# The Effects of Welding Conditions on Allowable Heat Input in Repair Weld of In-Service Pipeline

Y. P. Kim, J. H. Baek, W. S. Kim, I. W. Bang and K. H. Oh

## Abstract

Nowadays, repair welding on in-service natural gas pipeline is a matter of primary concern of gas company. The main purpose of this study is to investigate the effects of welding conditions on the allowable heat input for crack-free welds and welds without burn-through onto in-service natural gas pipeline. First of all, single pass weld bead on plates of the various thickness was deposited to evaluate the penetration of weld metal, the depth of heat affected zone and the hardness of repair weld under various welding conditions. Also, finite element analysis has been conducted to validate experimental results of bead-on plate welds and to develop appropriate model for repair welding.

The welding experiments of bead-on-plate weld confirmed the influence of plate thickness, heat input and welding process on safety. And, the finite element model was demonstrated by comparing experimental results. The agreement between the computed and measured values was shown to be generally good. Therefore, It is possible to predict the safety of repair welding under various welding conditions with experimental results and finite element analysis model.

**Key Words :** Repair weld, Natural gas pipeline, API 5L X65, Heat input, Burn-through, Vicker's hardness.

# 1. Introduction

The defects on the pipelines occur by construction faults, corrosion, third-party interference and ground movement. When a segment of a pipeline is found to be defective, one of repair methods is the way, which consists of removing its contents and cutting out the defective segment after shutting down the pipeline. However, the cost is extremely high in terms of lost revenue and the disruption of service. Therefore, most pipeline companies have developed in-service repair methods without removing the line from service.[1] And these repair methods are practiced widely throughout the natural gas, petroleum, and petrochemical industries.

In general, so as to avoid removing the line from service, direct deposition of weld metal and welding of appurtenances such as full- encirclement sleeve, patches, stopple fittings and half-sole are required.

There are three primary concerns with welding on in-service pipelines. The first concern is for welder safety because of the possibility of blowing up pressurized pipe during welding. The second concern is for the integrity an accelerated cooling rate as the result of the flowing contents' ability to remove heat from the pipe wall in service. These welds, therefore, are likely to have high heat-affected zone (HAZ) hardness values and to be susceptible to hydrogen cracking. The third concern is for the load carrying ability, such as tensile strength, fracture toughness and fatigue strength. Prior studies provide datum for the separate effect of welding conditions; welding process, heat input and flow rate, and mechanical properties[2-4]

Nowadays, repair welding on in-service gas pipeline is a matter of primary concern of gas company. Therefore, this study was undertaken to investigate the effect of welding conditions on the allowable heat input of repair weld onto in-service natural gas pipeline.

First of all, single pass weld bead on plates of the various thicknesses was deposited to evaluate the penetration of weld metal, the depth of HAZ and the hardness of repair weld under various welding conditions. Also, finite element analysis has been conducted to develop appropriate model for repair welding. This analysis model was validated by means of data obtained on experimental results of bead-on plate welds. The results of analysis are temperature profile and cooling rate under various welding conditions.

# 2. Experimental procedure

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**Table 1** The chemical compositions (wt%) of the steel plate and weld metals welded by SMAW and GTAW

| Elements | C | Mn | P | S | Si | Nb | V | Ti | Cu | Ni | Cr | Mo | $C_{IIW}^*$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| API 5L X65 Plate | 0.091 | 1.51 | 0.024 | 0.002 | 0.30 | 0.060 | 0.057 | 0.048 | 0.031 | 0.019 | 0.031 | 0.003 | 0.36 |
| SMAW weld metal | 0.065 | 1.27 | 0.018 | 0.005 | 0.56 | 0.017 | 0.021 | 0.041 | 0.029 | 0.561 | 0.041 | 0.273 | 0.38 |
| GTAW weld metal | 0.067 | 1.51 | 0.023 | 0.014 | 0.95 | 0.013 | 0.013 | 0.029 | 0.125 | 0.026 | 0.046 | 0.005 | 0.34 |

$C_{IIW} = C + Mn/6 + (Ni+Cu)/15 + (Cr+Mo+V)/5$.

