

A Critical Comparative Study of Welding Simulations Using FEA

Narayanamoorthy Kathari¹, K. Ramesh Reddy², J. Bharat Kalyan³

PG Student, Annamacharya Institute of Technology and Sciences (AITS), Tirupati, Andhra Pradesh, India¹

Assistant Professor, Department of Mechanical Engineering, (AITS), Tirupati, Andhra Pradesh, India²

Senior Technology Specialist, ANSYS Software Private Limited, Hyderabad, Telangana, India³

ABSTRACT: Welding is the most commonly used metal joining technique; here the joint is formed by melting and fusion of the base material with the filler material. Upon cooling the joint thus formed is as strong or even stronger than the base material. However, the process of welding generates permanent strains thereby producing residual stresses. This often leads to undesirable levels of distortion in the components, if the welding process is not properly controlled. Thereby a welding simulation will help the fabricators to study the levels of residual stresses etc. before the actual fabrication. The finite element analysis which is typically employed by the engineers is a standard two step procedure, where the model is solved for temperatures and deformations consecutively. Most commonly used practice is to employ element birth and death technique to perform the welding simulation. The present work is a critical comparative study of the simulation with and without using the element birth and death technique. The conclusions drawn from this study can provide necessary guidelines to the engineers attempting to perform welding simulations.

KEYWORDS: FEA, welding, simulation, residual stresses, deformations, Element Birth & Death.

I. INTRODUCTION

Modelling and simulation of welding have always been known to pose challenges to the engineers and researchers, due to the complexity involved in the entire process. Capturing welding process using computer simulations involves modelling multiples physics like heat transfer, phase change, moving heat source, nonlinear stress-strain behaviour and change in material behaviour in HAZ (heat affected zone). Though the studies on modelling of thermal behaviour started almost seven decades ago, weld modelling and residual stress analysis continues to be an area where there is a vast scope for engineering research. Earliest work in this area is by Rosenthal [1], who attempted to find out transient temperature distribution of welded plate considering moving point heat source. Rykalin [2] pointed out that variable thermal properties, latent heat of fusion & pattern of heat distribution are important factors for determining the temperature distribution. Of the available models Goldak [3] and Gaussian heat source model by Pavelic et al [4] are the most popular among the researchers. The present work uses Gaussian heat source model to simulate the moving heat source to determine the transient temperature distribution of the welded cylinders. However, the focus of the paper is not to study the heat source modelling and temperature distribution, but to critically evaluate the residual stresses and strains after the cooling. For this purpose, the findings from Paulo Roberto et al [5] are directly adapted in this work, Paulo studied the effect of parameters like heat input span, amplitude of heat input and weld speed on the bead width & penetration depth. For simplicity the present work does not consider the effect of phase change and radiation as the primary focus is on stress analysis of the body with a well-defined thermal input. Ideally a strongly coupled finite element analysis, where the heat convergence and force-displacement convergence is done simultaneously is suitable for the above present problem. All the governing equation of thermal and structural mechanics are solved together. However, such a formulation is computationally expensive, it has been observed that most of the engineering problems suffer solution convergence issue with such a formulation. The other method is to solve the problem sequentially where the domain is solved for temperatures in the first step, obtained temperatures are applied as input body load and solved for displacements in this second step. Though this method is not strongly coupled in physics, it gives reasonably

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accurate results. One such work is Thermomechanical analysis of circumferentially welded thin-walled plates by Tso-Liang et al [6]. The author uses a sequential two step analysis for a circumferential butt welded pipes, he concludes that the temperature near the weld bead and HAZ rapidly changes with the distance from the centre. A high tensile residual axial stress occurs on the inner surface, and a compressive residual stress is produced on outer surface. On the inner surface the vicinity of the weld line contains large tensile hoop stresses, whereas on the outer surface the hoop stresses are of compressive nature. Another extensive work done in this area is by M E Qureshi [7], the author uses element birth and death technique to simulate the deposition of the weld filler material in circumferential welding. This approach is validated with experiments on low carbon steel (AH36) and stainless steel (AISI-304). The present work also uses the sequential two step procedure as explained above. The second step is a structural analysis with bilinear material input to model the nonlinear stress strain behaviour. A bilinear isotropic hardening model is used to analyse the post yield response of the material. Two different structural analyses are carried post to the thermal analysis with Gaussian heat source. The first structural analysis is a straight forward thermomechanical analysis, the second one has the Element Birth and Death technique employed. A Finite Element Software ANSYS® is used to carry out the present analysis work.

