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Design and Optimization of Economizer Shell Nozzle PWHT (Post Weld Heat Treatment) Using Finite Element Analysis

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Abstract
Welding is widely used in all the fabrication processes for the development of structural components. Due to welding process the residual stresses are generated in the component which place crucial role in the design of the component. The design methodology is used for the design of the component. It do not contain any consideration of residual stresses due to which component may fail, so to increase the suitability of design component, to accommodate residual stresses finite element analysis method is used for reducing residual stress values, But after design modification welding process is required. After the complication of welding process post weld heat treatment (PWHT) analysis is required to reduce the residual stress value. PWHT is required for local area where actual welding process is done. The residual stress decreased with increasing the post weld heat treatment temperature and holding time. Post weld heat treatment (PWHT) is the most convenient method for stress relief of welds. But PWHT cannot completely eliminate the residual stresses. So, it is essential to determine the influence of PWHT parameters like holding temperature and time on the stress relaxation for optimizing the process. This work can be used for selecting process parameters for reducing residual stresses by simulation process. In this paper residual stresses are discussed. The results are used for efficient and reliable working of application.

Keywords: engineering design, engineering processes, finite element analysis, design optimization.

Introduction

Welding represents one of the most complex manufacturing processes in terms of number of variables involved and factors contributing to the final output. Welding has been used in the fabrication of structures ranging from conventional industrial applications to high-tech engineering applications like boiler manufacturing, high-pressure vessel applications, nuclear, aerospace, marine etc. Compared to mechanical joining methods welding offers some significant advantages including flexibility of design, improved structural integrity and weight & cost savings. Welding however induces thermal strains in the weld metal and base metal regions near the weld, resulting in stresses, which in turn combine and react to produce internal forces that cause bending, buckling, and rotation. These displacements are termed as welding distortions. Despite the recognition of welding as one of the most important fabrication processes in engineering industries, there is little scientific understanding present in productivity measurement and evaluation of welding processes [1].

The problems of weld induced imperfections like residual stresses and shape change behavior evolve almost simultaneously with the introduction of welding as a joining method and harmful stresses in metals due to welding. Tremendous efforts were made in the last couple of decades showing remarkable development in new welding technologies for defect free resilient structures capable of excellent in-service thermal and structural load bearing features. Despite these considerable technological innovations in high temperature joining technologies, the problems of weld induced imperfections like residual stresses and deformation/distortion is still a major challenge for the welding engineers due to the complex nature of the welding phenomenon [2].

Weld induced residual stresses:

Residual stresses are those stresses that would exist in a body if all external loads and restraints were removed. Various technical terms have been used to refer to residual stress, such as internal stress, initial stress, inherent stress, reaction stress and locked-in stress etc. Mechanical structures suffer from residual stresses (generally undesirable) during different phases of their life cycle. In engineering structures most of the residual stresses are induced during their manufacturing phase including casting and forging, sheet metal forming and shaping (shearing, bending, grinding, machining etc.) and welding. Welding residual stresses are produced in a structure as a consequence of local plastic deformations introduced by local temperature history consisting of a rapid heating and subsequent cooling phase. During the welding process, the weld area is heated up sharply compared to the surrounding area and fused locally. The material expands as a result of being heated. This expansion is restrained by the surrounding cooler area, which gives rise to thermal stresses. The thermal stresses partly exceed the yield limit, which is lowered at elevated temperatures. Consequently, the weld area is plastically hot-compressed. After cooling down too short, too narrow or too small compared to the surrounding area, it develops tensile residual stress, while the surrounding areas are subjected to compressive residual stresses to maintain the self-equilibrium [3].

Figure 1.1 shows a tentative longitudinal and transverse residual stress distribution pattern in center cross sections of rectangular plate with centric weld. Due to the heating and cooling cycles and constraints from surrounding materials, high longitudinal stress is developed at central section of the plate. As the distance from the weld center increase, the longitudinal stress gradually decreases. Along the transverse direction, the longitudinal stress changes to compressive, whereas along the longitudinal direction it reduces to zero, as dictated by the equilibrium condition of residual stresses. Similar transverse residual stress with minor differences in distribution from the longitudinal stress and smaller magnitude can be observed.

