THE EFFECTES OF HEAT INPUT AND GAS FLOW RATE ON WELD INTEGRITY FOR SLEEVE REPAIR WELDING OF IN-SERVICE GAS PIPELINES

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ABSTRACT

The experimental and numerical study has been conducted on the sleeve repair welding of API 5L X65 pipeline. SMAW and GTAW were applied to weld the sleeve. The macrostructure and hardness of repair welds have been examined. The finite element analysis of the multi-pass sleeve-fillet welding has been conducted to validate the experiment and investigate the effects of in-service welding conditions. The effect of gas flow rate on the hydrogen cracking was investigated. The effect of internal pressure on residual stresses and plastic strain was investigated. The allowable heat input was predicted considering the maximum temperature of inner surface of pipe and cooling rate at CGHAZ.

Keywords
Repair welding, gas pipeline, weld integrity, heat input, gas flow rate

1. Introduction

When a segment of a buried natural gas pipeline is found to be defective, one of the repair methods is to vent the gas within the pipeline and cut out the defective segment after shutting down the pipeline. However, the cost is extremely high in terms of venting and stopping the gas supply. Therefore, most pipeline companies have developed in-service repair methods without removing the line from service and these repair methods are used widely throughout the natural gas, petroleum and petrochemical industries [1-4].

The direct deposition of weld metal, sleeve-repair welding and hot-tap welding are typical examples of in-service welding. There are two important concerns with welding on in-service pipelines. The first concern is the possibility of burn-through due to the localized heating, leading to loss of material strength on the inner surface of pipe during the welding process. The second concern is the high cooling rates of the weld by the flowing gas which quickly removes heat from the pipe wall, resulting in accelerated cooling of the weld. The high cooling rate can promote the formation of the heat-affected zone (HAZ) microstructure with high hardness, making these welds susceptible to cold cracking. The rapid cooling can be compensated by increasing heat input, but the increased heat input can promote weld penetration and the possibility of burn-through. Thus suitable weld procedures must ensure the optimal HAZ hardness without cracking and no burn-through with proper heat input.

A series of hot-tap welding research programs was carried out at Battelle and EWI [5-7]. Taking Vickers Hardness 350 HV as a low cracking potential, the maximum inside surface temperature of 982°C was regarded as the limiting maximum temperature to prevent burn-through for low hydrogen electrode welding. However, the estimation of HAZ cracking was highly simplified and not applicable to today's higher strength pipeline steels. Also, burn-through limits were predicted by only the maximum inside surface temperature and the effects of internal pressure and stresses were not considered. Recently, finite element method offers a computational tool for simulation and analysis of in-service welding of gas pipelines [8-10]. In addition to the transient thermal field and cooling rates by the thermal analysis, the stress field and burn-through have been analyzed using a thermo-elastic-plastic model or thermo-elastic-viscoplastic model by finite element method.

The objective of this work is to develop an appropriate numerical model for the sleeve-repair welding of in-service gas pipelines and to investigate the effects of in-service welding conditions. The model has been used to predict the temperature distribution, maximum HAZ hardness and the distributions of residual stresses and plastic strain. The experimental study has also been conducted on the sleeve-repair welding with internal pressure. The calculated maximum HAZ hardness was used to predict the occurrence of cold cracking and the effect of gas flow rate on the maximum HAZ hardness was investigated. The effects of internal pressure on residual stresses and plastic strain distribution were investigated. An analysis of the 1-pass fillet welding was also carried out to assess the allowable heat input for sleeve-fillet welding.

2. Experiments and Finite Element Analysis

Experimental procedure

The schematic illustration of the sleeve-repair welding is shown in Fig. 1. Two sleeves are attached to pipe around damaged sections and then circumferential fillet welding and longitudinal butt welding are performed. Shield metal arc welding (SMAW) and gas tungsten arc welding (GTAW) processes were applied to sleeve-repair welds. The welding conditions of fillet welding is shown in Table 1. The preheating was not applied considering the field welding conditions. The welded materials were sectioned and polished to observe the distribution of the weld metal and the HAZ. The penetration of weld metal and depth of HAZ were measured. The micro-hardness measurements with 500g load were made in base metal, coarse grained HAZ (CGHAZ), fine grained HAZ (FGHAZ) and weld metal of pipe and sleeve.