II. THERMAL ANALYSIS

During the welding process, the thermal field is governed by the heat conduction equation given by:

$$\frac{\partial}{\partial x} \left(k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k(T) \frac{\partial T}{\partial z} \right) Q_v = \rho(T) C_p(T) \frac{\partial T}{\partial t}$$

Where T is the temperature, k(T) is the thermal conductivity, ρ(T) is the specific mass, Cp(T) is the specific heat and QV is the volumetric heat flux. The thermodynamic boundary conditions on the external surfaces of the solid comprise heat transfer for convection. The heat flow density for convection (qc) in the environment gas or liquid is given by Newton's heat transfer law;

$$q_c = \rho(T) h_c (T - T_0)$$

Where T is the temperature of the external surface, T0 is the temperature of gas or liquid and hc is the coefficient of convective heat transfer. This coefficient depends on the convection conditions on the solid surface, besides the properties of the surface and the environment. In this study, the heat of the welding arc was modelled by a traveling three-dimensional distribution of heat source with a Gaussian distribution. Therefore, the heat flux distribution on the surface of the solid is related to the instantaneous position of the heat source

$$q = C_2 e^{-\frac{[(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2]}{C_1^2}}$$

Where,

q=heat flux on the desired surface

C1=Radius of the beam

C2=Source Power Intensity

(X0, Y0, Z0) =Instantaneous position of the center of the heat flux which is on the 'path' at the distance of 'v x t' from the 'start point'.

V=Velocity of the moving heat source

T=Time

The model is meshed with SOLID90 element in ANSYS, the element has 20 nodes with a single degree of freedom, temperature at each node. The 20-node elements have compatible temperature shapes and are well suited to model curved boundaries. Figure 1 shows the finite element model for thermal analysis, the bead and HAZ region is meshed

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with finer elements compared to the rest of the model. Figure 2 shows the temperature plots of the cylinder as the heat source moves around the circumference during the welding process.

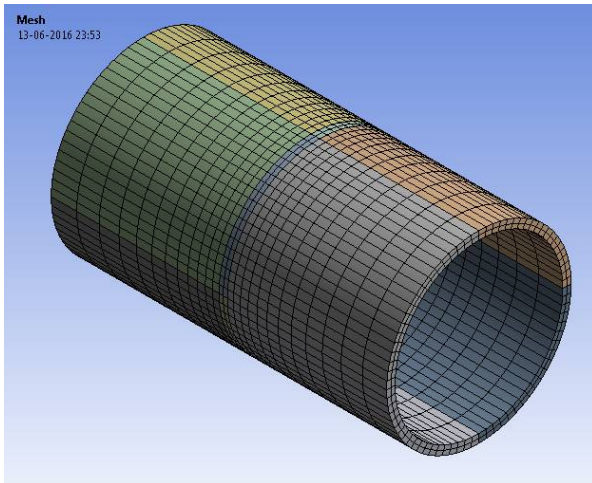


Figure: 1 Finite Element Model

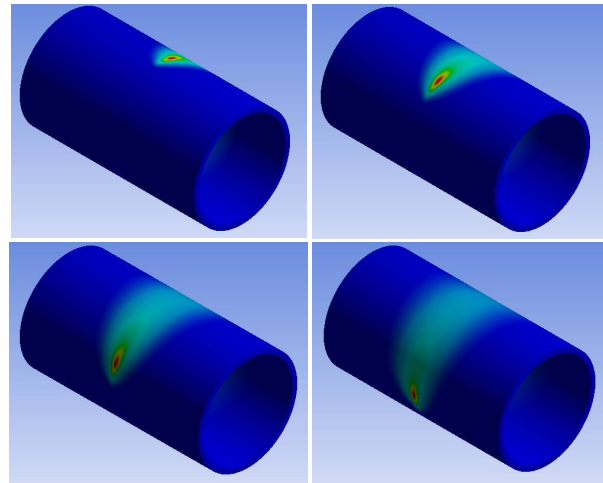


Figure: 2 Movement of the Heat Source

The transient analysis is run for total of 10000 seconds to ensure proper cooling of the cylinder after welding. The Figure 3 shows the temperatures at different time points during the welding and cooling phases.

