On The Effect of Four Interlayers' Thicknesses with Gradually Varying Thermal Expansion Coefficient Between Dissimilar Welds of 2.25Cr-1Mo Steel and Alloy 800H

Saqib Anwar, Ateekh Ur Rehman, Yusuf Usmani, Ali M. Al-Samhan
Industrial Engineering Department, College of Engineering, King Saud University
P.O. Box 800, Riyadh 11421, Saudi Arabia
sanwar@ksu.edu.sa, arehman@ksu.edu.sa, yusmani@ksu.edu.sa, asamhan@ksu.edu.sa

Abstract

Dissimilar metal welds (DMWs) are commonly employed in various scenarios including the power plants and petrochemicals sector. However, DMWs have been reported for premature failures because of the stresses generated in the weld region owing to the high variation in the coefficient of thermal expansion (CTE) of the different welded pipes' materials. To overcome the problem of high CTE difference in the weld region some researchers have demonstrated the use of the interlayers between the welded pipes which gradually varies the CTE. In this paper, dissimilar metal welding of 2.25Cr-1Mo steel (CTE = 12 μm/m˚C) and Alloy 800H (CTE = 14.4 μm/m˚C) materials is studied which have a large difference of 20% between their CTEs. To overcome the effect of the high CTE difference between the 2.25Cr-1Mo steel and Alloy 800H, four interlayer materials are added in the weld region, namely; Inconel 625 (12.8 μm/m˚C)/ Inconel 718 (13 μm/m˚C)/ Inconel 600 (13.3 μm/m˚C)/ and Nimonic-PE16 (13.8 μm/m˚C). This results in the gradual variation of the CTE from 2.25Cr-1Mo steel to Alloy 800H. However, no previous research is reported which studied the effect of the thickness of the interlayers on the distortion generated in the weld/joint. This study employs the finite element (FE) analysis to study the effect of the interlayers' thicknesses on the distortion developed in the joint. For this purpose, a fully coupled temperature-displacement analysis is used. Furthermore, the FE analysis is conducted under the commonly encountered service conditions in the power and petrochemical sectors, i.e., superheated steam passing through the pipe at a temperature of 454˚C and pressure of 21.55 MPa. To systematically study the effect of the interlayers' thicknesses, a Taguchi L9 design of experiment (DOE) approach is employed by using the levels of thickness as 40 mm, 70 mm, and 100 mm for each interlayer material. The results of the FE analysis reveals that varying the interlayers' thicknesses between the 2.25Cr-1Mo steel and Alloy 800H have a significant effect on the distortion produced in the joint. Moreover, optimization analysis revealed that employing the interlayers' thickness combination of Inconel-625 = 100 mm, Inconel-625 = 40 mm, Inconel-625 = 40 mm, Nimonic = 40 mm lead to minimum distortion of 2.27 mm in the joint.

Keywords
Dissimilar welds, 2.25Cr-1Mo steel, Alloy 800H and finite element modelling

1. Introduction

High performance is a must to be fulfilled requirement for materials employed in tough working conditions of power plants and petrochemical sectors where 475˚C temperature and 215.5 bars pressure are commonly occurring conditions (Hilkes and Volker 2009; Lippold 2014). The situation is more aggravated when the materials are subjected to the temperatures that are not constant rather keep varying from room temperatures to high temperatures of superheated steam in power plants. Ceramics based materials usually cannot be employed under temperature reversal conditions. Furthermore, it is not economically viable to make steam handling equipment such as pipes with ceramics due to their poor manufacturing properties such as lack of weldability due to extremely high melting points. Only few metallic materials conform to such tough working conditions. Low alloy ferritic 2.25Cr-1Mo steel is used extensively as a structural material in steam generating system of power plants and petrochemical industries (Nelson, Lippold, and Mills 2000). Similarly, austenitic stainless steel 800H is employed in the heat exchangers (Tillack and Guthrie 1998). This necessitates the fabrication of dissimilar metal weld (DMW) between ferritic and austenitic steels. When the DMWs are developed by using the conventional welding techniques such as fusion welding, the experience has demonstrated that failures of DMW can occur prematurely at service times below the design life of the plant (DuPont and Mizia 2010; Klueh and F 1982). These failures are attributed to number of factors, which are discussed as follows. Larger difference (20%) in the coefficient of thermal expansion (CTE) exists between the ferritic 2.25Cr-1Mo steel (CTE = 12 µm/m˚C) and austenitic 800H alloy (CTE = 14.4 µm/m˚C). This large difference in CTE, combined with the large differences in creep strength across the interface, lead to highly localized shear stresses along the fusion line (King, Sullivan, and Slaughter 1977). Inconel filler metals (with an intermediate CTE) are used to improve service life of dissimilar metal welds between 2.25Cr-1Mo steel and Alloy 800H. However, service failures continued indicating that the steep differences in CTE, microstructure, and property gradients are still problems. Further improvement of the service life of 2.25Cr-1Mo steel to Alloy 800H weld still exists by developing graded transition joints (DuPont and Mizia 2010).