SMAW and GTAW processes were applied to bead-on-plate welds to compare the influence of welding process. The SMAW welds were made with 2.6mm, low hydrogen electrode-E9016-G. GTAW welds were carried out with 2.4mm, ER70S-G electrode. The chemical compositions of the API 5L X65 steel plate and weld metals welded by SMAW and GTAW are listed in Table 1.

Bead-on plate welds were deposited on a 100mm wide and 200mm long plate and the plates had thickness of 4, 6, 8 and 10mm. The schematic geometry of welding plate is shown in Fig. 1. Recording equipment was used for measuring the welding voltage, welding current and welding speed. The initial temperature of plates was from 0℃ to 15℃.

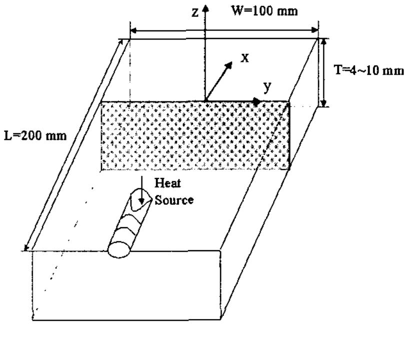

**Fig.1** The schematic geometry of welding plate

The bead-on-plate welds were sectioned and polished so that an etched section would show the distribution of the weld metal and the HAZ for each test. The penetration of weld metal and depth of HAZ were measured from the bead-on-plate welds as shown in Fig. 2. Also, the hardness of coarse grained HAZ (CGHAZ) in bead-on-plate welds was measured as shown in Fig. 2.

## 3. Computational procedure

The commercial finite element code, ABAQUS[5], was used for heat transfer analysis in bead-on-plate welds.

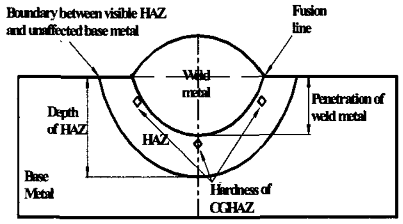

**Fig.2** The cross sectional view of the bead-on-plate weld

The finite element mesh is shown in Fig. 3. The two dimensional cross section perpendicular to the welding direction was modeled, and due to symmetry only half of the plate was analyzed. The mesh is composed of 368 nodes and 330 elements and because the temperature gradient is very severe in weld zone, the weld zone was refined for the accurate thermal analysis.

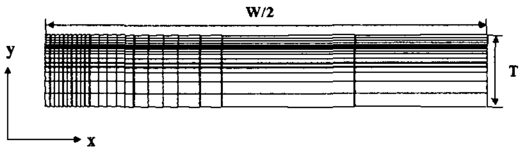

**Fig.3** Finite element mesh

The heat input by the moving heat source was modeled with the double ellipsoidal power density distribution model.[6] But it is difficult to take into account the weaving effect of the oscillating arc across the weld centerline with the heat source model mainly due to the small diameter of electrode and low heat input. So the heat source model was modified as the distribution of heat in the width direction was uniform.[7]

The power input is chosen from the gross power and the arc efficiency. The arc efficiency used in the analysis is 0.75 in SMAW and 0.40 in GTAW. The temperature dependent thermal property and latent heat effect of fusion were considered. Boundary heat transfer was modeled by heat convection and radiation at all the surfaces of plate.

## 4. Results and discussion

### 4.1 The prediction of allowable heat input by bead-on-plate welds

Although welding on a pressurized pipeline is often necessary to repair damage of corrosion and to add a branch pipeline such as hot tap, the practice entails certain risks. Previous studies have shown that it difficult to burn through a pressured carrier pipe over 3.2mm pipe wall thickness when the heat input was limited.[8] Also, a more difficult challenge has been to be achieving crack-free welds, especially when the pipeline is in-service.