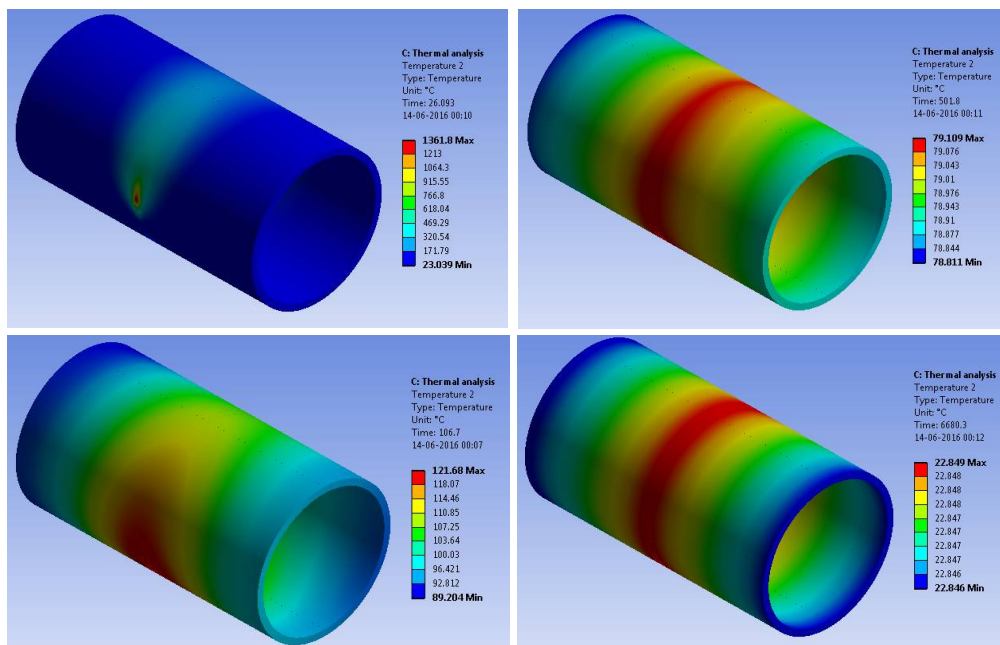


Figure: 3 Temperature distribution during the welding & cooling phases

III. STRUCTURAL ANALYSIS

For performing the structural analysis is meshed with SOLID186 elements in ANSYS, this element is a higher order 3-D 20-node solid element that exhibits quadratic displacement behaviour. The element is defined by 20 nodes having three degrees of freedom per node; translations in the nodal x, y, and z directions. The cylinder is fixed in axial degrees of freedom on one of the sides and is arrested in hoop degree of freedom at 4 equidistant points circumferentially. These are minimum constraints given to the model to avoid rigid body motion. The temperatures obtained in the thermal analysis are mapped on to the structural mesh as body loads. A transient structural analysis is carried out with the given inputs without time integration effect. If time integration is used ANSYS solves the transient dynamic equilibrium equation, this is not required here as the model is not subjected to any vibrating load. The inertia and damping effects can be ignored in this simulation. Temperature dependent material properties are used to capture the temperature effects the below figures 4 & 5 shows the values of Young's modulus for and Poisson's ratio for stainless steel AISI 304.