In Figure
Plate thickness, t
Plate width, W
Plate length, L
σ_1= Transverse Residual Stress
σ_2= Longitudinal Residual Stress

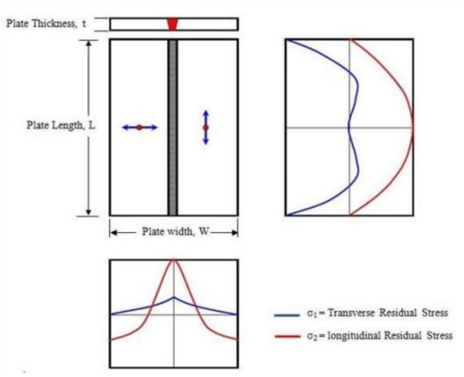

Figure 1.1 Schematic representations of residual stresses in welded rectangular plate [4].

Method

Post Weld Heat Treatment

In most modern papers post weld heat treatment is performed after welding, generally at a higher temperature and with different objectives than preheat/ interpass heating. PWHT may need to be applied without allowing the temperature to drop below the specified minimum for preheat/ interpass heating. PWHT can have both beneficial and detrimental effects. Three primary benefits of PWHT are recognized viz., tempering, relaxation of residual stresses and hydrogen removal [4].

Post Weld Heat Treatment (PWHT) reduces the residual stresses formed during welding. It also restores the macro structure of the steel. Mandatory in high pressure applications, constructors have to strictly follow PWHT requirements to avoid component failures [4] .

Why is it so important? Welding is one of the most critical processes in the manufacture of pressure vessels like the boiler of a thermal power plant. The temperature of the molten weld pool during the process is in the range of 2000 deg C. The heat increase is rapid and instantaneous. When this small strip of molten pool cools down the shrinkage results in thermal stresses that are locked up inside the metal. This also can change the macrostructure of the steel. This is because:

- The rest and bulk of the steel is almost at ambient temperature.
- Deposition of layers of weld metal creates a thermal gradient across the cross section of the weld.
- Not only the weld area but also the adjacent area is affected (HAZ).
- The sudden cooling and the phase change results in a macro structure that is not the same as the original steel, resulting in property changes that make the steel weaker and brittle.
- These residual stresses and macro structure changes, combined with operating stresses, can lead to catastrophic failure of the pressure vessels.

PWHT eliminates these effects by heating, soaking, and cooling the weld area in a controlled manner to temperatures below the first transformation point, giving the macro structure sufficient time to readjust to its original state and removing the residual stress. Pre-heat, on the other hand, is the warming up to the welding process and is at lower temperatures [5].

Factors to Consider

The factors that contribute to these stresses and macro structure changes are:

- Thickness of the weld. Higher thickness increases thermal gradients and resulting residual stresses.
- Difference in the material. Welding two materials of different combinations results in different macro structures of the base metals and the weld pool.
- Difference in geometry of the weld parts can cause different thermal gradients that can lead to residual stresses.
- The entrainment of Hydrogen during welding can lead to stress corrosion cracking during operation. The hydrogen has to diffuse out of the weld during the PWHT process.
- The weld area and HAZ have higher hardness making the steel more brittle. In Sour gas applications, this can lead to corrosion cracking. PWHT controls the hardness to acceptable levels.
- PWHT consists of heating the metal after the welding process in a controlled manner to temperature below the first transformation point, soaking at that temperature for a sufficiently long time, and cooling at controlled rates. The different methods to carry out PWHT depends more on practical constraints.
- By gas firing in a stationary furnace. This is normally done in manufacturers works were it is economical to have such a permanent furnace and gas supply system. Most of the boiler manufacturers have such gas fired furnaces.
- Boiler drums are stress relived after welding completion by heating the entire drum in a large furnace.
- Steam headers with large number of welded nozzles are also heat treated in a similar manner.
- PWHT of welded smaller parts takes place in the furnace at one time or in batches.

- By gas firing or electrical heating in temporary furnaces. This avoids cost in transporting the finished products from fabrication location to facilities that have fixed furnaces.
- Localized PWHT. Construction sites and fabrication shops use this method.
- The most common method is by electrical resistance heating. Ceramic beaded heating coils are wound over the weld area. The current controls the temperature gradients.
- Induction heating is one method that is gaining popularity even though the cost is high. This is a more welder friendly process. Unlike resistance heating only the pipe becomes hot. The temperature gradients are uniform across the thickness.
- By internal gas firing. Large vessels, columns, spherical tanks, sour tanks, etc. are heat treated by firing gas internally. This requires special equipment and skilled contractors and is a much more elaborate process. Thermal expansion of the vessel has to be considered during the PWHT process.
- Thermocouples on the surface measure and record the temperatures during PWHT. This recording is a must and is the only record of the heat treatment having been done [5].