Some solutions have been presented in the literature to improve the DMWs service life. For example, (Coleman and Gandy 2007) suggested the use of filler metal in fusion welding with an intermediate CTE (e.g. Inconel 82 and Inconel 182). However, CTE and creep resistance mismatch are found to be still problems even when using the Ni-based filler metals for welding 2.25Cr-1Mo and Alloy 800H (Coleman and Gandy 2007).

In order to mitigate the above existing problems of DMWs, it is proposed to develop transition joints of four Ni-based alloy interlayers between 2.25Cr-1Mo steel and Alloy 800H by using the friction welding process, as shown in Figure 1. The interlayers are selected in such a way that they facilitate the gradual increase in the CTE value from 2.25Cr-1Mo steel to Alloy 800H. These proposed Ni-based based interlayers are Inconel 625 (CTE value 12.8 µm/m˚C), Inconel 718 (13 µm/m˚C), Inconel 600 (13.3 µm/m˚C), and Nimonic PE-16 (13.8 µm/m˚C). Some of the specific merits of friction welded DMW with interlayers over that obtained with conventional fusion welding are summarized as follows: (1) Smooth transition in CTE; number of interlayers with smooth transition of CTE rather than a single interlayer of filler material in case of fusion welds. It will reduce the CTE mismatches between 2.25Cr-1Mo and Alloy800H and hence will reduce the stress concentration along the weld interface which is found to be the root cause of failures. (2) Absence of partially melted zone (PMZ); The fusion welding will lead to the formation of PMZ and a martensitic formation at the fusion line of 2.25 Cr-1Mo steels (with Inconel 82 electrode). Being solid state welding, PMZ and therefore, martensite formation will be absent in the case of the friction welded transition joints. (3) Defect free welds; due to the absence of melting phenomenon. the welded interlayers will be free of porosity, cracking and slag inclusions in contrast to fusion welded metal counterparts.

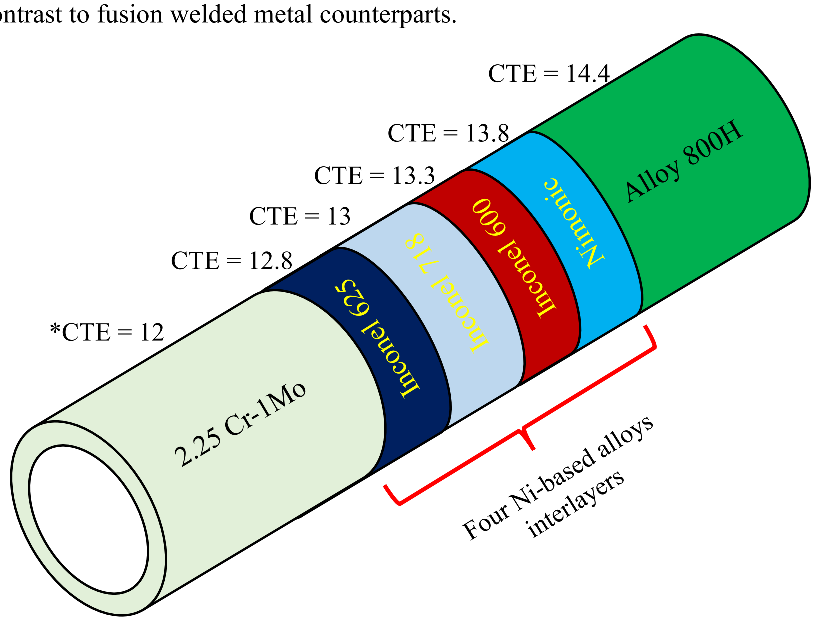

Figure 1: Friction welded Ni-based alloys interlayers between 2.25 Cr-1 Mo and Alloy 800H. * CTE values are in µm/m˚C units

In view of smooth and gradual transition of coefficient of thermal expansion than the state of the art fusion welds, the proposed interlayers of Ni-based alloys will result in gradual rather than abrupt change in physical, mechanical and metallurgical properties. With the proposed approach, the functional graded transition friction welded joint can be inserted in between 2.25Cr-1Mo steel and Alloy 800H pipes. It will allow to weld two similar welds at either end of the transition joint, as shown in Figure 2. This will avoid welding these dissimilar metals by fusion welding which are prone to failure.

