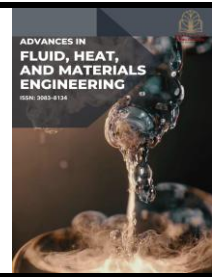




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Residual Stress and Deformation Analysis of Steel Sleeve Repair Welding of API 5L X65 Specification in Gas Pipeline Using Simulation Approach

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ABSTRACT

Sleeve welding repair is one of the medium scale maintenance jobs for gas pipeline. It is widely used due to avoid gas pipeline shutdown. However, there were issues raised on weldment quality and pipe burn-through. The weld quality issues were mainly resulted from excessive residual stress and deformation. The purpose of study was to determine the suitable steel sleeve dimensions and gas pipeline internal flow conditions that minimized the residual stresses and deformation. For accuracy, the pipe was modelled according to API 5L X65 standard while the steel sleeve was modelled according to properties of ASTM A131-74 grade AH. Apart from that, the weldment was modelled according to AWS standard E7018 electrode as-weld properties. The 3-dimensional model was created using SolidWorks 2018 whereas the numerical simulation was done using ANSYS v19.2. In order to achieve the objective, the study has focused on studying the thermal history, residual stresses and deformation on the pipe. From the numerical simulation, it was found that, sleeve-to-pipe gap exceeding 3 mm has increased the residual stress significantly. Then, the result has indicated there were no prominent relation between sleeve length, residual stress and deformation. From the thermal history results, there were no sign of burn-through. The increment of gas flow rate and pressure has also increased the weld cooling time while reduced the residual stress and deformation. For this study welding process, 200mm long and 8.5mm steel sleeve with no gap under 20m/s flowrate, 4.4 MPa was chosen as suitable setup.

1. Introduction

Natural gas consumption in Malaysia was growing as projected by the Energy Commission (ST) Malaysia in 2016 to hit 216,636,030 MMBtu by the year 2020, with a growth of 5.13% [1,2]. Gas supply operations are extensive because Petronas Gas Berhad has built an integrated 2,500 km pipeline network in Peninsular Malaysia [3]. A separate study reported that weld-material failure accounted for 24% of the gas-pipeline failures in its dataset [1]. Recent AFHME research has also used

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computational fluid dynamics to examine double leaks in a subsea pipeline, reporting local pressure fluctuations and turbulence around the leakage regions [4]. Recent review literature covers in-service repair techniques ranging from local weld deposition and mechanical clamps to metallic and composite sleeves; full-encirclement steel sleeves remain an established option for restoring pipeline capacity without a shutdown [5]. Accordingly, the present study focuses on welded sleeve repair and its residual-stress implications.

This study focuses on a Type B full-encirclement steel sleeve, a welded repair that transfers load across a damaged pipeline section [5,6]. The circumferential fillet welds close the sleeve ends and enable the repaired section to sustain internal pressure. Recent numerical and experimental investigations confirm the value of coupled thermal and mechanical modelling for in-service pipeline welding [7]. The principal safety concerns are burn-through, formation of hard or brittle heat-affected-zone microstructures, high residual stresses, and hydrogen-assisted cracking [8]. Earlier full-scale failure analyses relied on fractography, metallurgy, and fracture mechanics [9], but experiments remain costly and difficult to conduct on pressurized pipelines. Recent studies have therefore refined burn-through criteria and made extensive use of numerical or hybrid approaches [7,8,10-18]. The updated literature also highlights the roles of fillet-weld geometry, residual stress, and hydrogen in repair-weld integrity [16,17]. A recent multiphysics model of Type B sleeve welding reported a maximum peak-temperature error of about 1% and a cooling-curve error of about 10% at lower temperatures when compared with experiments [11]. These findings support the finite element approach adopted in the present study.

Sleeve welding requires careful control of geometric and operating parameters because pressure, flow rate, heat input, and preheating can materially change the predicted welding-stress field [12]. Minimum sleeve thickness is one of the important parameters [19,20]. Another study included sleeve thickness when investigating the minimum distance between two sleeve repairs [20]. Sleeve length is also relevant to the repair configuration, although earlier work reported a limited effect on local residual stress for the ranges investigated [15,21]. These parameters are closely related to the operating conditions used during gas transportation, including pressure reduction for repair safety [19,20]. Internal flow changes convective heat removal and therefore the weld cooling rate [11,16,18]. In this study, the finite element method was implemented in ANSYS v19.2 to avoid the experimental risk of welding on a highly pressurized pipe and to simplify the coupled thermal-mechanical analysis [10,11]. The investigated variables were sleeve thickness, sleeve length, sleeve-to-pipe gap, internal pressure, and gas flow rate. The objective was to identify a suitable sleeve geometry and internal flow condition for the modelled sleeve-welding procedure.

2. Methodology

This study used ASTM A131-74 grade AH whereas the low carbon steel grade was high in strength and chemically inert which is usually used for ship structure. However, Qureshi mentioned that the ASTM A131-74 grade AH steel for piping purposes which was mentioned as suitable for piping [22]. Then, Lincoln Welding guideline has specifically recommended the E7018 electrode to complete the sleeve weld of this steel grade. The present study was aimed to investigate the effect of welding thinner, thicker and equal sleeve length to the pipe. According to Table 1, the selected API 5L X65 pipe thickness was 9.5 mm. Hence, specimen 1 was set to be thinner, specimen 2 was of equal thickness and specimen 3 thickness was greater than the pipe. However, the sleeve thickness was kept above 5mm as DEP 31.38.60.10 standard mentioned that thickness below 5mm would increase the risk of pipeline blow out [23].

This study examined sleeve lengths of 200 mm (shorter than the pipe diameter), 508 mm (equal to the pipe diameter), and 800 mm (greater than the pipe diameter). Earlier studies reported no direct or only limited effects of sleeve length on local residual stress for the configurations studied [15,21]. Otegui et al. recommended limiting the sleeve-to-pipe gap to 3.0 mm [20]. Therefore, the present models used gaps of 0 mm, 2 mm, and 4 mm to evaluate a no-gap case, a case within the cited tolerance, and a case exceeding it.

