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Research Article

Consideration of Differential Thermal Expansion Rates during Stress Analysis of Cladded Pipes

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Abstract

The application of Corrosion resistance alloy (CRA) cladded pipes has become more customary across the Industry in recent years for high corrosive services (e.g. Sour gas). These pipes serve as a replacement not only to carbon steel pipes (Having high potential to corrosion over a period of time) but also as a replacement to expensive Alloy Steel / Stainless Steel pipes. CRA cladding technology involves application of a metallurgical junction on carbon steel pipes with an inner coating of high corrosion resistance alloy material (e.g. SS316, Alloy 625). This paper's is intended to study the stress generated in the piping on account of differential thermal expansion Coefficients considering bimetallic approach while satisfying the ASME B 31.3 code requirements per para 301.7.3. Further results obtained are compared using analytical and finite element models.

Keywords: *Corrosion resistance alloy (CRA), Clad, Abaqus*

Introduction

Production fluids often contain high sulfur or CO2 content and require the usage of materials suitable to resist corrosive environment. When the H2S and CO2 content is too high, the corrosion resistance properties of C-Mn steel are enhanced with Corrosion resistance alloy (CRA).

Cladded Pipes & Fittings are used in water, oil and gas industries, sub-sea applications and petrochemicals & refineries. Generally the outer part of the pipe is made of carbon steel to withstand the inner pressures, while the inner high alloyed cladding of the pipe is meant to protect against corrosion.

There are two types of cladding process:

- Metallurgical Bonded
- Mechanically Bonded

In this paper we are going to study about Metallurgical bonded CRA clad pipes. As per ASME B31.3 (2016) para 301.7.3 this paper assess thermal stresses imposed in CRA clad pipes due to differential thermal expansion Coefficients of base pipe material and cladded pipe material.

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CRA Cladded pipes

CRA pipes usage is recommended in areas where dynamic stress, high pressure and a high level of corrosiveness is present in the fluid media being transported. By using clad materials, the strength and toughness of carbon-manganese steels is combined with the corrosion resistance property of high-alloyed materials.

Cladded pipes meet the highest standards towards durability, corrosion resistance and cost effectiveness. These pipes are cost effective and have savings ranging from 25 to 40% due to the manufacturing process and nature of the base metal (Butting,2014).

Metallurgical clad pipes offer the advantage of smaller wall thicknesses compared to austenitic solid-wall pipes and solid-wall pipes made from nickel-based alloys. Other benefits include considerable weight savings and reduced material costs.

Figure 1 Image of cladded pipes

Design parameter and material properties

Commonly used CRA materials include SS (TP 316L), Alloy 825 and Alloy 625. Among these SS (TP316 L) clad pipes are used primarily in most of the applications as compared to other Alloy 625 and Alloy 825. As per supplier demand information, CRA cladded pipes up to 16" & below diameters are primarily in demand as compared to other larger diameter pipes.
Considering above aspect, analytical and finite element analysis is carried out using following clad pipe parameters as per Table 1.

Table 1: CRA Clad 16 inch Pipe details (ASME B36.10M)

	SCH-XS	SCH-80	SCH-160
Base Material Thickness (mm)	9.7	18.4	37.4
Clad Material Thickness (mm)	3	3	3
Net Pipe Thickness (mm)	12.7	21.4	40.4

Length of Clad Pipe used for study = 1000 mm
Initial/Installed Temperature = 21 ° C
Design Temperature = 200° C

The Material properties of clad pipe are shown in Table 2.

Table 2: Material properties of Clad Pipe (ASME B31.3-2016)

Properties	Base Material	Clad material		
	A333	A312 TP 316	Alloy 825	Alloy 625
Young's Modulus (Mpa)	190	183	187	197
Expansion coefficient (mm/mm/° C)	12.27	17.26	15.84	13.86
Poisson's ratio	0.3	0.3	0.3	0.3

Methodologies

To study the effect on different CRA clad pipes such as SS316, Alloy 825, and Alloy 625 subjected to constant temperature, analytical method & finite element method is used for a constant thickness as well as varying pipe thickness.