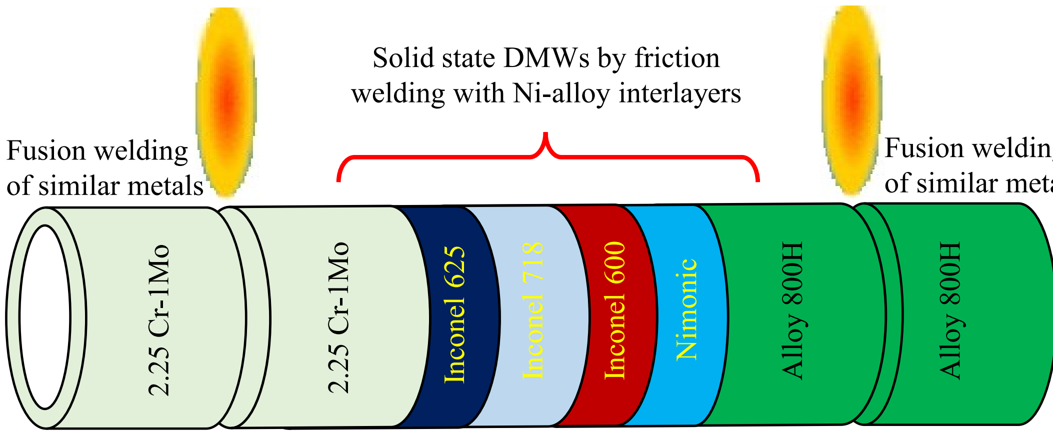

Figure 2: Two similar welds by fusion welding at either end of the DMW transition joint.

Some studies have been presented on the FE modelling of the friction welding process. For instance, (Asif. M, Shrikrishana, and Sathiya 2015) presented a FE model to simulate the rotary friction welding process for UNS S31803 duplex stainless steel joints. They used the FE results to analyze the temperature history and axial shortening of the welded rods. (Łukaszewicz 2018) developed a FE model for studying the temperature field during the rotary friction welding of AISI 1040 steel rods. Similarly, (Qinghua et al. 2006) studied the effect of rotary friction welding parameters on temperatures, stresses and strains developed during the friction welding of Al-Cu-Mg alloys round bars. However, none of the previously reported studies focused on the use of interlayers and its effect on the distortion produced in the welded joint. Since there is no previous literature published on using the friction welded Ni-alloys based interlayers between the 2.25Cr-1Mo and Alloy800H materials. So there exist a challenge on how to select the appropriate thickness of the Ni-alloys interlayers. The goal of this paper is to employ the finite element (FE) modelling as a precursor prior to the actual friction welding experiments to determine the appropriate thickness of the Ni-alloys based interlayers between 2.25Cr-1Mo steel and Alloy 800H. The presented work is part of a project where the target is to develop successful DMWs between 2.25Cr-1Mo steel and Alloy 800H materials by using the solid state rotary friction welding technique.

2. Finite element modelling

To understand the effect of the interlayers' thicknesses between the 2.25Cr-1Mo steel and Alloy 800H at high temperature, a finite element (FE) model was developed. The FE model was developed by using a commercially available FE modelling package ABAQUS 6.13. Since it is required to investigate both distortion and thermal effects simultaneously, a fully coupled temperature-displacement analysis was used. To consider a more realistic scenario of a power plant such heat exchanger application, the 2.25Cr-1Mo steel and Alloy 800H alloys along with the interlayers are considered in the FE model as pipes rather than considering these as rod or bar. Also, the FE analysis of the DMW joint/pipe with interlayers is conducted under the typical working condition of a power plant, i.e., steam temperature of 475˚C at a pressure of 215.5 bars (21.55 MPa) (Hilkes and Volker 2009). A view of the FE model with four interlayers sandwiched between the 2.25Cr-1Mo steel and Alloy 800H with applied boundary conditions is shown in Figure 3.

