect in the HF ERW process, especially the penetrator, was observed to be

Fig. 10 Cross section of weld containing penetrator.

closely related with the movement of the bridge formed after flashing near apex point. The bridge swept molten metal on the surface of strip edges at a very high speed towards to welding point and its movement seems to be caused by asymmetric distribution of electromagnetic force around bridge. At welding conditions where the bridge sweeps completely the narrow gap, the weld contained lesser weld defects. At higher welding heat input rates, sweeping action of the bridge became irregular and led to refilling of molten metal into the narrow gap. At these conditions, the density of the weld defect, especially the oxide inclusion, became increased. The refilling action of the molten metals into narrow gap during the irregular sweeping action seems to be the main reason for the formation of penetrator defect in weld of HF ERW process.

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