Recipe for welding simulations

During the welding, complicated phenomenon such as temperature dependency of material properties, phase transformation (melting and evaporation) occurs for short time in localized region. Further, the stress/strain development during the welding is complex to visualize, since it is a three dimensional time and temperature dependent problem. Although, the experimental investigations provide valuable insights into the process of welding, many experimental techniques are complex and expensive and some quantities, such as the transient stress/strain development during welding, cannot be measured at all. Furthermore, traditional trial and error approach based on costly and time consuming welding experiments encounters hindrance to sound welds due to welding process parameters optimization. In order to get an appropriate insight into the process, extend the application of welding process on shop floor level with reliability and cost effectiveness, appropriate control techniques are mandatory. A synergistic approach involving both finite element modeling and experimental work has proven very useful Numerical simulations based on finite element (FE) models provide a very suitable tool for investigating the thermal and mechanical consequences of welding process. The availability of 64-bit high performance computing machines and enhanced finite element computational techniques has made it possible to simulate temperature fields developed from welding process. In contrast to experimental investigations, finite element models allow an extensive variation of welding process and heat source parameters, without having to deal with the practical limitations. The finite element models can be used for detailed studies of temperature and stress/strain during and after the welding thereby improving the understanding of the process. Once, the models have been validated, the results from the simulations can be used to demonstrate the physical essence of complex phenomenon in welding processes explicitly and can be utilized as the basis for welding process optimization. The computer simulation of welding processes enables the welding engineers to predict residual stress fields of welded structures. However, the simulation of welding process altogether is not a simple computational task due to the involvement of multi field interaction like thermal, mechanical and metallurgy. Also the filler metal deposition, moving heat source, material behavior at elevated temperature along with geometric nonlinearities made it even more complex manufacturing task for finite element community engaged in materials and processes modeling. Several commercially available finite element codes such as ANSYS®, ABAQUS®, FEMLAB®, MSC MARC®, ADINA® and SYSWELD® etc. are available which can be employed to carry out such type of manufacturing processes simulations [6].

In the current project work i have used ANSYS® for simulation. Its coding comprises elements activation/deactivation functionality, meshing algorithm, heat source modeling, material models, heat flux distribution as per analytical model and material properties management depending on the temperature reached in elements etc. To simplify the simulation procedure, generally recognized finite element simulation of welding process requiring; transient thermal analysis and structural analysis is employed.

1.1. Preamble

This report describes the modeling and analysis of PWHT of Nozzle insulation ring. The weld for insulation ring was modified locally and PWHT is carried out locally. Therefore to check the effect of local PWHT, Finite element analysis is performed [7].

1.2. Analysis Details

The PWHT analysis is carried out as per below details,

Rate of Heating above 300 ^{0}C : 56 ^{0}C /hr
Holding Temperature : 690 ^{0}C +/- 10 ^{0}C
Holding time : 8 hr
Rate of Cooling upto 300 ^{0}C /hr : 56 ^{0}C /hr

1.3. Local PWHT Details

Rate of Heating above 300 ^{0}C : 56 ^{0}C /hr
Holding Temperature : 690 ^{0}C +/- 10 ^{0}C
Holding time : 5.5 hr
Rate of Cooling upto 300 ^{0}C /hr : 56 ^{0}C /hr

1.4. Material of construction

Material of construction considered for FEA analysis is as given below:

Channel Barrel : SA 336 Gr. F22 CL3
Nozzle N3 : SA 336 Gr. F22 CL3
Insulation Ring : SA 387 Gr. 22 CL2

1.5. Material properties

ASME Sec II Part D, Ed. 2013 is referred for physical properties of materials as follows

Material	**Design temp (^{0}C)**	**Modulus of elasticity (MPa)**	**Allowable stress (MPa)**	**Yield stress (MPa)**
SA 336 Gr. F22 CL3	395	184400	161.4	241.8

FINITE ELEMENT MODEL

Software description:

The finite element analysis software used for performing analysis is ANSYS Mechanical APDL16.0 developed by ANSYS Inc. USA. The software runs on windows 7 operating system.

Modeling data:

3D geometry is created as per the dimensions given in following drawings-

General Arrangement drawing ,

Design Data, Detailed Fabrication drawing .