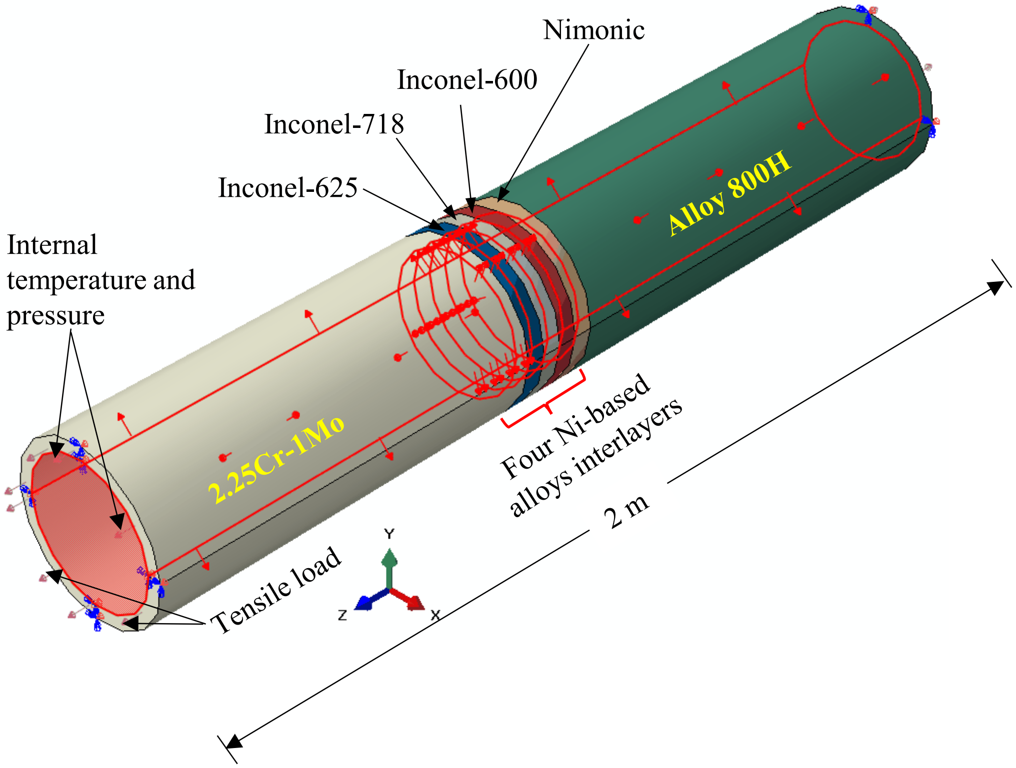

Figure 3: Internal temperature and pressure, and tensile load applied to the joint/pipe

Details of the materials' mechanical and thermal properties used in the FE model are shown in Table 1 and Table 2, respectively. The plasticity properties of all the materials were also incorporated in the FE model. A tensile load of 1500 MPa was applied at both ends of the joint/pipe, as shown in Figure 3. The tensile load was applied to consider the condition that the DMW joint is welded between to pipes that exert tensile stress on the joint. In all the simulations, an external temperature of 25°C was applied to the external surface of the joint, while the internal temperature was set at 475°C. The total length of the joint/pipe was fixed as 2 m. The thickness of the interlayers was varying in between the 2.25Cr-1Mo steel and Alloy 800H, while keeping the overall joint/pipe length as 2 m. The goal of the FE simulation was to change the thickness of the interlayers and then evaluate the distortions developed in the joint. For this purpose, three levels of thicknesses were considered for each interlayer, namely, 40 mm, 70 mm, and 100 mm. A design of experiment (DOE) approach was employed to systematically study the influence of the interlayers' thickness. A standard Taguchi L9 design was used for this purpose. The DOE L9 runs are shown in Table 3. C3D8RT eight-node thermally coupled reduced integration brick elements were used for meshing.

Table 1: Mechanical properties of the materials used in the FE model

	2.25Cr-1Mo steel	Interlayer-1 (Inconel-625)	Interlayer-2 (Inconel-718)	Interlayer-3 (Inconel-600)	Interlayer-4 (Nimonic)	Alloy 800H
Elastic modulus (GPa)	215	207.5	200	214	198	197
Poisson ratio	0.268	0.278	0.294	0.327	0.3	0.339
Yield strength (MPa)	230	517	1036	310	450	200
Tensile strength (MPa)	500	930	1240	655	900	531
Percentage elongation (%)	20	42.5	12	40	28	50

Table 2: Thermal properties of the materials used in the FE model

	2.25Cr-1Mo steel	Interlayer-1 (Inconel-625)	Interlayer-2 (Inconel-718)	Interlayer-3 (Inconel-600)	Interlayer-4 (Nimonic)	Alloy 800H
Coefficient of thermal expansion, CTE (µm/m°C)	12	12.8	13	13.3	13.8	14.4
Conductivity (W/m°C)	36.3	9.8	11.11	14.9	11.72	11.5
Specific Heat (J/kg°C)	439.34	410	435	444	544	460
Density (Kg/m^3)	7800	8440	8190	8470	8000	7940

Table 3: L9 DOE for interlayers' thickness and the corresponding distortion produced in the joint