Computational procedure

The commercial finite element code, ABAQUS [13], was used for the thermal and mechanical analysis of sleeve-repair fillet welding. The sequentially coupled analysis of thermal and mechanical analysis was performed. An axisymmetric model was used to calculate the distributions of temperature, residual stresses and plastic strain during the multi-pass sleeve-fillet welding of in-service API 5L X65 pipeline. The welding conditions listed in Table 1 were used at the simulation of multi-pass sleeve-fillet welding. The values of internal pressure and gas flow rate are 4.4 MPa and 0 m/sec, respectively. An analysis of the 1-pass fillet welding was also carried out to assess the allowable heat input for sleeve-fillet welding.

An axisymmetric finite element mesh for sleeve-fillet welding was made as shown in Fig. 2. In Fig. 2, the r-coordinate and z-coordinate correspond to the radial and axial direction of pipe, respectively and the welding direction is hoop direction. The x-coordinate was defined along the inner surface of pipe in order to describe the distributions of residual stresses and strain. The origin of the axis corresponds to the position at inner surface of pipe below the weld root of root pass. The half of the geometry was modeled by applying symmetry condition at the center line of the axial direction. The finite element model of Fig. 2 (a) consists of 750 quadrilateral elements and 919 nodes. A refined finite element mesh was used in and near weld region.

The modeling of 1-pass welding is efficient to investigate the effects of heat input on penetration, burn-through and cold cracking. The finite element mesh for 1-pass welding near weld region is shown in Fig. 2 (b). The geometry of pipe and sleeve is equal to that of the finite element mesh of Fig. 2 (a) and only the mesh of weld metal was changed in the simple triangular geometry.

3. Results And Discussion

Temperature Distributions

The geometry of the fusion zone and HAZ can be predicted from the peak temperature distributions. The peak temperature distributions were obtained from the calculated transient temperature field. The fusion zone is determined by the melting temperature and the geometry of the HAZ can also be determined by Ae_3 temperature. The HAZ consists of several sub-zones which are normally defined by the peak temperatures. Lundin et al. [11] reported that the average peak temperatures of 1316°C and 954°C are commonly used to represent CGHAZ and FGHAZ, respectively.

It can be seen that the size and shape of fusion zone and HAZ observed in macrostructures are in good agreement with the isothermal lines of melting temperature and Ae_3 temperatures, respectively. From the agreement between the calculated and experimental weld geometries, it is known that the temperature distributions at multi-pass sleeve-fillet welding can be satisfactorily calculated from the model.

The temperature profile has higher values when the welds are in contact with the pipe such as 2, 3 and 6 passes than when in contact with sleeve. The highest peak temperature which corresponds to maximum inside surface temperature was 515°C at 6 pass. This value is much lower than 982°C, which is the limiting maximum inside surface temperature preventing burn-through [7]. Excessive deformations or burn-through around welds were not observed in case of welding the pipe with 4.4MPa internal pressure. The heat input of 4 pass welding is 43.2 kJ/cm due to the low welding speed, but burn-through was not found numerically and experimentally.

Hardness Distributions and Effect of Gas Flow Rate on Maximum HAZ Hardness

The measured hardness values at base metal, CGHAZ, FGHAZ and weld metal are shown in Table 2. The hardness at CGHAZ of pipe has the highest value of 235 HV which is much lower than 350 HV. The calculated maximum HAZ hardness is 242 HV and in good agreement with the measured value. The cold crack was not observed at the macrostructures of fillet welds. The natural gas flowing within a pipeline can increase the cooling rate of in-service welds. The safe flow rate of natural gas within a pipeline is generally below 18 m/sec and the normal operating flow rate is around 10 m/sec. The effect of gas flow rate on the maximum HAZ hardness was numerically investigated at the gas flow rate from 0 m/sec to 20 m/sec.