Analytical Analysis

$$\Delta_1 = L\alpha_1 \Delta T \ldots\ldots\ldots\ldots\ldots\ldots Equation\ (1)$$
$$\Delta_2 = L\alpha_2 \Delta T \ldots\ldots\ldots\ldots\ldots\ldots Equation\ (2)$$
$$\delta_1 = \frac{PL}{A_1E_1} \ldots\ldots\ldots\ldots\ldots\ldots Equation\ (3)$$
$$\delta_2 = \frac{PL}{A_2E_2} \ldots\ldots\ldots\ldots\ldots Equation\ (4)$$

Δ_1 = *Thermal Expansion in Carbon steel pipe*
Δ_2 = *Thermal Expansion in Clad pipe*
α_1 = *Coefficient of thermal expansion of Carbon steel pipe*
α_2 = *Coefficient of thermal expansion of clad pipe*
δ_1 = *Expansion due to pulling effect from Clad pipe on Carbon steel pipe*
δ_2 = *Compression due to pulling effect from Carbon steel pipe on Clad Pipe*
A_1 = *Area of Carbon steel pipe* $= \pi(D_1 - t_1)t_1$
A_2 = *Area of Clad pipe* $= \pi(D_2 - t_2)t_2$
E_1 = *Young's Modulus of Carbon steel pipe*
E_2 = *Young's Modulus of Clad pipe*

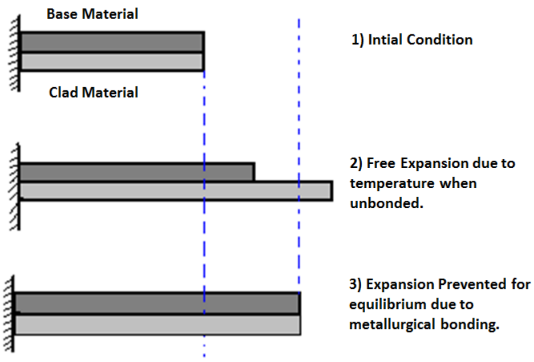

Figure 2: Image shows the behavior of bi-material clad pipe

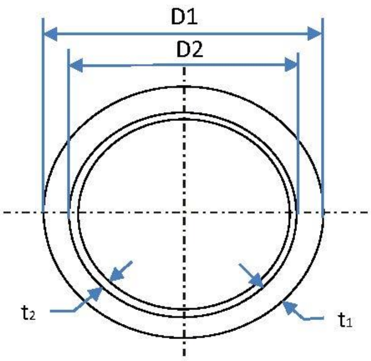

Figure 3: Dimensions of Clad Pipe

From equilibrium $\Delta_1 + \delta_1 = \Delta_2 - \delta_2 \ldots\ldots\ldots\ldots\ldots\ldots Equation\ (5)$

$$\delta_1 + \delta_2 = \Delta_2 - \Delta_1 \ldots\ldots\ldots\ldots\ldots\ldots Equation\ (6)$$
$$\text{PL}\left(\frac{1}{A_1E_1} + \frac{1}{A_2E_2}\right) = \text{L}\,(\alpha_2 - \alpha_1)\,\Delta\text{T} \ldots\ldots\ldots\ldots\ldots\ldots Equation\ (7)$$

For Simplification $(D_1 - t_1) = (D_2 - t_2) = D$

$$P = \frac{(\alpha_2-\alpha_1)\Delta T \times \pi \times D}{\left(\frac{1}{t_1E_1}+\frac{1}{t_2E_2}\right)} \ldots\ldots\ldots\ldots\ldots\ldots Equation\ (8)$$

Compressive Stress in Clad Pipe $= \frac{P}{A_2} = \frac{(\alpha_2-\alpha_1)\Delta T}{t_2\left(\frac{1}{t_1E_1}+\frac{1}{t_2E_2}\right)} \ldots\ldots\ldots\ldots\ldots\ldots Equation\ (9)$

Actual Expansion in Clad Pipe $= (\Delta_1 + \delta_1)$ or $(\Delta_2 - \delta_2) = \text{L}\alpha_1\Delta\text{T} + \frac{PL}{A1E1} \ldots\ldots\ldots\ldots Equation\ (10)$