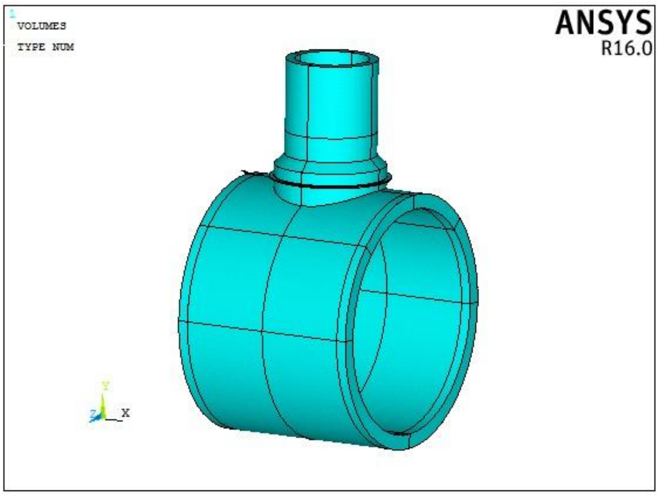

Figure 2-1 3D Model

Finite element mesh properties:

The model is meshed using 3-D brick element. The characteristic of the elements used for FEA are as follows;

Type of element : 3-D Brick element - Hexa element (Solid 185)

No. of nodes per element: 8

No. of faces per element: 6

Degree of freedom: 3 translational i.e. UX, UY and UZ

Criteria and controls adopted in mesh

All the geometries are mapped meshed because the mapped mesh has very structured and ordered elements. The necessary partitions are made to make accurate meshing which satisfies the quality check on the elements. The detail of meshing for structural analysis is given in Fig The detail of meshing for structural analysis is as given below:

Total no. of elements in the model : 38028

Total no. of nodes in the model : 48402

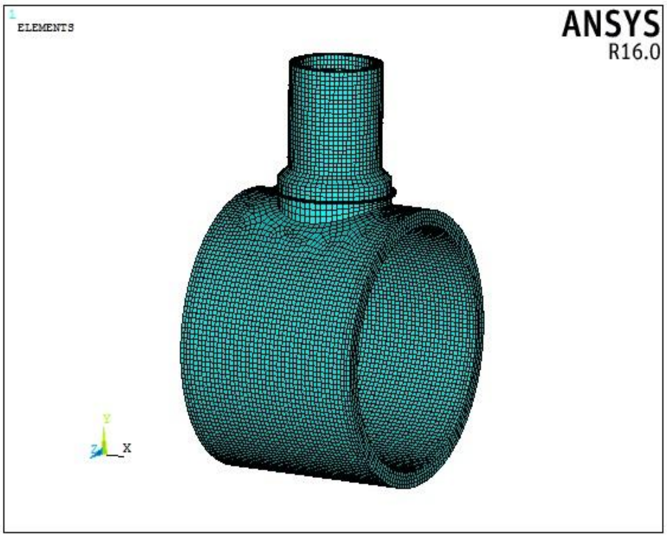

Figure 2-2 Meshed Model

3.0 Boundary condition

3.1 Thermal load

Thermal analysis is carried out in following steps

1. Welding at 1500 ^{0}C
2. Full Equipment PWHT as per Section 1.2
3. Welding at 1500 ^{0}C
4. Local Equipment PWHT as per Section 1.2

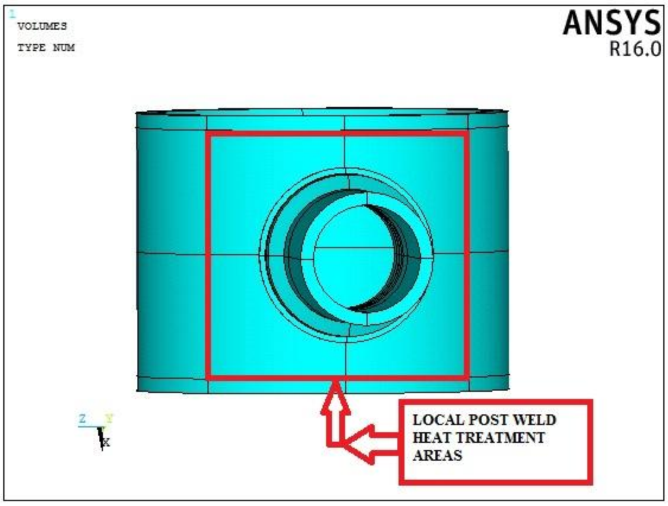

Figure 3-1 Local PWHT Areas

3.2 Structural load:
Structural calculation are carried out to calculate residual stress due to PWHT thermal effect for full equipment and local area