2.1 Heat Source Modelling

A moving three-dimensional Gaussian heat source was used to represent the weld arc, consistent with recent finite element studies of in-service pipeline welding [7,12,14,24]. The source definition used welding velocity, heat input, beam radius, power intensity, and welding time. Recent numerical work on Type B sleeves also shows that sleeve length, internal pressure, and structural restraint can affect the predicted stress response [25]. Table 1 summarizes the modelling inputs.

Table 1

3D Gaussian welding heat source modelling input

Welding speed (mm/s)	Heat input (kJ/mm)	Electrode beam radius, r (mm)	Voltage, V (V)	Current, I (A)	Welding efficiency, η (%)	Power source intensity (W/mm^2)
3	1.040	3.2	26	120	75	72.73878

2.2 Heat Transfer Modelling

Two heat-transfer regimes were represented: forced convection at the inner pipe wall due to the flowing gas, and natural convection plus radiation at the external surface. This treatment is consistent with numerical and experimental in-service welding studies [11,16,18,26]. Earlier circumferential-weld simulations similarly transferred the computed thermal history to the mechanical solution for residual-stress prediction [27]. Burn-through analyses have also applied internal forced-convection and external heat-loss boundary conditions [28]. Methane was used as the representative internal gas to remain comparable with earlier pipeline-welding simulations [13,18]. The internal flow was assumed to be fully developed and at steady state, allowing a constant heat-transfer coefficient to be applied along the inner wall. Table 2 lists the thermo-physical properties used for methane.

Table 2

Thermo-physical properties of methane gas [13,18,29,30]

Case index	Internal pressure (Mpa)	Flow rate (m/s)	Fluid density (kg/m^3)	Specific heat conductivity ($kJ/(kg.K)$)	Thermal conductivity ($W/(m.K)$)	Dynamic viscosity (Pa.s)	Heat transfer coefficient (W/m^2K)
1	0	0	0.657	2.191	321.1	10.3×10^{-6}	25
2	1.6	10	10.9	2.284	321.1	11.0×10^{-6}	292
3	4.0	20	28.5	2.623	321.1	12.6×10^{-6}	1101
4	4.4	20	32.4	2.745	321.1	12.9×10^{-6}	1375

For external condition of the pipe which was modelled based on Qureshi's model of total heat transfer coefficient that accounted for both natural convection and radiation which dominate at the weld region. The model can be described in the piecewise-linear function as in Eq. (1) [22].

$$h_{total} = \begin{cases} = 0.68T \times 10^{-8} & (W/mm^2) & 0 < T \leq 500^\circ C \\ = (0.231T - 82.1) \times 10^{-6} & (W/mm^2) & T > 500^\circ C \end{cases} \quad (1)$$

2.3 Model Verification

The model-verification approach followed Alian et al., who used experimental secondary data to verify a modelling technique even though the project geometry differed from the benchmark case [8,31]. In this study, Qureshi's work was used to benchmark the thermal-history and residual-stress procedures [22]. Figure 1 presents the validation results. All the results were in good agreement where thermal history has at most 9.3% error. Validation results of residual axial stress obtained were qualitatively agreeable to the Qureshi's work where the shape and features were adequately captured [22].

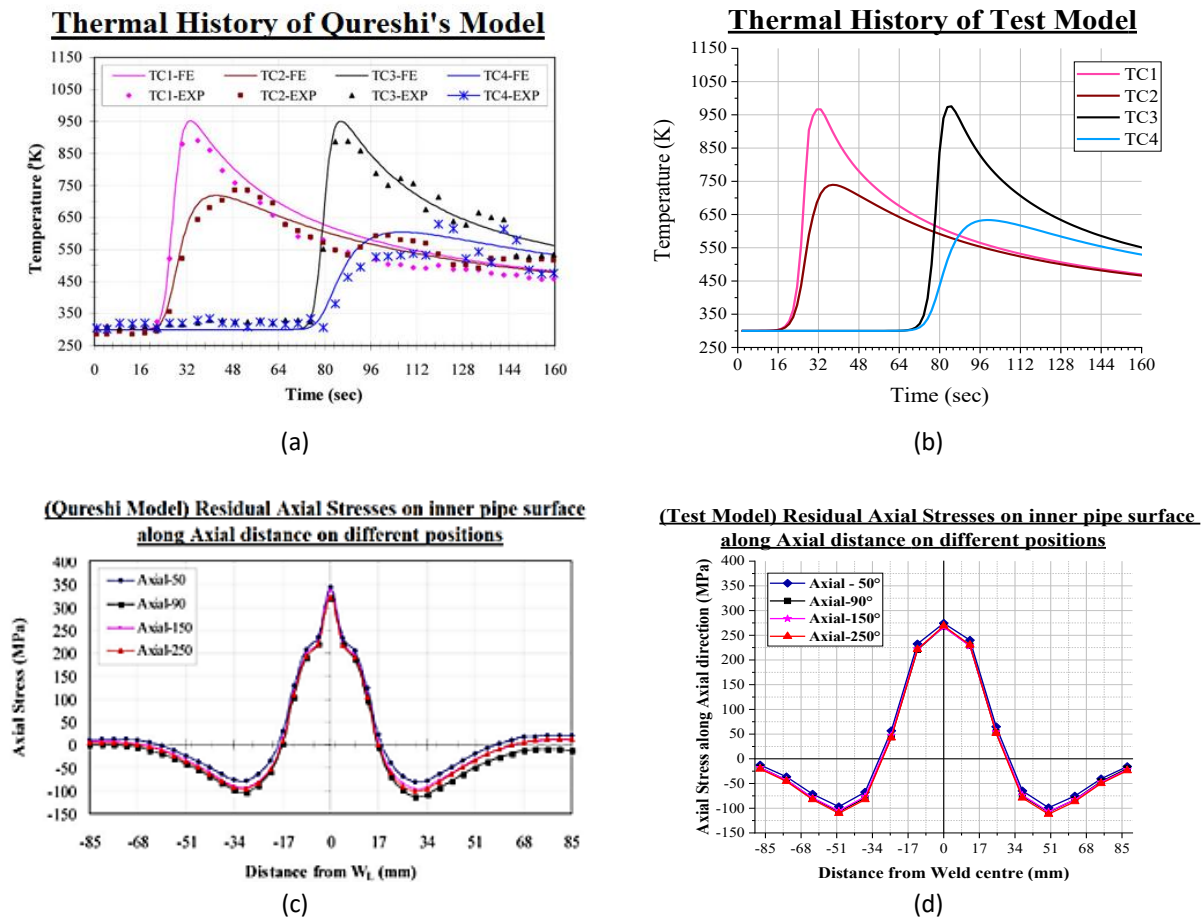


Fig. 1. Model verification (a) Qureshi's thermal history [22] (b) Test model thermal history (c) Qureshi's model axial residual stress [22] (d) Test model axial deformation