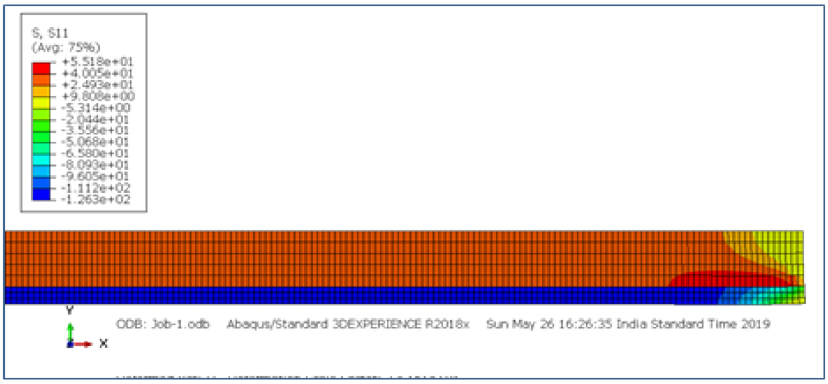

Figure 4: First Principle Stress Contour for SS-316 Clad Pipe

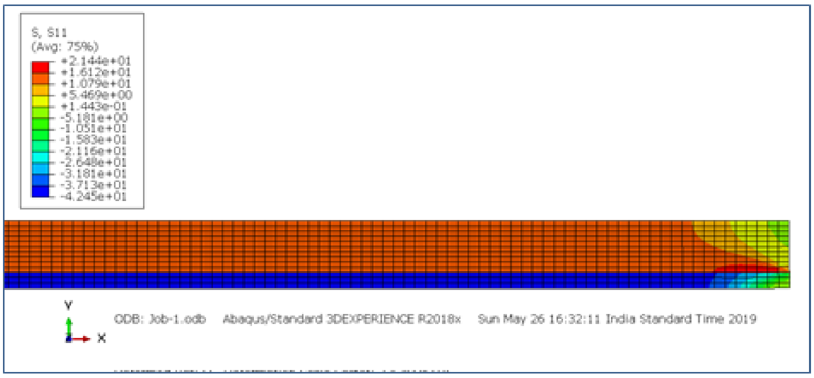

Figure 5: First Principle Stress Contour for Alloy 625 Clad Pipe

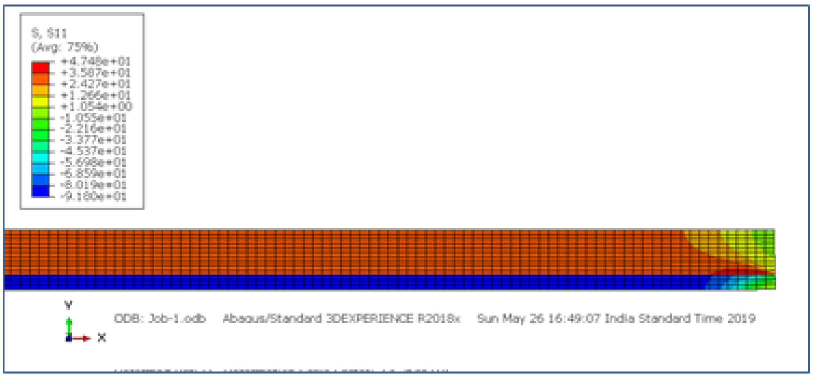

Figure 6: First Principle Stress Contour for Alloy 825 Clad Pipe

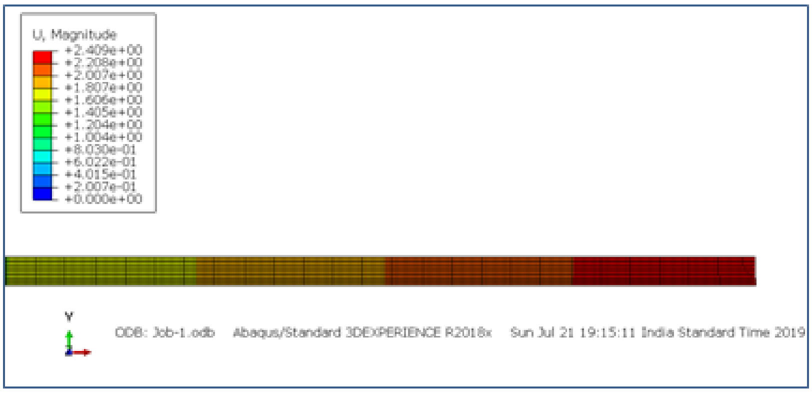

Figure 7: Actual expansion Contour for SS-316 Clad Pipe

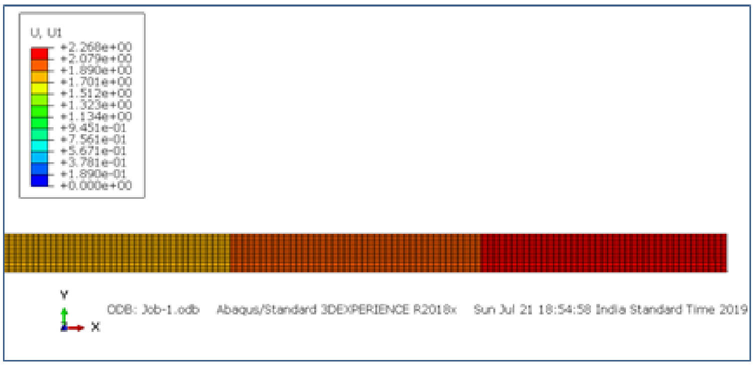

Figure 8: Actual expansion Contour for Alloy 625 Clad Pipe

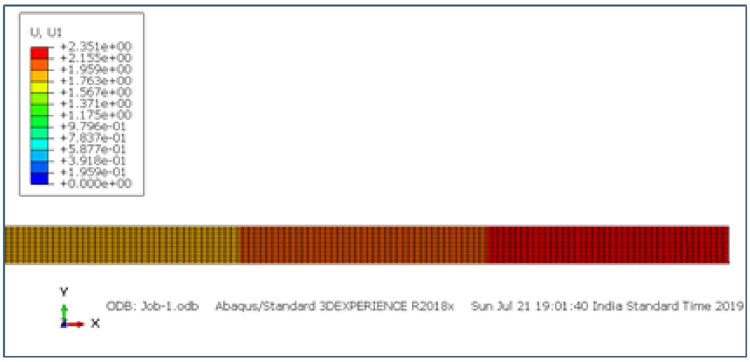

Figure 9: Actual expansion Contour for Alloy 825 Clad Pipe

Finite Element Analysis

Finite element method is used to evaluate the behavior of cladded pipes when subjected to differential expansion. For the analysis purpose 2-D models are prepared using ABAQUS. The FE analysis is carried out with 4-node CPS4R solid element, by applying constant temperature. Three distinct 2D models created considering base pipe material as carbon steel and clad material as SS 316, Alloy 625, and Alloy 825 respectively. The properties of material are provided and mesh model is developed. After solving, the first principle stress contour at nodal region is shown in Figures 4, 5, and 6. And also actual expansion contour at nodal region is shown in Figures 7, 8, and 9.

Result Comparison

The study on stresses and actual expansion rates using 12.7 mm thick pipe along length on the bi-material clad pipe subjected to constant temperature are compared. The evaluated stresses using analytical vs Finite element method are tabulated in Table 3.

Table 3: Comparison of stresses for different clad pipes

Clad Material	Analytical (Mpa)	FEA (Mpa)	Variation (%)
SS 316	134	126	6.0
Alloy 825	98	92	6.1
Alloy 625	45	42	6.7