Acceptance criteria

The acceptance criterion is as per ASME VIII, Div 2, Edition 2013 Part 5 "Design by Analysis requirement";

- Equivalent stress derived from the average value across the thickness of a section of the General Primary Stress (Pm) produced by internal pressure and other mechanical loads but excluding geometrical discontinuities and all secondary and peak stresses must be less than S; where S is the allowable stress of material at design temperature.
- Equivalent stress derived from the average value across the thickness of a section of the Local Primary Stress (PL) produced by internal pressure and other mechanical loads including geometrical discontinuities but excluding all secondary and peak stresses must be less than 1.5 S.
- Equivalent stress derived from the average value across the thickness of a section of Local primary membrane stress plus primary stress proportional to distance from centroid produced only by mechanical load (PL + Pb) must be less than 1.5 S.
- Equivalent stress derived from the addition of primary membrane stress and secondary bending stress (PL+ Pb+ Q) across the thickness of a section must be less than 3 S.

4.1. Allowable stress

Maximum allowable stress, S as per ASME Sec II Part D, Edition 2013, Table 5A for material at design temperature.

4.2. Stress categorization

Stress Limits are considered as per ASME Section VIII, Div 2, Ed.2013 and is reproduced below;

Material	**S in MPa**	**Pm in MPa**	**PL in MPa**	**PL+Pb+Q in MPa**
SA 336 Gr. F22 CL3	161.4	S = 161.4	1.5 S = 242.1	3 S = 484.2