Run	Interlayer-1 (Inconel-625) thickness (mm)	Interlayer-2 (Inconel-718) thickness (mm)	Interlayer-3 (Inconel-600) thickness (mm)	Interlayer-4 (Nimonic) thickness (mm)	Maximum relative distortion (mm)
1	40	40	40	40	3.44
2	40	70	70	70	2.366
3	40	100	100	70	4.42
4	70	40	70	100	2.674
5	70	70	100	40	3.796
6	70	100	40	70	3.372
7	100	40	100	70	3.66
8	100	70	40	100	3.458
9	100	100	70	40	3.274

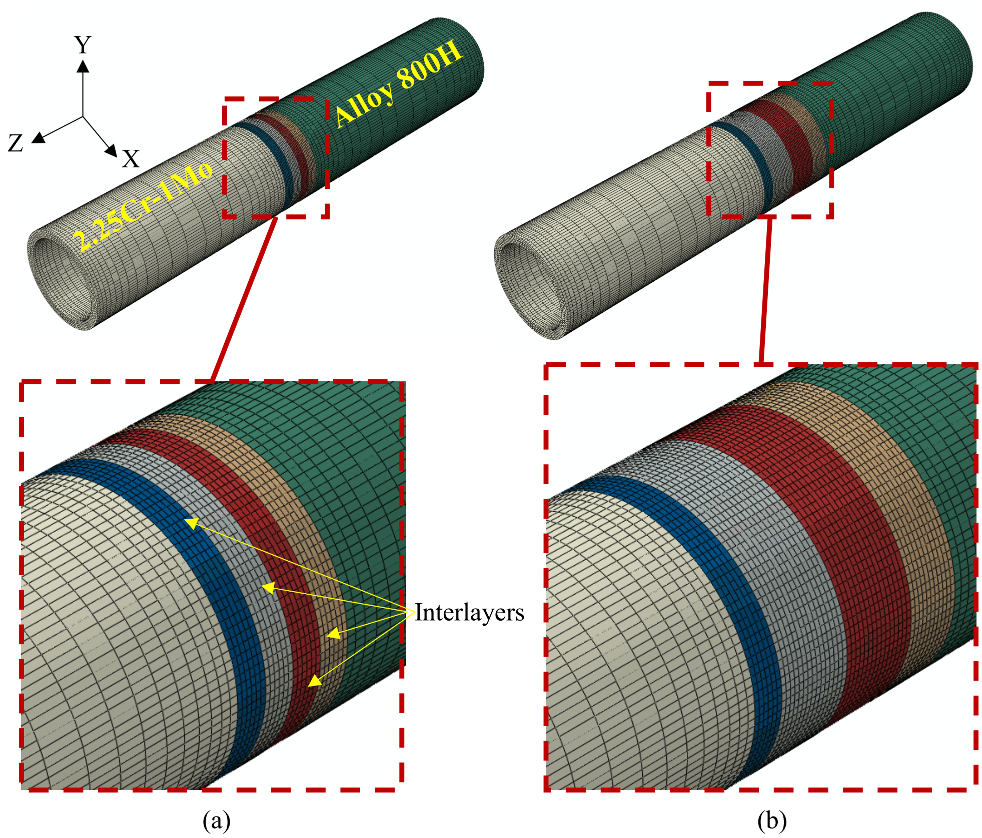

Figure 4: A meshed view of the FE model with varying interlayers' thicknesses, (a) and (b) correspond to run-1 and run-3, respectively, in DOE Table 2.

A meshed view of the FE models with four interlayers of varying thicknesses between the 2.25Cr-1Mo steel and Alloy 800H materials is shown in Figure 4. A fine mesh was used in the interlayers' region and near the ends of the joint, i.e., in the regions where high distortions are expected and the boundary conditions are employed.