2.4 Grid Evaluation

The grid independence test (GIT) was conducted on every model using the maximum inner and outer wall temperature on the weld root of two locations. The grid of all specimens obtained have shown mesh independence at Refined Model 3 (RM3) with at most 3.97 % relative error form specimen 3. Specimen 1 has recorded 1.6 % error. Specimen 2 has recorded 2.8 %. The error was below 7 % as prescribed by Shah [32]. Apart from that, computational time, for Specimen1 was 12.45 minutes, Specimen 2 was 11.90 minutes and Specimen 3 was 13.03 minutes. For quality assessments, all three specimens were tested based on skewness and orthogonal quality metrics provided by ANSYS [33,34]. The Table 3 below summarized the selected specimens mesh model quality evaluation results.

Table 3
Thermo-physical properties of methane gas [13,18,29,30]

Specimen	Orthogonal quality (Greater than 1)		Maximum Skewness (Lesser than 0.95)		No of elements
1	0.526	Good	0.809	Acceptable	14333
2	0.518	Good	0.646	Good	12713
3	0.299	Good	0.708	Good	16576

3. Results and Discussion

The data present in this section aimed to present a strong and convincing case on why certain dimensions or gas operating conditions should be chosen. Note that, all probing path locations that applied to all evaluation, "Distance from weld center" were as illustrated in Figure 2 below.

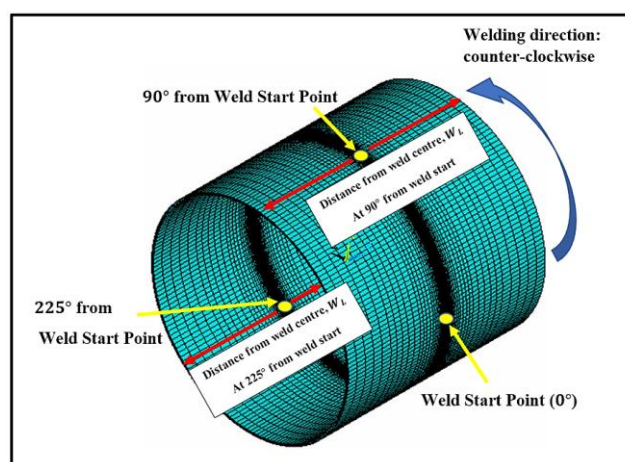


Fig. 2. Probing path location [22]

3.1 Thermal Analysis

Processed data presented here was aimed to pick the best sleeve welded pipe dimensions and gas operating condition for gas pipeline sleeve welding from the lens of temperature history. Temperature contour map would not be shown for all simulated models as it would not contribute much in selecting the best model and flow condition. For illustration, Figure 3 below show two temperature contours.

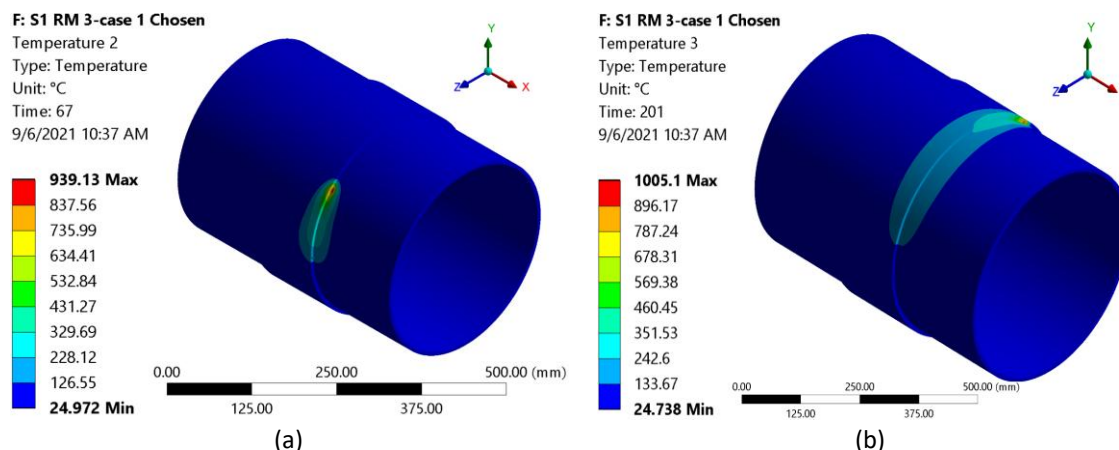


Fig. 3. Temperature contour (a) 67 s (b) 201 s

First, the effect of burn-through was studied by collecting the inner pipe wall temperature. The results were illustrated as in Figure 4 below. The legacy labels (44) and (41) embedded in the source graph correspond to revised references [23,28], respectively. Generally, all specimens have not exceeded the burn-through limit as prescribed by DEP 31.38.60.10 [23]. The Results were agreeable with Kim's study where his study has indicated around 400 °C to 500 °C for inner pipe wall temperature at 4.4 MPa of operating pressure [30]. Figure 5 has illustrated Specimen 1 has much lower inner pipe peak temperature. Note that specimen 1 difference from 2 and 3 was dimensional changes. There was presence of air gap in Specimen 2 and Specimen 3. Hence, the presence of air gap might have influenced the inner pipe wall temperature increment. Then, specimen 2 was 508 mm long while Specimen 3 was 800 mm where no notable changes were recorded.