As the gas flow rate increases, the heat transfer coefficient of inner surface of the pipe increases but the maximum HAZ hardness increases only a little as shown in Fig. 3. The maximum HAZ hardness at the gas flow rate of 20 m/sec is 257 HV, which is only 6 % higher than that with no gas flow rate. This result is in agreement with the fact that the cooling rates for thickness greater than 0.5 inch (12.7 mm) are little influenced by the fluid inside the pipe [7]. From Fig. 3, it can be suggested that the sleeve-repair welding of API 5L X65 pipelines of 14.3 mm thickness with the flowing gas can be performed without cold cracking at the given welding conditions.

Effect of Internal Pressure on Residual Stresses and Plastic Strain

During heating, the welds are expanded and the pipe is deformed toward the outside of pipe. During cooling, the pipe is bent toward the inside by the faster cooling of weld region. Therefore, the tensile axial residual stress is developed at the inner surface and the compressive stress at the outer surface. The hoop stress is tensile at both inner and outer surface of the pipe near welds. The effect of internal pressure on the residual stresses and plastic strain was investigated varying the magnitude of internal pressure from 0 MPa to the maximum operating pressure of 6.9 MPa. As shown in Fig. 4, the distributions of tensile residual axial and hoop stresses on the inner surface are hardy influenced by the variation of internal pressure. The effect of the increase of hoop stress by internal pressure is observed only in the compressive region. The residual plastic strain decreases as internal pressure increases. This is because the bending deformation toward the inside of pipe during cooling is reduced by internal pressure. The maximum plastic strain is 0.63 % at no internal pressure condition. The equivalent plastic strain, which characterizes permanent deformation, can be used as an indicator of cumulative damage of the material during the welding process. Because the pipe material has more than 30 % elongation, which is much higher than the maximum plastic strain, at the temperature range from room temperature to near 1000°C, it is known that the severe loss of material strength or excessive deformation on the inner surface of pipe will not occur by the above plastic strain. In fact, the condition in which internal pressure has a significant effect on in-service welding is that the temperature of the inner surface of pipe is high enough to cause burn-through. The calculated maximum inside surface temperature is much lower than the temperature of burn-through generation. It can be suggested that the sleeve-repair welding of API 5L X65 pipelines of 14.3 mm thickness can be carried out without burn-through at the maximum operating pressure of 6.9 MPa.

Allowable Heat Input at 1-Pass Sleeve-Fillet Welding

An analysis of the 1-pass fillet welding was carried out to assess the allowable heat input for sleeve-fillet welding. The SMAW was considered and the heat input was varied from 5 kJ/cm to 50 kJ/cm. The gas flow rate was varied from 0 m/sec to 20 m/sec to investigate the effect of gas flow rate on the maximum HAZ hardness. Fig. 5 shows the variations of maximum inside surface temperature and maximum HAZ hardness with the variations of heat input and gas flow rate. The calculated maximum inside surface temperatures show the lower values than the burn-through prediction temperature of 982°C at all of the conditions as shown in Fig. 5 (a). The calculated maximum HAZ hardness shows the lower values than the limiting hardness of 350 HV at all of the conditions as shown in Fig. 5 (b). From Fig. 5, it is known that Burn-through and cold cracking will not occur at the practical range of heat input and gas flow rate at 1-pass sleeve-fillet welding.

4. Conclusions

An axisymmetric finite element model has been developed to simulate the multi-pass sleeve-fillet welding process of in-service API 5L X65 pipelines of 14.3 mm thickness. The model has been used to predict the temperature distribution, maximum HAZ hardness and the distributions of residual stresses and plastic strain.

The predicted maximum inside surface temperature was much lower than the limiting maximum temperature preventing burn-through. The calculated maximum HAZ hardness was in good agreement with the measured value. The maximum HAZ hardness increased only a little as the gas flow rate increases. The calculated maximum HAZ hardness was much lower than the maximum allowable HAZ hardness for avoiding cold cracking. Burn-through was not predicted from the calculated plastic strain distribution and the maximum inside surface temperature. The effect of internal pressure on the residual stresses and plastic strain was small. The equivalent plastic strain showed a little decrease as internal pressure increases. From the numerical simulation, it can be suggested that the sleeve-repair welding of API 5L X65 pipelines of 14.3 mm thickness can be carried out without burn-through at the maximum operating pressure.