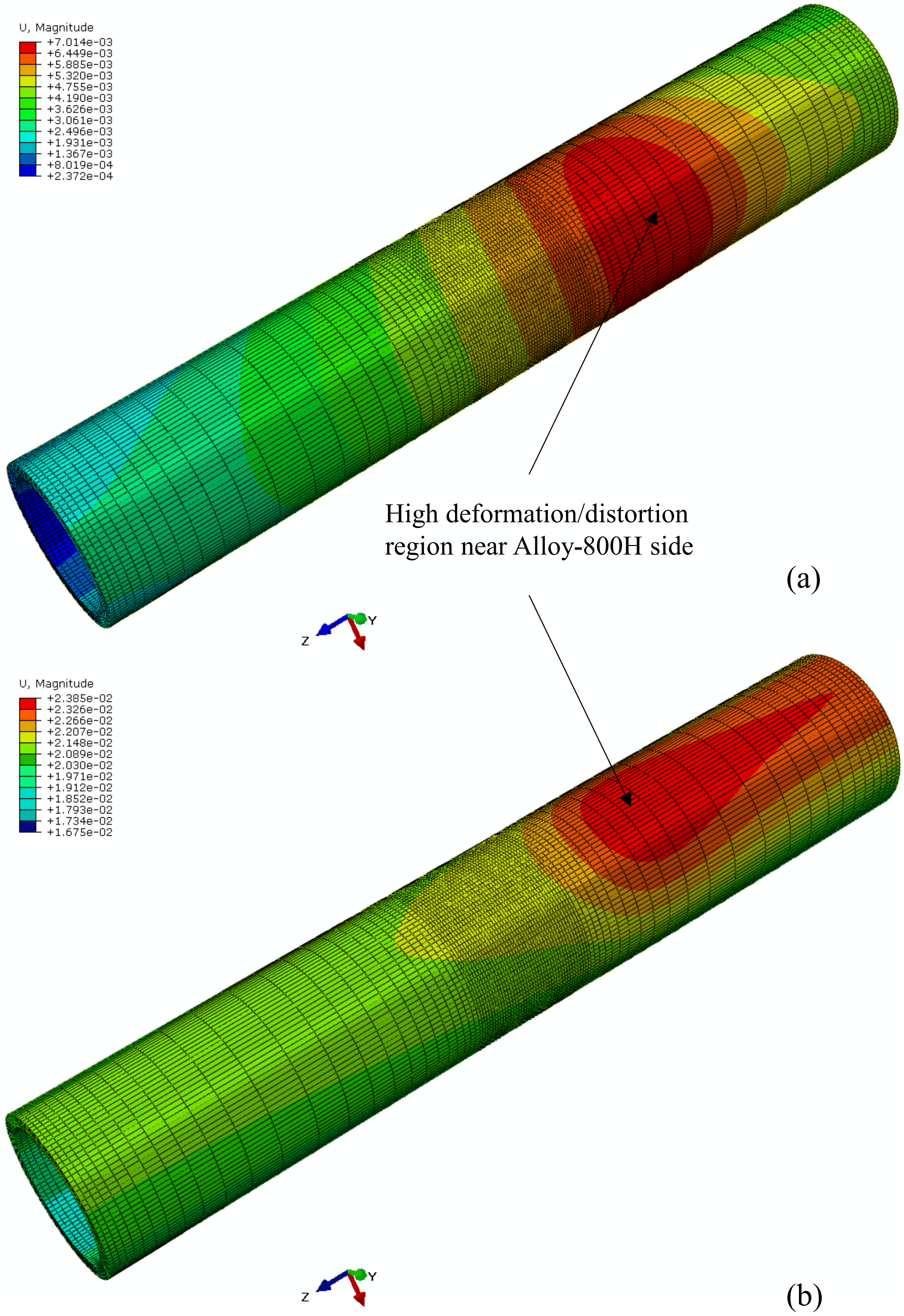

Figure 5: Simulated deformation results in the pipe, (a) run-3 and (b) run-4. The scale of the legends is in meters

3. Results and Discussion

The results of the FE simulations in terms of the maximum relative distortion/deformation produced in the rod are listed in Table 3. The maximum relative distortion is calculated by taking the difference between the highest and the lowest point on the top/external surface of the joint after the FE simulation. An example of the deformation produced in the pipe is shown in Figure 5 for DOE run 3 (see Figure 5(a)) and run 4 (see Figure 5(b)). The difference in the deformation behavior is prominently visible between Figure 5(a) and (b). This shows that the change in the interlayers' thicknesses can have significant effect on the distortion produced in the joint.

A comparison of the relative distortion produced in the joint for the L9 simulations is shown in Figure 6. It can be seen that by changing the interlayers' thicknesses both the pattern and the magnitude of the distortion changes in the joint. This shows that the interlayers' thickness significantly affects the distortion produced in the joint. From the L9 simulation results it can be said that the combination of the interlayers thicknesses in run-2 yields the lowest distortion in the pipe. It can be noticed that the maximum distortion is always produce towards the alloy 800H side. This could be due to its lowest yield strength among all the materials used in the joint (see Table 1). Therefore, under the high thermal stresses the alloy 800H side shows the highest deformation.