5.0 RESULTS AND INTERPRETATION

5.1. Thermal results – Full equipment PWHT

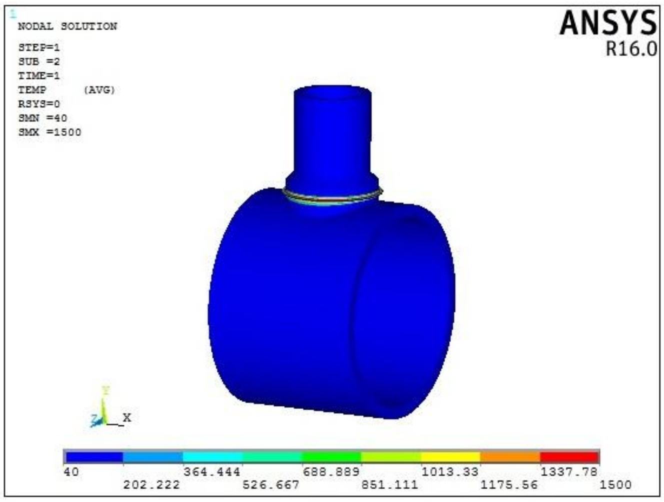

Figure 5-1 Weld Temperature Plot in ^{0}C

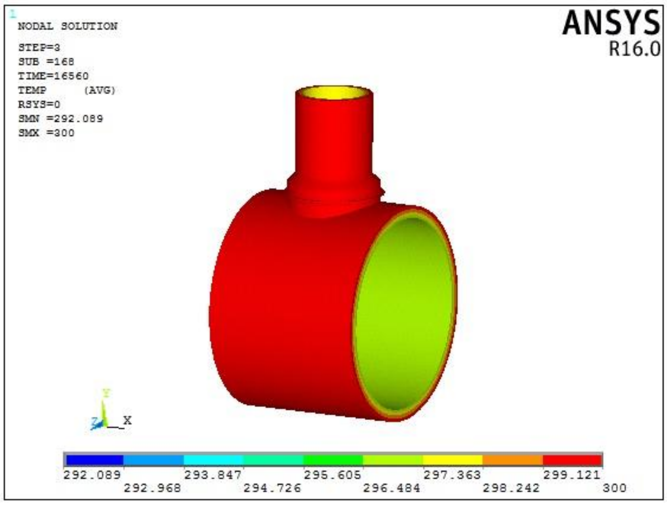

Figure 5-2 PWHT Temperature Plot in ^{0}C

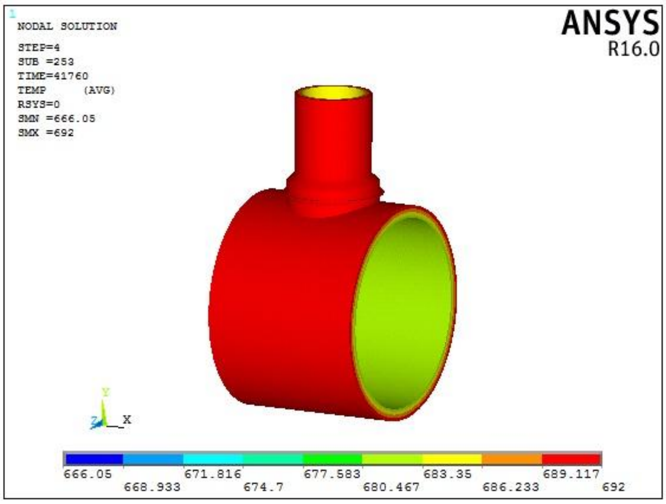

Figure 5-3 PWHT Temperature Plot in 0C

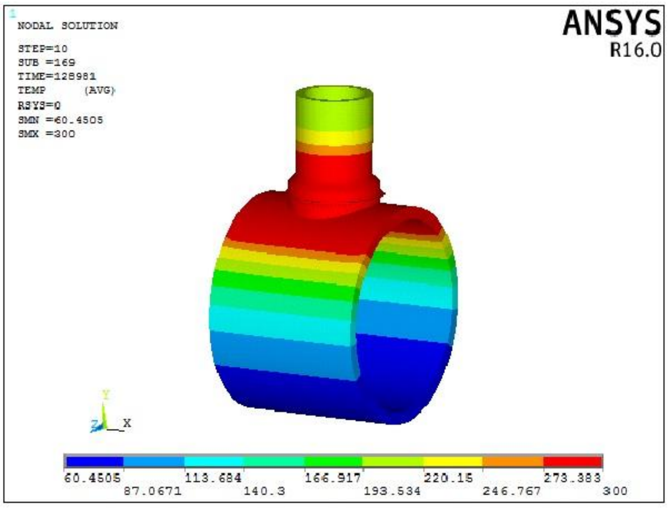

Figure 5-6 PWHT Temperature Plot in 0C

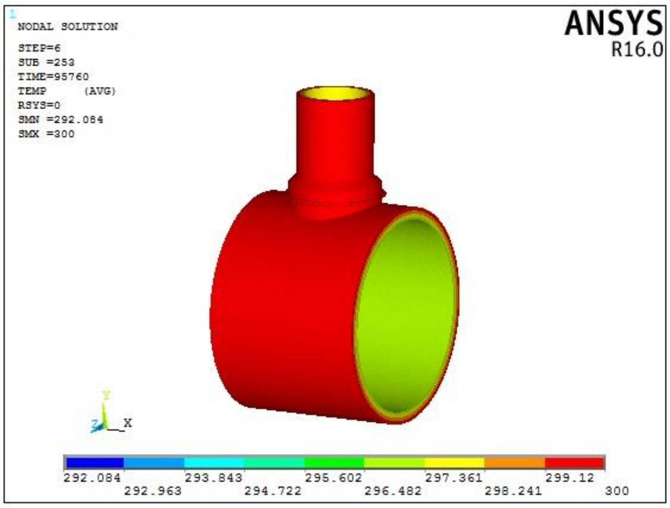

Figure 5-4 PWHT Temperature Plot in ^{0}C

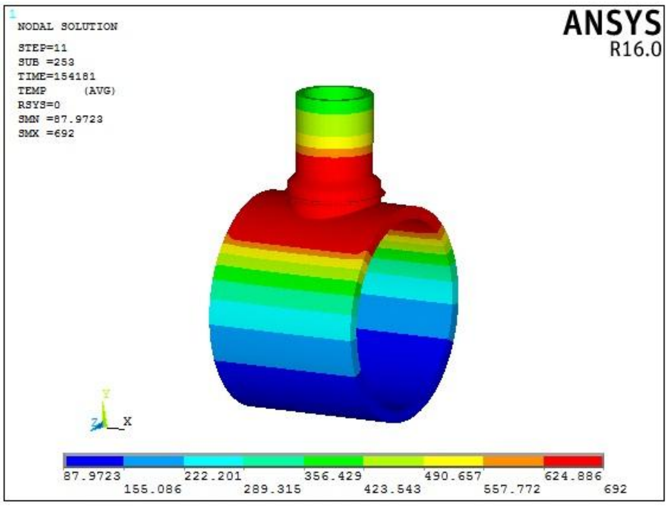

Figure 5-7 PWHT Temperature Plot in ^{0}C

5.2. Thermal results – local PWHT

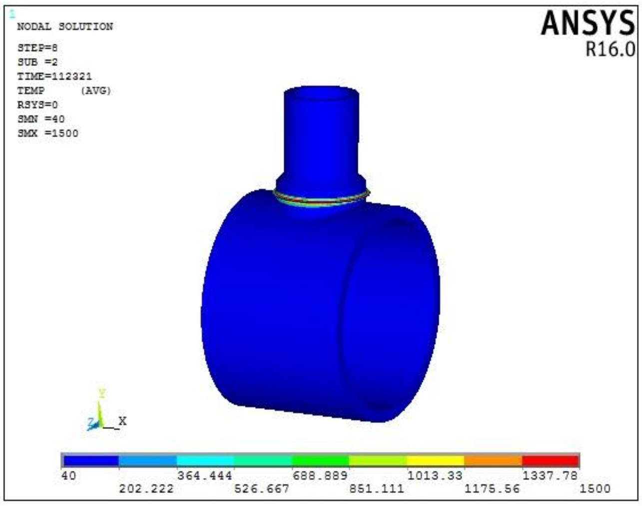

Figure 5-5 Weld Temperature Plot in ^{0}C

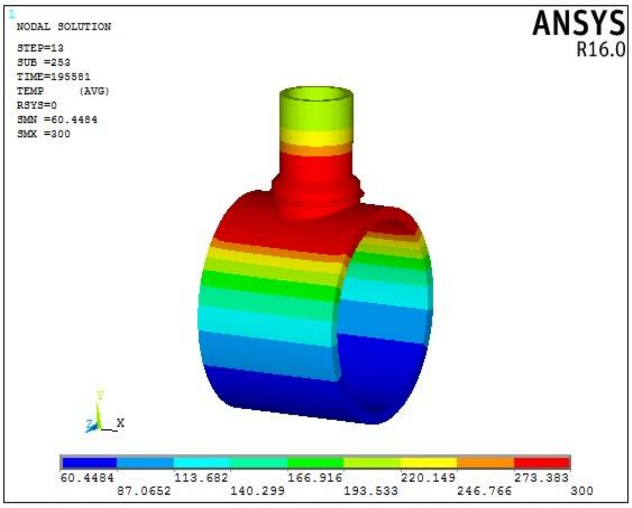

Figure 5-8 PWHT Temperature Plot in ^{0}C

5.3. Structural results – full equipment PWHT

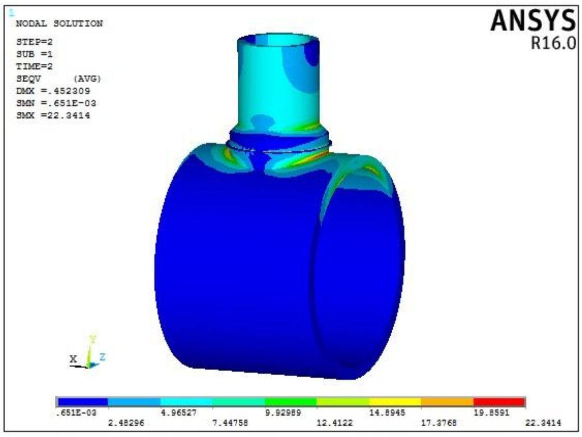

Figure 5-9 Weld Residual Stress in MPa