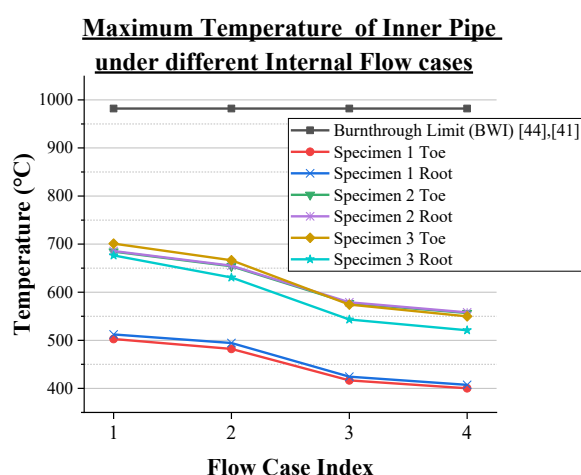


Fig. 4. Maximum temperature of inner pipe

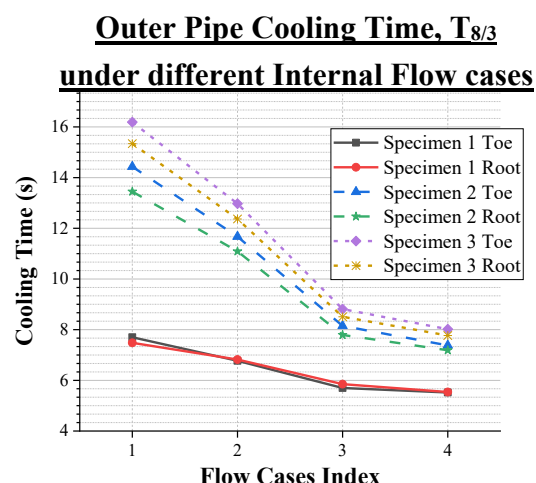


Fig. 5. Outer pipe cooling time of different cases

Furthermore, the increment in thickness from specimen 2 (9.5 mm) to specimen 3 (10.5 mm) has also not showing any significant influence to the inner pipe wall temperature. However, it was noted that pipe pressure increased from 0 to 1.6 MPa would result in reduction of inner wall temperature which was quite similar to increment from 4.0MPa (case 3) to 4.4MPa (case 4). Next, there were a dramatic drop in temperature when flow rate increased from 10 m/s of case 2 to 20 m/s in case 3. A summary of how gas pipeline condition has affected the inner wall pipe temperature was tabulate as shown in Table 4.

Table 4

Effect of operating condition to inner pipe wall peak temperature

Case	Specimen 1		Specimen 2		Specimen 3	
	Average inner temp (%)	Temperature decrement (%)	Averaged inner temp (°C)	Temperature decrement (%)	Averaged Inner temp (°C)	Temperature decrement (%)
1	507.45	-	685.03	-	688.85	-
2	488.27	3.93	654.57	4.65	648.54	6.22
3	420.55	16.1	578.21	13.21	558.84	16.05
4	403.83	4.14	557.40	3.73	535.33	4.39

Apart from investigating the inner pipe wall peak temperature, outer pipe cooling time $T_{8/5}$ was investigated as well. Generally, outer pipe wall cooling time for all specimens has decreased from case 1 to case 4 while the cooling time has increased from specimen 1 to specimen 3. $T_{8/5}$ has shown the specimen 1 case 3 (4 MPa, 20 m/s) trend and Specimen 1 case 2 (1.6MPa, 10 m/s) trend (Figure 5) have shown agreeable results with Wang's data where Wang's was 7.9 sec [18]. Minor difference

might incur by material difference (X52 pipe and X65 pipe) [18]. Figure 5 also hinting Specimen 1 inner wall cooling time was more insensitive to changes in flow conditions where both Specimen 2 and 3 were showing stepper cooling time decrement. This implied that specimen 2 and 3 were relatively more sensitive to internal flow condition changes. It was also noted that pressure changes did not affect much on cooling time where all specimens were noted to have smaller decrement in cooling time from case 3 (4.0 MPa) to case 4 (4.4 MPa). Figure 5 has also highlighted that presence of sleeve-to-pipe gap (specimen 2 and 3) could decrease the cooling time by a large scale relative to specimen 1 with no sleeve-to-pipe gap.

For quantitative comparison Table 5 below has summarized the effect in percentage of cooling time decrement. The increasing the sleeve-to-pipe gap from 2 mm to 4 mm (Specimen 2 to Specimen 3) reduced the cooling time by about 2-4%, with the difference decreasing as the flow condition changed from Case 1 to Case 4. In contrast, introducing a gap between Specimen 1 and Specimen 2 markedly changed the cooling time. The 0 mm gap therefore provided the most favourable response among the present models. Lengthening and thickening the sleeve produced a relatively small change in cooling rate, consistent with earlier reports that sleeve-length effects were limited for the configurations investigated [15,21]. The cooling-time curves converged as the internal flow increased, suggesting that geometric effects diminished from Case 1 to Case 4. Interpretation of cooling time remains dependent on the resulting microstructure [35], which was outside the scope of this study because an exact continuous-cooling-transformation diagram and microstructural observations were unavailable.

Table 5

Effect of operating condition to weld cooling time

Case	Specimen 1		Specimen 2		Specimen 3	
	Average cooling time, $T_{8/5}$ (s)	Relative decrement (%)	Average cooling time, $T_{8/5}$ (s)	Relative decrement (%)	Average cooling time, $T_{8/5}$ (s)	Relative decrement (%)
1	7.59		13.94		15.77	
2	6.795	11.70	11.38	22.50	12.67	24.43
3	5.775	17.66	7.97	42.79	8.66	46.30
4	5.53	4.43	7.29	9.40	7.90	9.69