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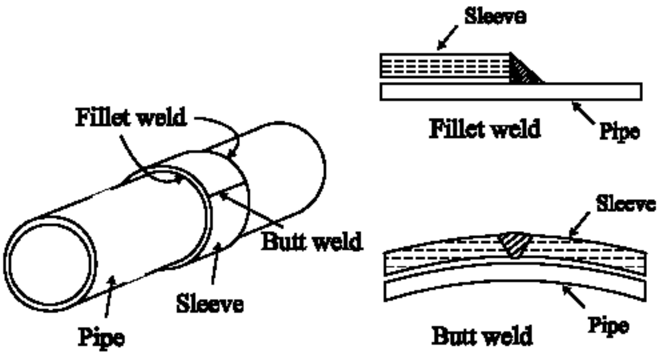
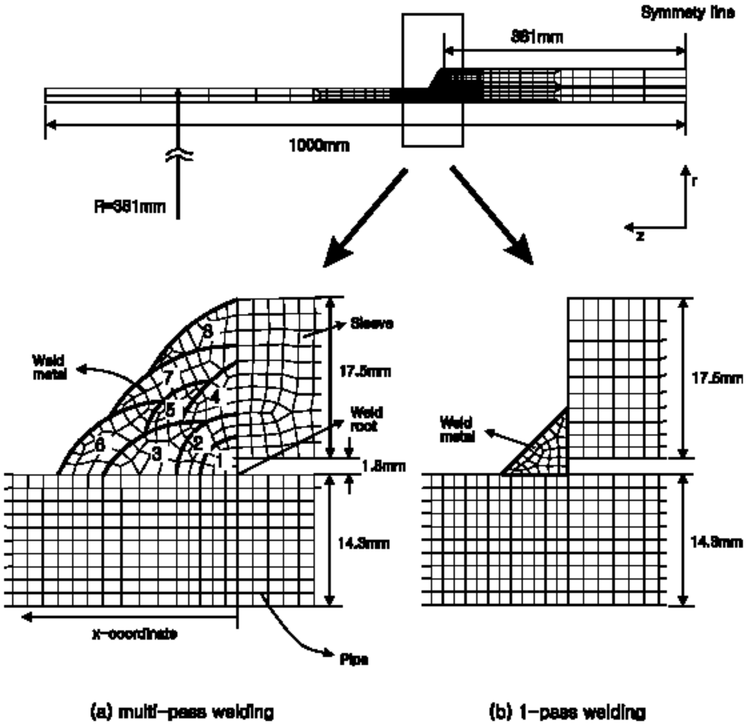


Figure 1 Schematic illustration of sleeve-repair welding of pipeline

Table 1 Welding Conditions for Sleeve-Fillet Welding.

Pass number	Process	Electrode diameter (mm)	Current (A)	Voltage (V)	Welding speed (cm/min)	Heat input (kJ/mm)
1	GTAW	2.4	194	23	16	1.67
2	SMAW	2.6	96	29	5	3.34
3	SMAW	2.6	96	30	9	1.92
4	SMAW	3.2	120	30	5	4.32
5	SMAW	3.2	117	30	10	2.11
6	SMAW	2.6	100	30	7	2.57
7	SMAW	3.2	122	31	5	4.54
8	SMAW	3.2	118	30	9	2.36



(a) multi-pass welding

(b) 1-pass welding

Figure 2 Axisymmetric finite element mesh for sleeve-fillet welding.