The main value of the previous work in terms of preventing burn-through was in showing that controlling welding conditions to limit the inside surface temperature to less than 982℃ will prevent burn-through.[2] Therefore, we can predict the burn-through of repair weld based on either measurement of inside surface temperature or metallographic examination. During welding of a material, welding arc affects the microstructure of the base metal adjacent to the weld deposit. The HAZ in the base metal adjacent to fusion zone does not undergo melting but experiences complex thermal and stress alterations. The HAZ consists of several sub-zones, which are normally defined by the peak temperature of the welding thermal cycle. C.D. Lundin et al. reported that the 1316℃ average peak temperature is commonly used to represent the CGHAZ.[9] And the 954℃ average peak temperature is commonly used to represent the fine grained HAZ (FGHAZ). Therefore, we can consider that near-burn-through has occurred when the boundary between FGHAZ and base metal reaches the inside plate surface.

The penetration of weld metal and depth of HAZ for bead-on-plate welds on 4, 6, 8 and 10mm thick plates are presented in Fig. 4. Heat inputs ranged from a minimum of 3.9 kJ/cm to 10.7 kJ/cm for SMAW and from a minimum of 6.6 kJ/cm to 30.2 kJ/cm for GTAW. Although a great deal of scatter is present, the trend of increasing the penetration and depth of HAZ in the SMAW and GTAW welds with increasing heat input is evident. Also, the penetration and depth of the HAZ in SMAW welds were deeper than those of in GTAW welds at a given heat input.

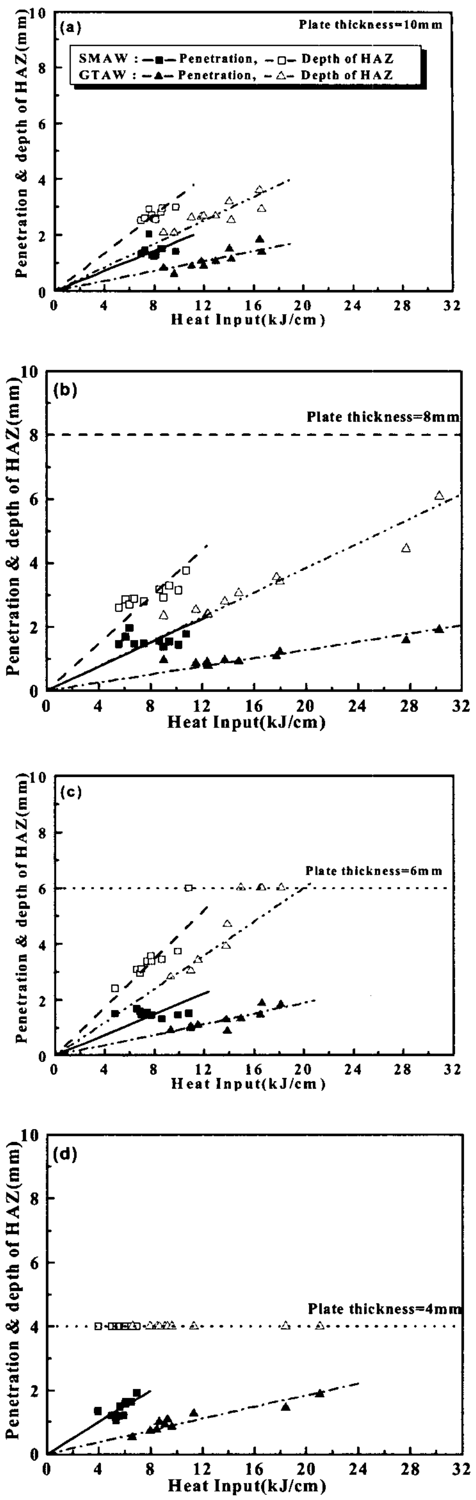

**Fig.4** The effects of heat input and welding process on the penetration and depth of HAZ in bead-on-plate welds on (a) 10mm, (b) 8mm, (c) 6mm and (d) 4mm thick plates

The occurrence of burn-through is governed primarily by the plate thickness and the penetration of the welding arc into the pipe wall. Clearly, higher heat inputs are possible with larger plate thickness as shown in Fig. 4.

The safe limit to avoid burn-through predicted for 8mm and 10mm is greater than the highest heat input used and that a burn-through of 8mm and 10mm thick plates are extremely unlikely within the range of feasible heat inputs associated with SMAW and GTAW.