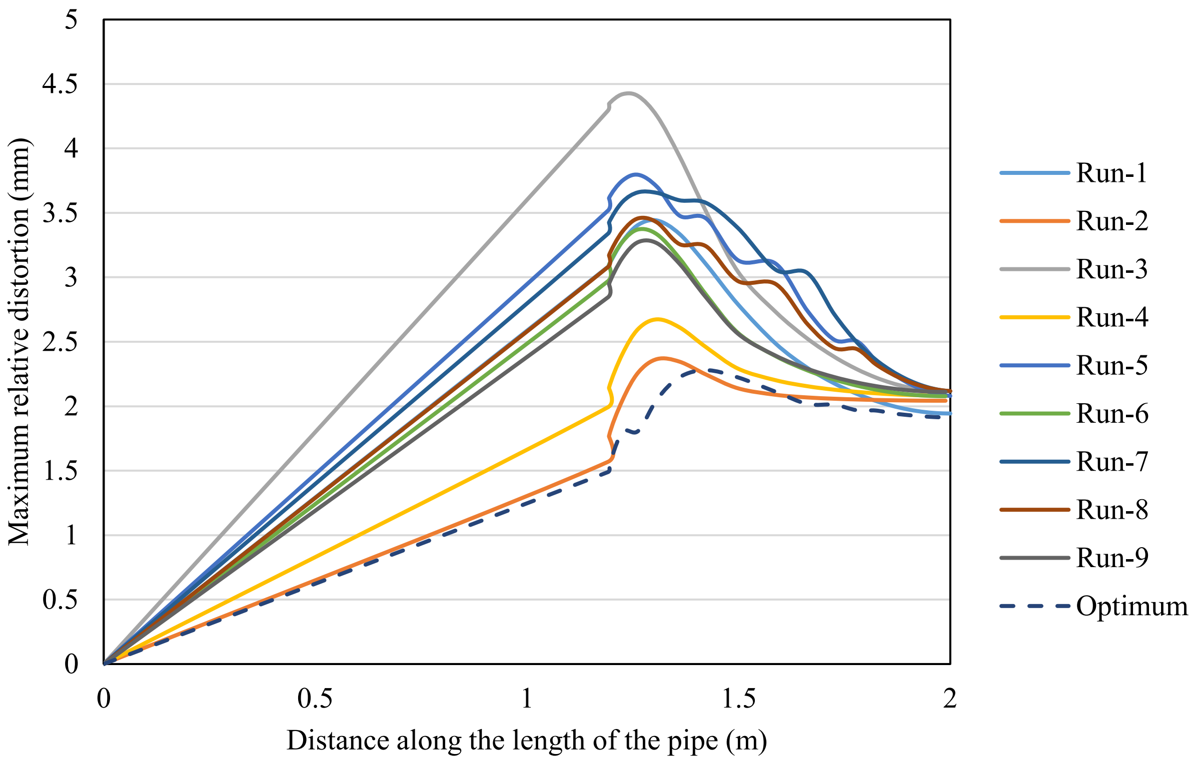

Figure 6: Comparison of the distortion results for L9 runs. Left end 2.25Cr-1Mo steel and right end alloy 800H.

After the completion of the FE simulations of the L9 experiments, it was attempted to find the optimum combination of the interlayers' thicknesses for minimizing the distortion in the joint. For this purpose, a response optimization was run by using the desirability approach in Minitab for minimizing a single objective, i.e., distortion. The thickness values determined by the response optimizer for the interlayers are; Inconel-625 = 100 mm, Inconel-625 = 40 mm, Inconel-625 = 40 mm, Nimonic = 40 mm. The FE analysis was re-run at the optimized values of the interlayers' thicknesses. The FE results shows the distortion in the joint reduced to 2.27 mm at the proposed optimum interlayers' thicknesses. It should be noted that this value of distortion is less than any of the combination of the L9 experiments as can be seen in Figure 6.

4. Conclusion

In this study a finite element model is presented to study the influence of the friction welded Ni-alloys based interlayers' thicknesses in between dissimilar materials of 2.25Cr-1Mo ferritic steel and austenitic Alloy 800H. The following main conclusions could be drawn.

- The FE simulation results shows that the distortion produced in the joint is quite sensitive to the interlayers' thickness used in the joint.

- The material in the joint with lowest yield point, alloy 800H in the current case, exhibits the peak distortion in the joint.
- The following combination of the interlayers; thickness can lead to minimum distortion (2.27 mm) in the joint; Inconel-625 = 100 mm, Inconel-625 = 40 mm, Inconel-625 = 40 mm, Nimonic = 40 mm.

Acknowledgement

This Project was funded by the National Plan for Science, Technology and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Kingdom of Saudi Arabia, Award Number (15-ADV3717-02).

References

Asif. M, Mohammed, Kulkarni Anup Shrikrishana, and P. Sathiya. 2015. "Finite Element Modelling and Characterization of Friction Welding on UNS S31803 Duplex Stainless Steel Joints." *Engineering Science and Technology, an International Journal* 18(4):704–12.