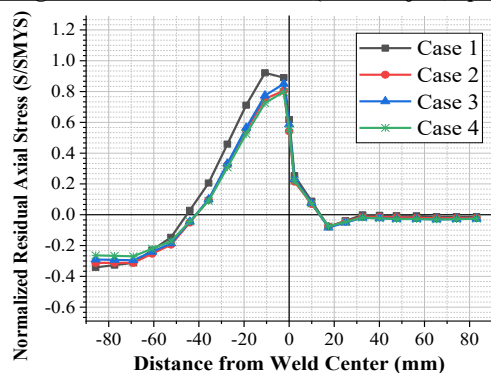
3.2 Residual Stress

First, the evaluation would start with qualitative analysis on residual axial stresses on all the specimens. Figure 6 below illustrated the residual axial stresses of 3 specimens under all flow cases with one of referred result [8] as comparison. Figure 6 has shown that plots of specimen 1 and 2 (Figure 6(a) and (b)) were very similar shape with Alian's work on residual axial stress [8]. This mean that this study was on the right path. The plots were was the inner pipe wall on weld region was experiencing high tensile stress (positive stress value) which signified the unrelieved tension accumulated caused by uneven thermal expansion and contraction differential as mentioned by Maddox [31]. Figure 6 has also shown that case 1 has generated the highest residual axial stress across all specimens. The trend of flow cases was following the number sequencing where case 1 has the highest residual stress followed by 2,3 and lowest was the fourth case. This means that pressure and flow rate increment did help to lower the axial residual stress by a small amount which. Note that, case 1 of all specimens has induced the highest residual stress which was aligned with the prediction of DEP 31.38.60.10 standard where welding under 0 m/s flow rate were dangerous [23].

From the plot shape in Figure 6, specimen 1 and 2 has an asymmetric axial stress distribution where the right side of the stress was near to zero while specimen 3 shows a symmetrical stress distribution. In short, specimen 3 has a wider span of pipe length which experiencing high tensile stress. From the graphs, it has suggested that specimen 1 has the lowest residual axial stress while has specimen 2 higher residual stress value with shorter span. Lastly, specimen 3 has the longest pipe length which was affected by high residual tensile stress. This might due to the specimen 3 sleeve-to-gap has exceeded the ceiling limit of 3 mm as recommended by Otegui *et al.*, [20].

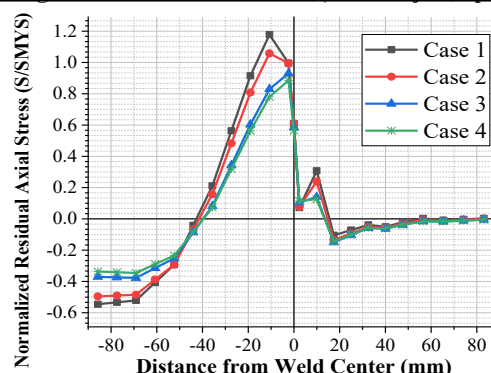
Looking at others specimens' geometry, it has not much changes induced by sleeve length and thickness. This was aligned with the result of Lazor that summarized sleeve length and sleeve-to-pipe gap did not contribute much effect on local stresses around the weldment region [15]. Hence, from the Figure 6, it has indicated that the introduction of sleeve-to-pipe gap of 2 mm from Specimen 1 to Specimen 2 did experience an increment in residual axial stress as predicted by two past studies [9,15]. From the three specimens, only Specimen 1 geometrical arrangement has axial residual stress that did not exceed the SMYS. Then, the flow condition of 4.4 MPa and 20 m/s (case 4) was most favorable in the aspect of reducing residual axial stress which was aligned with Chapetti *et al.*'s results [9]. In short, the residual stress results were helpful in determining the suitable steel sleeve dimension as well as suitable internal gas flow conditions.

**Normalized Residual Axial Stress Distribution
along distance from weld center (This Project, Specimen 1)**



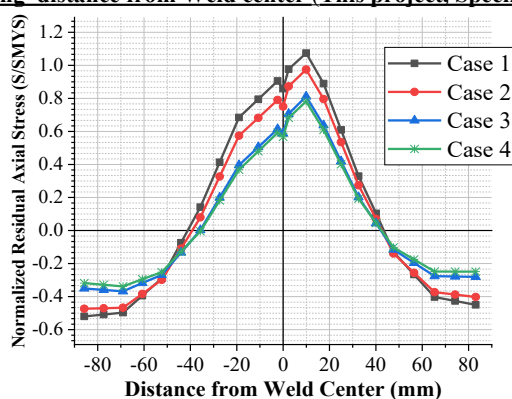
(a)

**Normalized Residual Axial Stress Distribution
along distance from weld center (This Project, Specimen 2)**



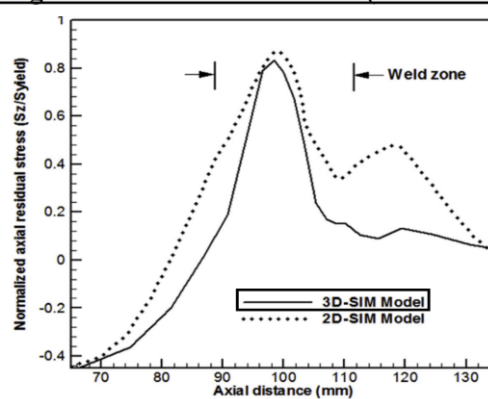
(b)

**Normalized Residual Axial Stress Distribution
along distance from Weld center (This project, Specimen 3)**



(c)

**Normalized Residual Axial Stress Distribution
along distance from Weld center (Alian's Result [1])**



(d)

Fig. 6. Residual axial stress distribution (a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Alian's result [8]

Next, the Figure 7 below was plotted to highlight the key data trend as the internal flow conditions changes from case 1 to 4. Besides it also has illustrated the changes in residual stresses when the flow conditions were altered from case 1 to case 4. Figure 7 shows that the von Mises stress was significantly higher than the axial stress because the von Mises measure combines the multiaxial stress components [36]. The von Mises stress was also more sensitive to changes in the internal flow conditions, which may reflect the contributions of hoop and radial stresses. Overall, Specimen 3 had the lowest von Mises and axial stresses, whereas Specimen 2 had the highest. A recent AFHME pressure-vessel study similarly used stress, strain, and displacement outputs to assess a pressure-loaded structure and reported the lowest deformation for the steel alloy because of its higher stiffness [37].