The actual expansion rate using analytical vs Finite element method is tabulated in Table 4.

Table 4: Comparison of Expansion for different clad pipes

Clad Material	Analytical (mm)	FEA (mm)	Variation (%)
SS 316	2.5	2.4	4.3
Alloy 825	2.4	2.3	3.3
Alloy 625	2.3	2.2	2.0

The stresses in different clad pipe Material with varying thicknesses (12.7, 21.4, 40.5 mm) using analytical vs Finite element method are tabulated in Table 5.

Table 5: Comparison of stresses for different clad pipes with different pipe wall thicknesses

Pipe Thickness (mm)		SS 316	Alloy 825	Alloy 625
		(Mpa)	(Mpa)	(Mpa)
12.7	Analytical	134	98	45
	FEA	126	92	42
21.4	Analytical	145	106	49
	FEA	142	103	48
40.5	Analytical	154	112	52
	FEA	152	111	51

Result Interpretation

It is observed from the results that the stresses and actual expansion rates calculated by the analytical solution are quite close to FE results.

Also, it is observed that the thermal stresses imposed on CRA clad pipe with increase in pipe wall thickness increases further.

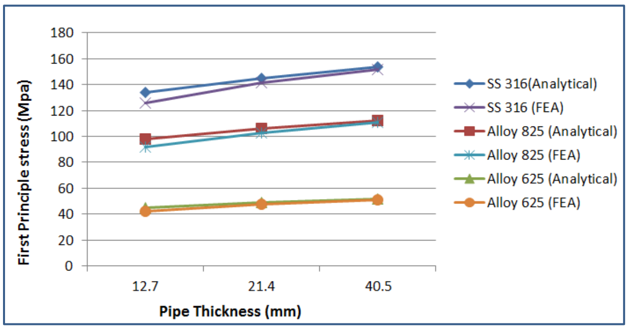

Figure 6: Variation in stresses for different clad pipes

Conclusion

From this study, it is evident that expansion stresses are quite significant in the clad pipes because of differential expansion rates of the two materials joined thru metallurgical bond.

The same needs to be considered while evaluating expansion stresses as per clause no. 301.7.3 of B31.3 and must be compared against the code allowable stress values.

Further, considering high actual expansion rates of CRA clad materials compared with carbon steel pipes, actual expansion rates should be considered while selecting shoe lengths to avoid support disengagement during operation.

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