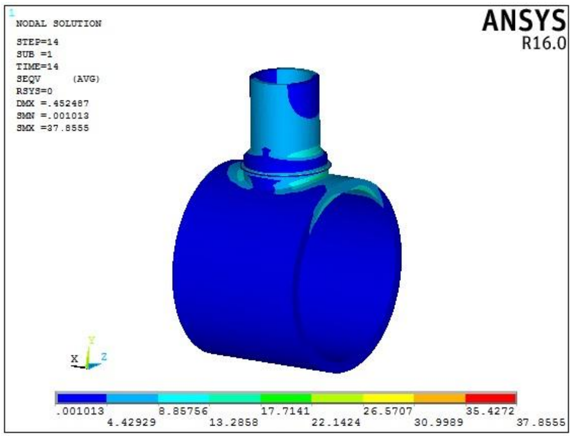

Figure 5-12 PWHT Residual Stress in MPa

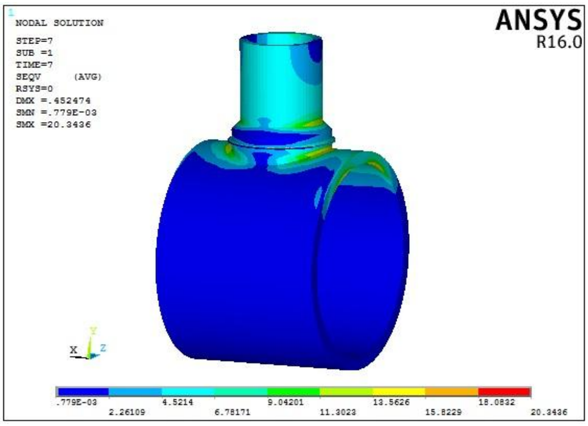

Figure 5-10 PWHT Residual Stress in MPa

5.5. Locations of stress classification lines

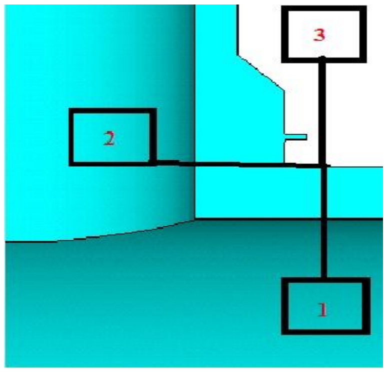

Figure 5-13 Stress Linearization Lines (SCL)

5.4. Structural results – local PWHT

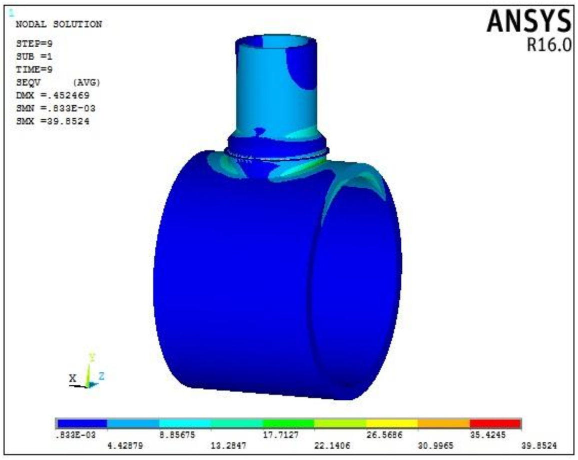

Figure 5-11 Weld Residual Stress in MPa

Table no. 1: Elastic Stress Analysis Results

Location of Stress Classification Line (SCL)	**Type of stress**	**Max Induced Von Misses stress (MPa)**	**Allowable Limit(MPa)**
1) Through Shell Thickness	PL	3.86	1.5 x S = 242.1
	PL + Pb + Q	8.58	3 x S = 484.2
2) Through Nozzle Thickness	PL	4.4	1.5 x S = 242.1
	PL + Pb + Q	8.44	3 x S = 484.2
3) Through Insulation Ring Thickness	PL	4.86	1.5 x S = 242.1
	PL + Pb + Q	8.16	3 x S = 484.2

Table no. 2: Final result full equipment PWHT and Local PWHT.

Condition	Process	Residual Stress (MPa)	PWHT Stress Relaxation (MPa)
1)Full Equipment PWHT	Weld	22.34	2
	PWHT	20.34	
2) Local PWHT	Weld	39.85	2
	PWHT	37.85	

Conclusion

The following conclusions were arrived at after analyzing the PWHT process for material Channel Barrel: SA 336 Gr. F22 CL3, Nozzle N3: SA 336 Gr. F22 CL3, Insulation Ring: SA 387 Gr. 22 CL2. The Welding process was simulated using ANSYS 16 Software. We conclude that when PWHT analysis is carried out for complete equipment and after some modification in the fabrication of the equipment if welding is carried out again there is no need to carry out PWHT again for complete equipment instead PWHT for localized area. Where welding process is carried out will reduce the residual stress. The post weld heat treatment gives 2 MPa relaxation to the residual stresses over welding processes on full equipment PWHT and local PWHT as well.

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