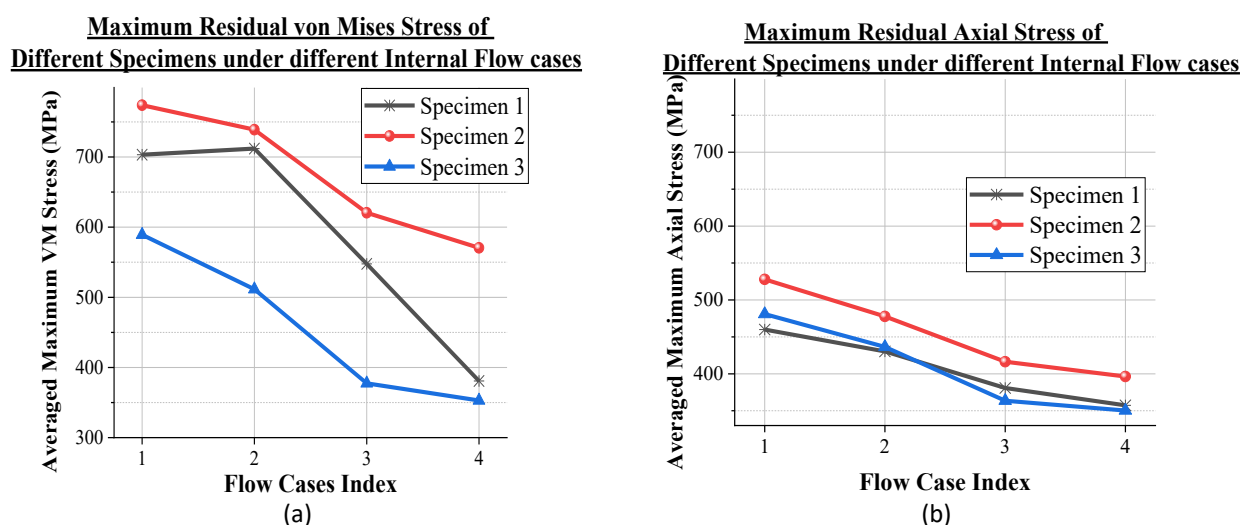


Fig. 7. Comparison of maximum residual stresses (a) Von Mises stresses (b) Axial stresses

Figure 8 illustrates the critical length of all specimens. In this study, the span of pipe carrying residual von Mises stress above 70% of the API 5L X65 specified minimum yield strength (448 MPa) was defined as the critical length, consistent with the DEP 31.38.60.10-Gen criterion [23]. This assessment is important because tensile residual stress near a weld can approach the material yield strength and reduce fatigue performance [31]. From Figure 8, Specimen 3 was seemed to be most sensitive to flow condition alterations. Specimen 1 and 2 have shown relatively minute downward trend. Above all, the result has indicated that the pressure and flow rate increment would reduce pipe critical length. This could minimize the impact of strength loss due to stress build up. The extent of critical length reduction was dependent to the steel sleeve dimension. Note that specimen 3 with highest sleeve-to-pipe gap (4 mm) was most sensitive to changes in internal flow conditions. In general, specimen 2 and 3 has higher critical length than specimen 1. This trend has aligned with Lazor's finding where his model 1.6 mm sleeve-to-pipe gap could easily induce extra 50 MPa residual stress at the weld root and toe region compared with the rest of the pipe assembly [15].

From the all the residual stresses results presented, there were some take away points to note for. First, flow case 4 would induce lowest residual axial stress as shown in Figure 7 where all specimens have shown the smallest residual axial stress. In contrast, case 1 has induced the highest residual stress. This trend was also happening to von Mises stress (Figure 7 (a)) and critical length distribution (Figure 10) where case 4 has induced the lowest impact on the stress build up. Regarding to sleeve dimension, specimen 1 has outperformed specimen 2 and 3 where it has consistently produced the least residual stress among the three specimens as shown in Figures 6 and 8.

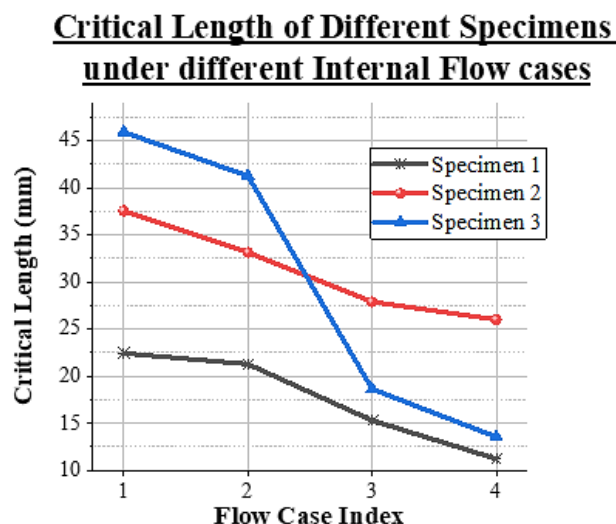


Fig. 8. Comparison of critical length between specimens under different flow cases

3.3 Pipe Deformation

The pipe deformation results were presented to consolidate the argument on selecting the specimen and flow condition which has the lowest impact on welding distortion. In order to illustrate the multi axial deformation, deformation contours were plotted based on specimen 1 under flow case 1 as shown in Figure 9 below. The results shown good qualitative agreement with Alian *et al.*'s [8] results where welded region would experience expansion and the expansion was not instantaneously lifted after the welding torch passed. To further study on deformation, this study has opted to focus on axial deformation near weld region. The axial deformation graphs of all specimens along axial direction under all flow cases were plotted as shown in Figure 10.