As shown in Fig. 4, linear regression through origin can be employed to calculate the allowable heat input of bead-on-plate welds on the basis of depth of the HAZ. The depth of HAZ ($d_{HAZ}$, mm) expressed in terms of proportional constant (A) and heat input (Q, kJ/cm) as $d_{HAZ} = AQ$. Table 2 shows the proportional constants and calculated allowable heat inputs on the basis of the depth of HAZ. The proportional constants were similar in 8mm and 10mm thick plates that were welded by the same welding process. However, the proportional constant of 6mm thick plates was higher than that of 8mm and 10mm thick plates. It can be considered that the heat transfer mode was changed at the thickness between 6mm and 8mm. C. D. Lundin et al. reported that with increasing thickness the heat flow pattern was changed from two to three dimensional[9] Therefore, we can consider that the critical thickness is between 6mm and 8mm for the welding conditions used.

As seen in Fig. 4(c), the HAZ penetrated 100% of the 6mm thick plate at 10.7 kJ/cm with SMA weld and at 14.9 kJ/cm with GTA weld. It shows that the calculated allowable heat input does not correspond exactly with measured heat input by experiments of bead-on-plate weld. It is because the depth of HAZ increases rapidly when it comes close to plate thickness as shown in Fig. 4(c).

A near-burn-through was thought to have occurred on 4mm thick plates at all heat input used regardless of welding process. Practically speaking, burn-through occurred on the bead-on-plate welds with heat input of 11.3, 18.4 and 21.0 kJ/cm by GTAW on 4mm thick plate. It was found that the microstructure near inside surface of the plates was a CGHAZ.

Trying to avoid burn-through necessitates minimizing welding-heat input. This can result in rapid cooling of the HAZ and can create the problem of hydrogen induced cracking(HIC) or stress corrosion cracking (SCC) there. From the stand point of HIC, it has been shown that HAZ microstructures with hardness of 400HV and higher are susceptible to HIC when the welding is done with low hydrogen electrodes.[2] And, previous study has shown that the HAZ microstructures with hardness of 248 HV and higher are susceptible to SCC when the welding is done onto in-service pipelines that are used to transport mildly sour produced gas.[10]

In general, the HAZ hardness is determined by the cooling rate of weld after welding and by the carbon equivalent of the material used to welding. Clearly, the hardness of the CGHAZ exhibited lower than 400 HV at all welding conditions used to bead-on-plate welding as shown in Fig. 5. This means that all of the welds were not susceptible to HIC.

Hardness decreased with increased heat input regardless of welding process. This is because increasing the heat input causes an increase in the time of exposure to temperature near the peak temperature and causes a decrease in cooling rate. For a given heat input, increasing plate thickness increased the hardness of the CGHAZ. This is because the cooling rate increases with an increase in plate thickness. The hardness of GTAW welds is higher than that of SMAW welds at a given heat input. The solid slag formed during SMAW process protects the already solidified, but still hot, weld metal from cooling. However, the drift of the shielding gas used to GTAW process causes enhanced convective heat loss from a part of the surface. Therefore, It is considered that GTAW process causes the HAZ to cool much more quickly in comparison with SMAW process.