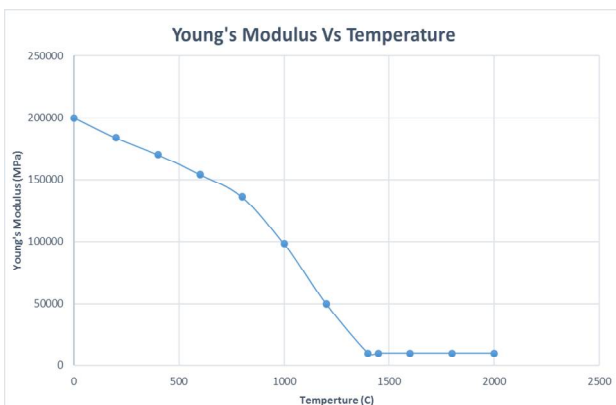


Figure: 4 Young's Modulus of AISI 304

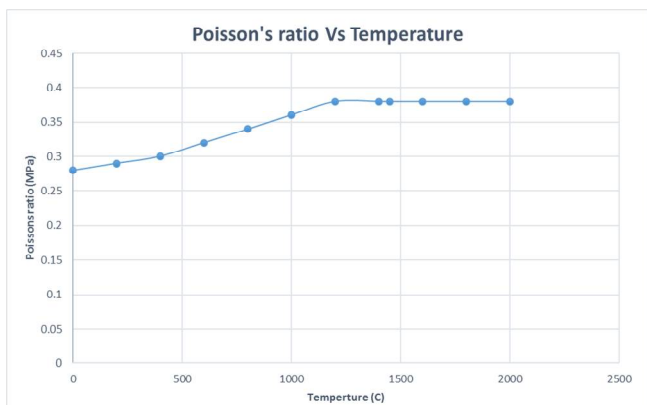


Figure: 5 Poisson's ratio of AISI 304

It is necessary to carry out an elastoplastic structural analysis, as the stresses are very likely to cross yield strength of the material. Bilinear Isotropic Hardening model is used to define the hardening behaviour after yield strength During hardening, the elastic domain undergoes a certain evolution. The elastic domain of a virgin material is bounded by the initial yield surface, also called the elastic limit envelope. Due to microstructural changes in the material induced by plastic flow, the elastic domain changes its size or position, or both. Its boundary at an intermediate state is usually called a loading surface. In an isotropic hardening model, the yield surface increases as the loading continues beyond the yield point as shown in the figure 6. The blue line in the below figure indicates the new yield surface at the point of unloading.

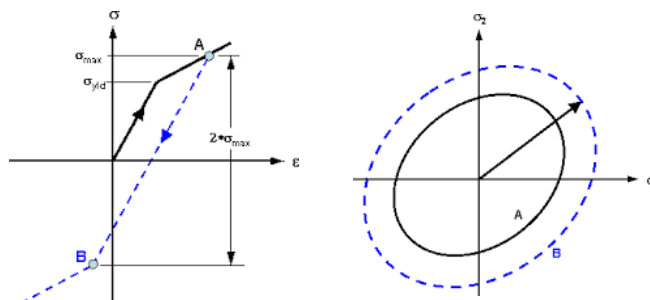


Figure: 6 Isotropic Hardening Behaviour

Figure 7 and 8 show the bilinear material behaviour for the base and weld metal, the weld material is stronger than the base hence has a higher yield strength at all temperatures, compared to the base metal.

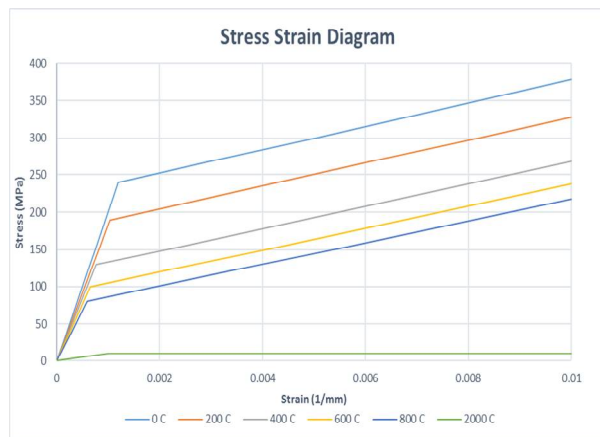


Figure: 7 Base Material

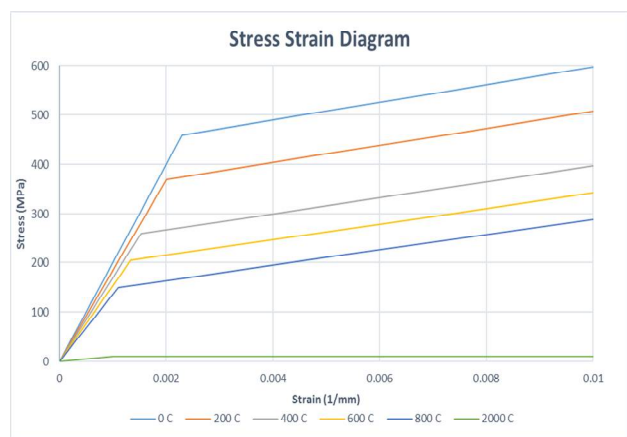


Figure: 8 Weld Material

Two structural analyses one with direct temperature loads and the second with Element Birth and Death technique are carried out. The element birth and death option can be used to deactivate or reactivate selected elements in such cases. The figures 9 & 10 show the difference between the direct method and Element birth and death technique. Figure 10 shows a discontinuity in temperatures ahead of the weld gun, as the material is yet to be deposited. The elements ahead of the weld gun are killed/deactivated as the weld gun progresses. This is enabled by writing a APDL script; which creates element components, which are be deactivated and activated appropriately with respect to the speed of the weld gun. The total analysis time for the structural analysis is 10000 seconds, welding process takes around 35seconds. 35 to 10000 seconds represents the cooling time. Temperatures at discrete time points are mapped to the structural analysis from the thermal solution. Proper care is taken to sufficiently represent the welding and cooling times while mapping the temperatures. More number of time points are taken during the first 35 seconds and gradually the time step is increased for cooling.