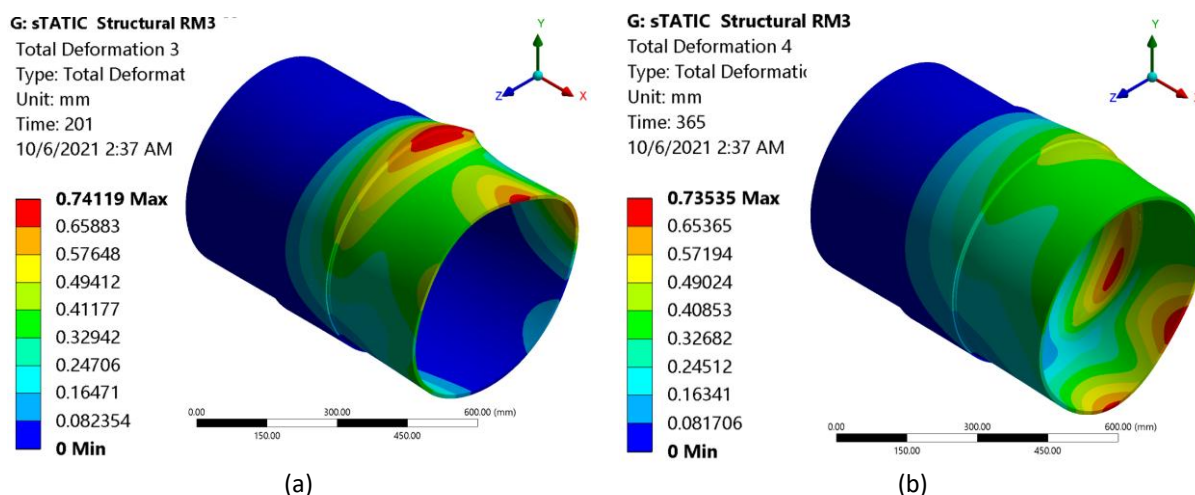


Fig. 9. Deformation contour at different time (a) 201 s (b) 365 s

Figure 10 shows good qualitative agreement between the present results (Figure 10(a) to (c)) and Qureshi's work (Figure 10(d)) [22]. However, there are notable differences because Qureshi's graph was based on one specimen and reported axial deformation or shrinkage at four circumferential locations (50 degrees, 90 degrees, 150 degrees, and 250 degrees). In contrast, the present study reports the average axial deformation at four locations (45 degrees, 135 degrees, 225 degrees, and

315 degrees) for each simulated case. Moreover, Qureshi's model was based on direct weld deposition, whereas this study modelled fillet-weld beads. Nevertheless, both sets of results show strong deformation gradients near the weld region, with expansion on the left side of the weld and shrinkage on the right.

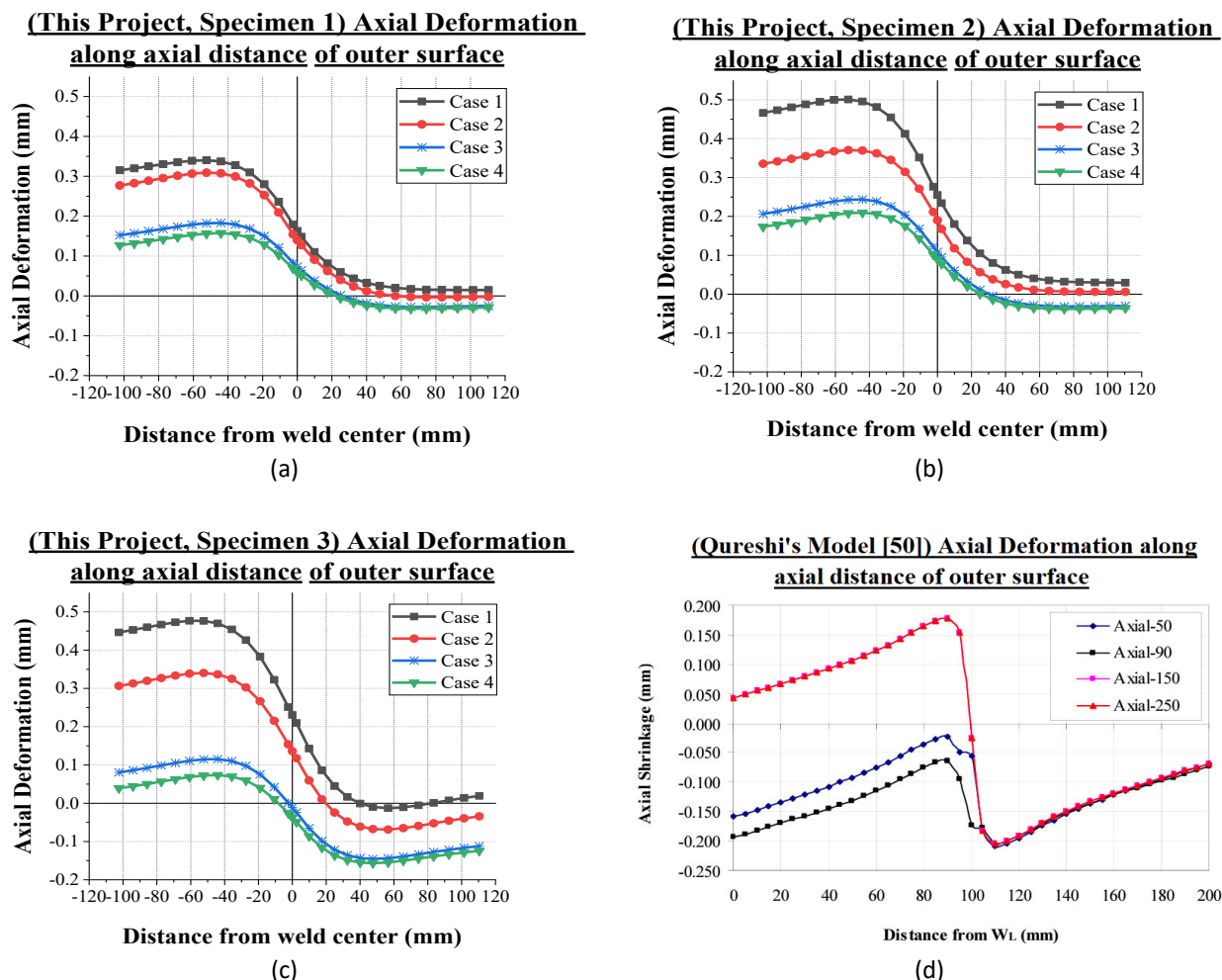


Fig. 10. Axial deformation distribution (a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Qureshi's result [22]. Note: the legacy label [50] embedded in panel (d) corresponds to revised reference [22].

Qualitatively, Figure 10 has hinted some notable axial deformation changes resulted from flow conditions and dimension alterations. First, Specimen 1 was the most insensitive model to flow condition changes whereas Specimen 3 was the most sensitive model. It might be the absence of sleeve-to-pipe gap in Specimen 1 was made it resistance to axial deformation as deduced by Lazor and Chapetti on 0 mm sleeve-to-pipe gap was more resistant to residual stress [9,15]. Second, it was noted that case 3 and 4 of all specimens were producing similar results with minor deformation increment in case 3. This was suspected due to introduction of an extra 0.4 MPa internal pressure on case 4 which would help to decrease the deformation by small amount. This was aligned with Chapetti's finding where higher operating pressure would reduce the residual stress [9]. In short, Figures 10(a) to (c) might be suggesting that case 3 and case 4 flow conditions were relatively independent of sleeve dimension alterations.