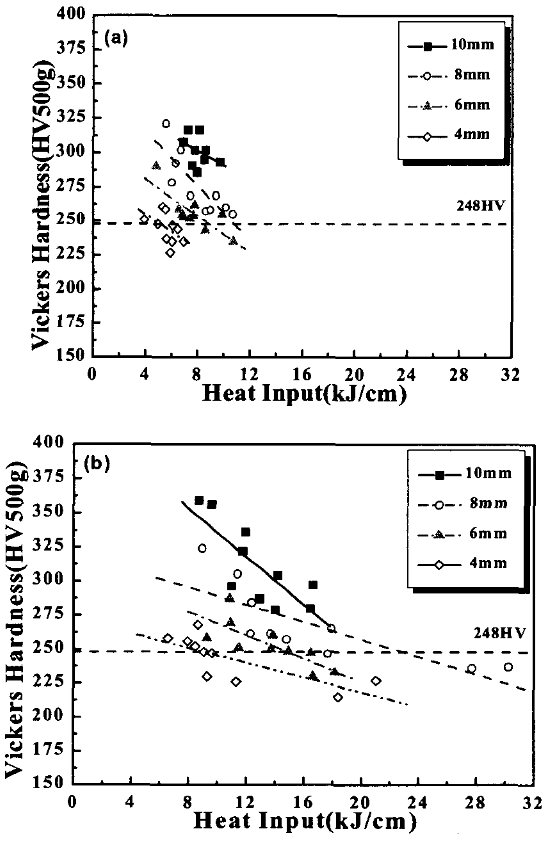

Fig.5 The Vickers hardness of CGHAZ for (a) SMAW weld and (b) GTAW weld on various plate thickness according to heat input

**Table 2** The proportional constant(A) of linear regression through origin and calculated allowable heat input on the basis of the depth of HAZ

| Plate thickness | SMAW | | GTAW | |
|---|---|---|---|---|
| | Proportional constant (A) | Allowable heat input (kJ/cm) | Proportional constant (A) | Allowable heat input (kJ/cm) |
| 10mm | 0.339 | 29.5 | 0.210 | 47.6 |
| 8mm | 0.367 | 21.8 | 0.192 | 41.7 |
| 6mm | 0.457 | 13.1 | 0.335 | 17.9 |

Fig. 5 also reveals the wide latitude of heat inputs at which this pipe material can be welded without the risk of SCC. Because of the limits imposed by the risk of burn-through, there is no allowable heat input that would produce a hardness as low as 248 HV in 4mm and 6mm thick plates as shown in Fig. 4. and Fig. 5. The allowable heat inputs which did not cause burn-through and susceptible SCC microstructure in SMAW welds, ranged from 11.0 kJ/cm to 21.8 kJ/cm on 8mm thick plate and from 18.0 kJ/cm to 29.5 kJ/cm on 10mm thick plate, as shown in Fig. 5 and Table 2. The allowable heat input ranges for the GTAW process were from 22.2 kJ/cm to 41.7 kJ/cm on 8mm thick plate, and from 19.5 kJ/cm to 47.6 kJ/cm on 10mm thick plate, as shown in Fig. 5 and Table 2.

## 4.2 FEM analysis

The heat transfer analysis in bead-on-plate welds using FEM has been conducted to validate the linear regression analysis of the depth of HAZ. The effect of heat input and the plate thickness on the depth of HAZ was analyzed. Based on the previous linear regression analysis of depth of HAZ and the hardness of CGHAZ, 10mm and 8mm thickness plates were analyzed. Because the welding variables (welding speed, voltage and current) was changed in each test, the average values of the welding variables for each case was used and the variation of heat input was considered with changing welding speed.

The calculated depth of HAZ is shown in Fig. 6 with analysis results and the linear regression lines. The linearly increasing trend of depth of HAZ with the increase of heat input is shown at both the calculated and measured data. So the linear regression analysis of the depth of HAZ with heat input is considered to be reasonable. The calculated depth of HAZ in SMAW is larger than that of GTAW at a given heat input and this is mainly due to the difference of the arc efficiency.

The predicted allowable heat input avoiding burn-through is lower than that of regression results and generally the calculated depth of HAZ is a little larger than the measured one and the regression result. This difference is more evident in 8mm thick plate than 10mm thick plate and shows the increasing tendency as the heat input increases. In numerical analysis, the arc heat input is given on the surface of the plate directly. But in the real welding situation after the molten weld metal is formed, the arc is given on the top surface of the filler metal and the thermal energy is transferred by the heat transfer through the molten weld metal. This problem can be solved by considering the addition of filler metal in numerical analysis. But the width and height of weld bead is changed by the variation of welding variables and this relationship generally does not show the linear trend on the variation of heat input, so the more general information of the change of weld bead shape with the