Coleman, K., and D. Gandy. 2007. "Alternative Filler Materials for DMWs Involving P91 Materials." Pp. 940–67 in *International conference on Advances in Materials Technology for Fossil Power Plants*. Marco Island, Florida, USA.

DuPont, John N., and Ronald E. Mizia. 2010. *Review of Dissimilar Metal Welding for the NGNP Helical-Coil Steam Generator*. Next Generation Nuclear Plant Project.

Hilkes, Jan, and Gross Volker. 2009. "Welding CrMo Steels for Power Generation and Petrochemical Applications." *Past, Present & Future*.

King, J. F., M. D. Sullivan, and G. M. Slaughter. 1977. "Development of an Improved Stainless Steel to Ferritic Steel Transition Joint." *Welding Journal* 56:354–58.

Klueh, R. L., and King J. F. 1982. "Elevated-Temperature Tensile and Creep-Rupture Behavior of Alloy 800H/ERNiCr-3 Weld Metal/2.25Cr-1Mo Steel Dissimilar-Metal Weldments." *ORNL*.

Lippold, John C. 2014. *Welding Metallurgy and Weldability*. John Wiley & Sons.

Łukaszewicz, A. 2018. "Nonlinear Numerical Model of Friction Heating during Rotary Friction Welding." *Journal of Friction and Wear* 39(6):476–82.

Nelson, T. W., J. C. Lippold, and M. J. Mills. 2000. "Nature and Evolution of the Fusion Boundary in Ferritic-Austenitic Dissimilar Metal Welds — Part 2: On-Cooling Transformations." *Welding Research* 267s-77s.

Qinghua, Li, Li Fuguo, Li Miaoquan, Wan Qiong, and Fu Li. 2006. "Finite Element Simulation of Deformation Behavior in Friction Welding of Al-Cu-Mg Alloy." *Journal of Materials Engineering and Performance* 15(6):627–31.

Tillack, D. J., and J. E. Guthrie. 1998. "Wrought and Cast Heat-Resistant Stainless Steels and Nickel Alloys for the Refining and Petrochemical Industries." *Nickel Development Institute*.

Biographies

Saqib Anwar is an Associate Professor in the Industrial Engineering Department at King Saud University, Riyadh, the Kingdom of Saudi Arabia (KSA). He earned B.S. in Industrial and Manufacturing Engineering from University of Engineering and Technology, Lahore, Pakistan, Master of Science and PhD in Manufacturing Engineering from University of Nottingham – UK. His research interests are in advanced manufacturing technologies and processes, such as additive manufacturing, conventional and non-conventional machining, fabrication and machining of nano-composites, and finite element modelling.

Ateekh Ur Rehman is Professor in Industrial Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia. He earned Bachelor of Engineering Degree in Production Engineering from SGGS College of Engineering, Masters in Advance Manufacturing Systems from Barkatullah University, Bhopal, India and PhD in Industrial Engineering from Indian Institute of Technology Bombay (IIT Bombay), Mumbai, India. His areas of interest are lean, agile and reconfigurable manufacturing system, supply chain management, multi criteria decision support systems for manufacturing systems and joining of metals.

Yusuf S. Usmani is a Lecturer in Industrial Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia. He earned Bachelor of Engineering Degree in Production Engineering from S. S. B. T's College of Engineering. & Technology and, Masters in in Production Technology and Management from V.J.T.I. Mumbai, University of Mumbai, India. His areas of interest are operations management, manufacturing engineering, joining of metals and supply chain management.

Ali M. Al-Samhan is currently working as Professor in Industrial Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia. Prof. Ali M. Al-Samhan has a B.Sc. and M.Sc. Degrees in Mechanical Engineering from King Saud University, Riyadh, KSA. He obtained his Ph.D. from School of manufacturing and mechanical engineering, Birmingham University, United Kingdom. Currently, he is a Full Professor and chairman of the Industrial Engineering Department, King Saud University. Prof. Al-Samhan served as a vice dean of scientific research at King Saud University. He also serves as a consultant for leading manufacturers in Saudi Arabia and member of SASO committee for industrial standardization. Also, he assists local manufactures, as R & D consultant, in developing more than 30 products introduced to Saudi market for 20 years ago. Also, he develops two BSc teaching laboratories in Industrial Engineering Department, for metal forming and manufacturing automation using PLC courses. His research interests focus on engineering materials and manufacturing processes, monitoring and controlling of manufacturing systems using artificial intelligence, product design and development, automation and mechatronics, and biomechanical engineering. Prof. Al-Samhan has many registered patents and published papers in leading journals of Industrial and Manufacturing Engineering. He is leading a number of funded projects from different organization in Saudi Arabia.