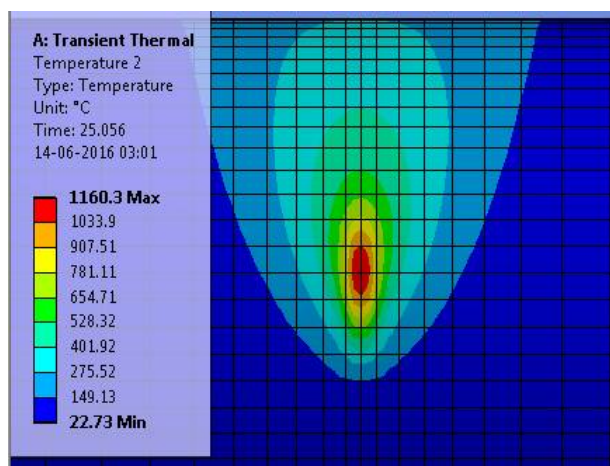


Figure: 9 Direct Method

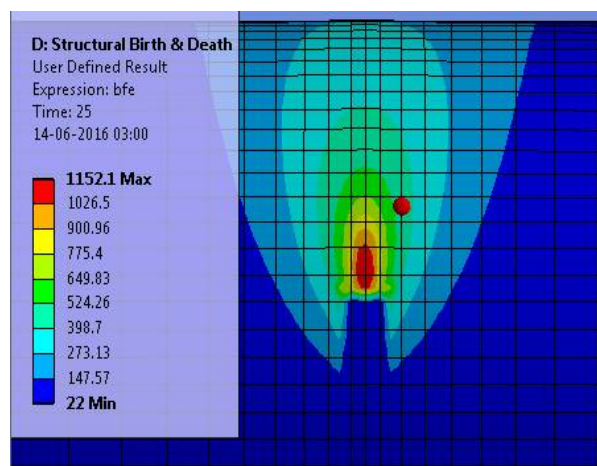


Figure: 10 Element Birth & Death Method

IV. RESULTS & DISCUSSION

The figures 11 and 12 shows the hoop displacement from the structural analysis using Direct method and Element Birth & Death technique. We can observe that the Element Birth & Death technique gives a high local displacement at the weld region and its vicinity compared to the Direct method. The below figures show the displacements at the end of the welding cycle (35 seconds).

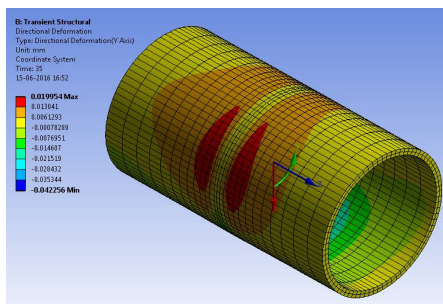


Figure 11 Hoop displacement Direct Method

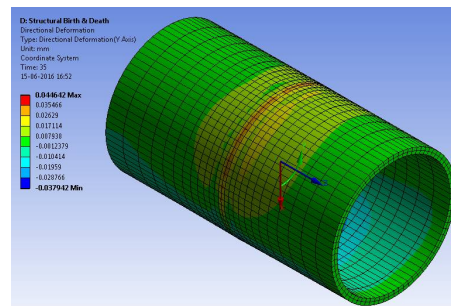


Figure 12 Hoop displacement Element Birth & Death

The axial displacements are shown in figures 13 and 14; the displacement contours are almost similar for both the cases; however, the displacement amplitudes are slightly higher for Element Birth & Death technique. The reason for higher displacement can be attributed to the deactivated elements, which do not offer any resistance to deformation during the welding cycle, whereas in the direct method all the elements offer resistance to deformation.