On the other hand, case 1 and 2 have formed another cluster of results where a huge leap of deformation was taken place across all specimens. Specifically, on specimen 2 and 3 has shown amplification of deformation under case 1 and 2 especially on the negative side (x-axis) of the weld

region. From the viewpoint of internal flow conditions, the increment of pressure by 1.6 MPa and flow rate by 10 m/s were not that impactful as specimen 2 and 3 has shown consistent deformation when flow condition changes from case 1 to 2. However, Figures 10(a) and (b) of specimen 1 and 2 respectively have shown huge deformation increment on the negative side of the weld center (x-axis) which might due to increment of sleeve-to-pipe gap from 0 mm to 2 mm. Note that the sleeve was located at the negative side of weld center (x-axis) was where the sleeve-to-pipe gap were located. In contrast, specimen 2 and 3 (Figure 10(b) and (c)) were showing consistent deformation under case 1 and 2 on the negative side of weld center (x-axis) despite of the sleeve-to-pipe gap has increased from 2 mm to 4 mm.

For specimen 1, the deformation increased from case 1 to 2 (Figure 10(a)) was not that high. The result might suggest that under same flow condition, the increment from 0 mm gap to 2 mm gap (specimen 1 and 2) would increase the deformation by a larger scale relative to the increment from 2 mm to 4 mm of gap (specimen 2 and 3). The presence of sleeve-to-pipe gap also increase the sensitivity to flow changes as shown in case 1 and 2 of specimen 1 and 2 in Figure 10(a) and (b). In short, specimen 1 sleeve dimensions has performed brilliantly in lowering the axial deformation at the same time remained relative insensitive to flow changes. Then, the flow case 4 have shown its consistency in reducing the axial deformation on all specimens.

Upon assessing the thermal history, residual stresses and deformation, the data collected were adequate to suggest a relatively superior sleeve dimensions and flow conditions. Hence, the evaluation would begin by ranking the specimens. The specimen evaluation matrix was tabulated as shown in Table 6.

Table 6

Specimen evaluation matrix

Evaluation criteria	Specimen 1	Specimen 2	Specimen 3
Inner piper temperature	1	2	3
Cooling time, $T_{8/5}$	1	2	3
Axial stress	1	2	3
Maximum von Mises stress	2	1	3
Critical length	1	2	3
Axial deformation	1	2	3

Rank 1 signified the best performing specimen while rank 3 was the worst among the three specimens. The ranking was based on two requirements. First, the flow case with lowest values of all evaluation criteria was ranked highest. Second, the specimens were also being assessed based on the sensitivity to flow conditions changes. From the data collected, it has been consistently pointing towards the Specimen 1 has the most insensitive sleeve dimensions. With all these data on hand, it was safe to say that specimen 1 with 8.5 mm thickness, 0mm sleeve-to-pipe gap and 200 mm sleeve length was the best dimension for current sleeve welding procedure while specimen 3 was the worst.

On the next section of the evaluation phase would focus on selecting the best combination of flow conditions based on the flow cases evaluation matrix as tabulated in Table 7 below. Rank 1 signified the best performing flow condition while rank 4 was the worst among the three specimens. The ranking was based one requirement. The flow case with lowest values of all evaluation criteria will be ranked highest. From the data collected, it has been consistently pointing towards the Flow case 4 as the best performing flow condition except for the thermal assessments. Henceforth, these data have sufficiently hinted that Flow case 4 with flow rate of 20 m/s and internal pressure of 4.4MPa was the optimal condition for current sleeve welding procedure.

Table 7
Specimen evaluation matrix

Evaluation criteria	Flow case 1	Flow case 2	Flow case 3	Flow case 4
Inner piper temperature	1	2	3	4
Cooling time, $T_{8/5}$	1	2	3	4
Axial stress	4	3	2	1
Maximum Von Mises stress	4	3	2	1
Critical length	4	3	2	1
Axial deformation	4	3	2	1

4. Conclusions

This project completed a numerical study of steel-sleeve repair welding on an API 5L X65 gas pipeline using ASTM A131-74 Grade AH steel for the sleeve. Specimen 1 provided the most suitable dimensions for the simulated setup, mainly because the absence of a sleeve-to-pipe gap reduced the axial-stress distribution and pipe deformation. The result is consistent with the cited recommendation that the sleeve-to-pipe gap should not exceed 3 mm [20]. Specimen 3, with a 4 mm gap, produced a wider residual axial-stress distribution. Sleeve-length changes had no significant effect within the investigated range, in agreement with earlier studies [15,21]. The maximum inner-wall temperature remained below the 982°C burn-through limit cited in DEP 31.38.60.10 [23]. Accordingly, the first objective was achieved: for this simulation setup, the suitable sleeve dimensions were 8.5 mm thickness, 200 mm length, and 0 mm sleeve-to-pipe gap.

For the internal gas flow condition, it was found that increasing the gas flow rate and pressure would reduce the cooling time by at least 4 % depending on the specimen dimensions. This was in congruence with past study [11] and it was noted that increasing small amount or pressure (0.4 MPa) did not increase the cooling time dramatically. At most it was 4.43 % for specimen 1. Then, it was found by increasing the gas flow rate from 10 m/s to 20 m/s has resulted inner pipe temperature decrement by least 13.2 %.

From the results, this study has achieved the first objective of identifying suitable steel sleeve thickness, length and sleeve-to-pipe gap. The specimen 1 dimension was chosen based on the relative minimal residual stresses and deformation data. Secondly, the gas flow conditions were identified where 20 m/s of flow rate with 4.4 MPa of internal pressure were suitable for current gas pipeline sleeve welding repair setup. This has fulfilled the study second objective. For future study it is suggested to focus on designing post heat-treatment process, characterizing the weld pool flow phenomenon, conduct microstructural observation, hardness test and perform experimental study based on current setup.

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