Table 2 Vickers Hardness of Sleeve-Fillet Welds

		Hardness (HV)
Weld metal	SMAW (4,5)	219.0
	GTAW (11)	211.0
CGHAZ	Pipe (3,10)	235.0
	Sleeve (6,12)	213.0
FGHAZ	Pipe (2,9)	202.5
	Sleeve (7,13)	196.5
Base metal	Pipe (1)	178.0
	Sleeve (8)	179.0

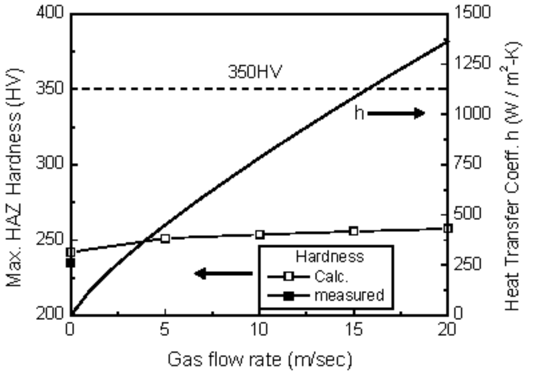
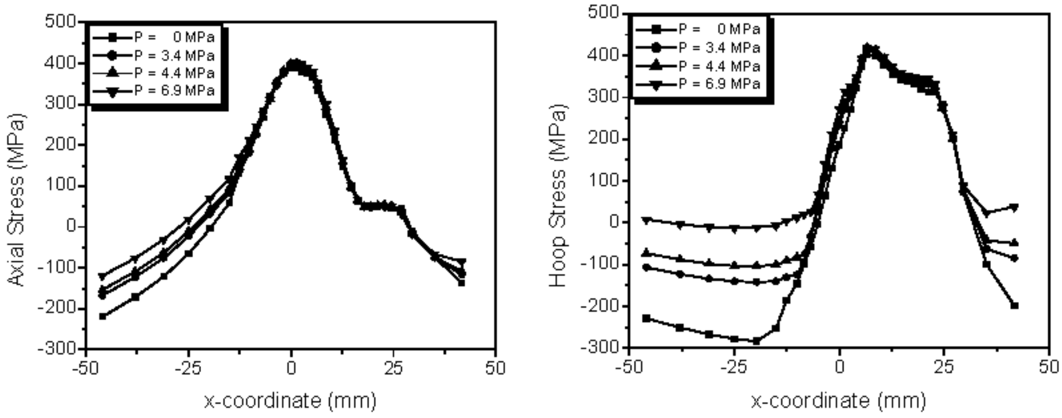
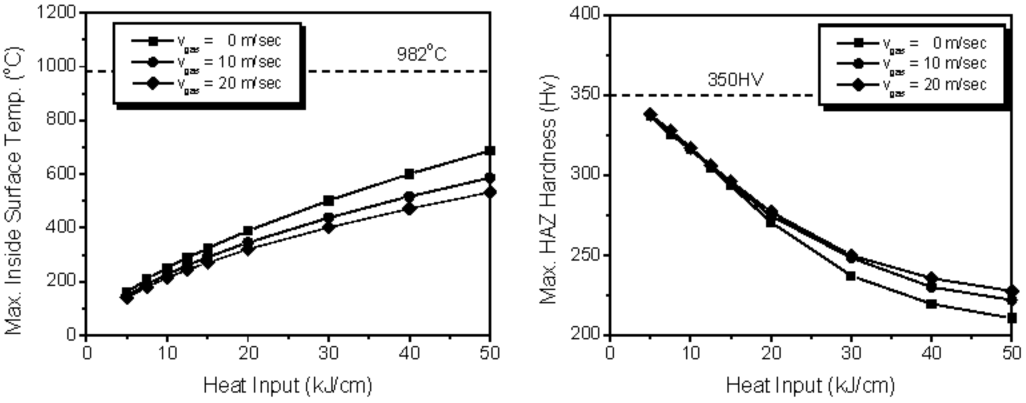


Figure3 Effect of gas flow rate on maximum HAZ hardness



(a) (b)

Figure 4 Effect of internal pressure on residual stress distributions along inner surface of pipe: (a) axial stress, (b) hoop stress



(a) (b)

Figure 5 Variation of (a) maximum inside surface temperature and (b) maximum HAZ hardness with heat input and gas flow rate at 1-pass sleeve-fillet welding.