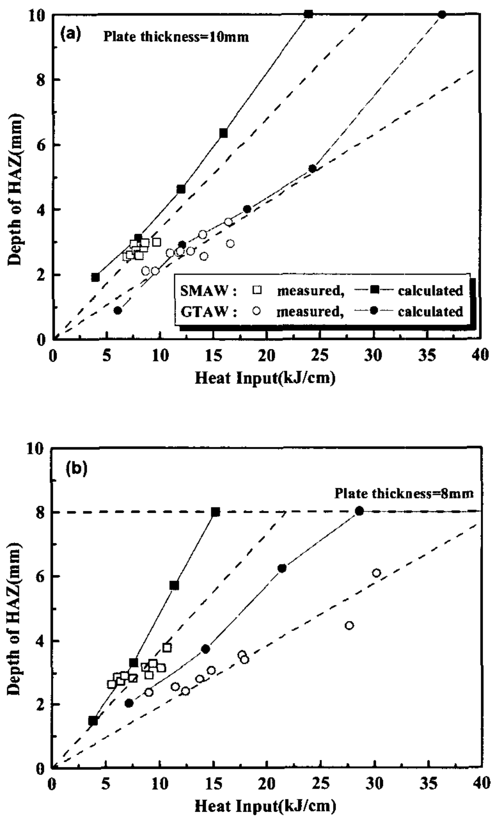

**Fig.6** The comparison of the analysis result and experimental result for the effects of heat input and welding process on the depth of HAZ in bead-on-plate welds on (a) 10mm and (b) 8mm thick plates

change of the welding variables is needed for the accurate calculation of the thermal profile of welds and the establishment of allowable heat input.

Fig. 7 shows the calculated cooling time from 800℃ to 500℃, $t_{8/5}$, with heat input and welding process at the region of the 1316℃ peak temperature. It is shown that the cooling time increases with increase of heat input. Also, It is shown that the cooling time is larger in SMAW than GTAW and larger in 8mm thickness plate than 10mm thickness plate. Because the hardness value of weldment decreases as the cooling time increases, this result is consistent to the result of Fig. 5.

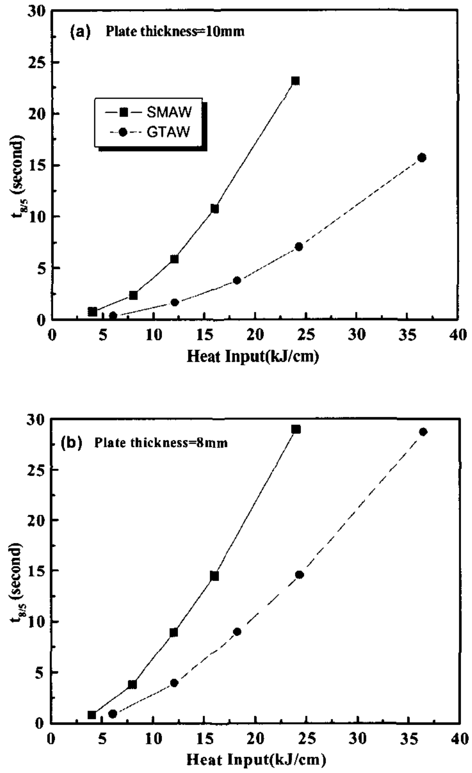

**Fig.7** The calculated cooling time $t_{8/5}$ with the heat input and welding process on (a) 10mm and (b) 8mm thick plates

## 5. Conclusion

From the results of metallographic examination and hardness survey of bead-on-plate welds, the penetration of weld metal and depth of HAZ in SMAW welds was deeper than that of in GTAW welds, at a given heat input. And, the hardness of the welds by GTAW process was higher than that by SMAW at a given heat input.

From the results of the bead-on-plate welds conducted to establish the limit parameters to avoid burn-through and stress corrosion cracking, it appears that it is feasible to carry out repairs with heat input, ranging from 11.0 kJ/cm to 21.8 kJ/cm on 8mm thick plate, and from 18.0 kJ/cm to 29.5 kJ/cm on 10mm plate with the SMAW process. The allowable heat input range for the GTAW process is from 22.2 kJ/cm to 41.7 kJ/cm on 8mm thick plate and from 19.5 kJ/cm to 47.6 kJ/cm on 10mm thick plate.

From the numerical analysis of heat transfer during bead-on-plate welding, it is known that the linear regression of depth of HAZ is reasonable and the variation of HAZ hardness with heat input and the plate thickness can be explained by the cooling time in HAZ.

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