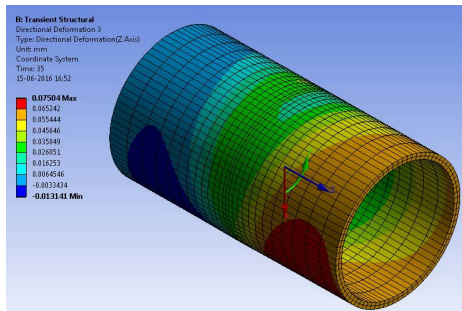


Figure 13 Axial displacement Direct Method

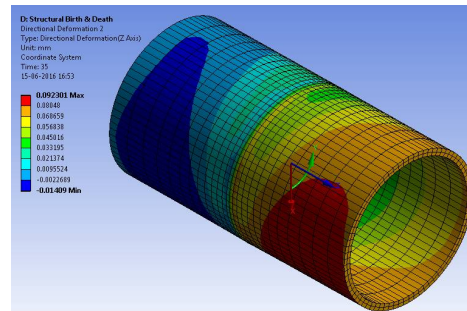


Figure 14 Axial displacement Element Birth & Death

Figures 15 & 16 show the displacements for the both methods at the end of cooling (1000 seconds). Figures 15 & 16 show the hoop displacements; here also the displacements at the weld region & vicinity are higher for the Element Birth and Death technique.

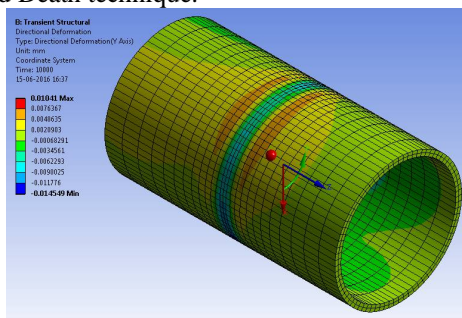


Figure 15 Hoop displacement Direct Method

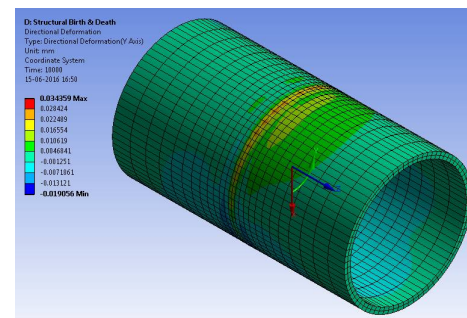


Figure 16 Hoop displacement Element Birth & Death

Figures 17 and 18 show the axial displacements at the end of cooling cycle; here again the local weld region has higher displacements in the second technique as discussed above. The local high deformations can be attributed to the local element activation/deactivation taking place during the welding phase. Higher displacements due to lower stiffness at the weld region due to element deactivation.

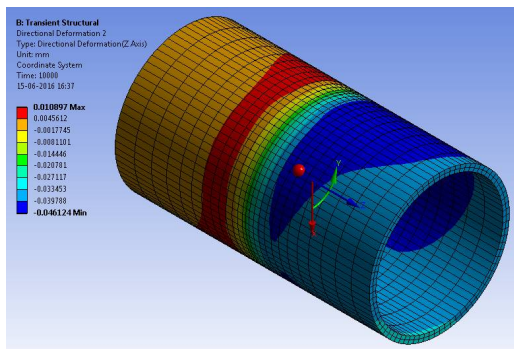


Figure 17 Axial displacement Direct Method

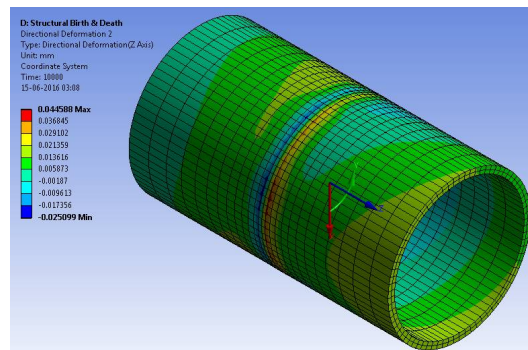


Figure 18 Axial displacement Element Birth & Death

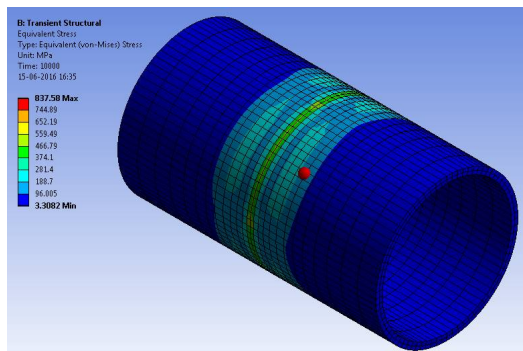


Figure 19 von Mises Stress Direct Method

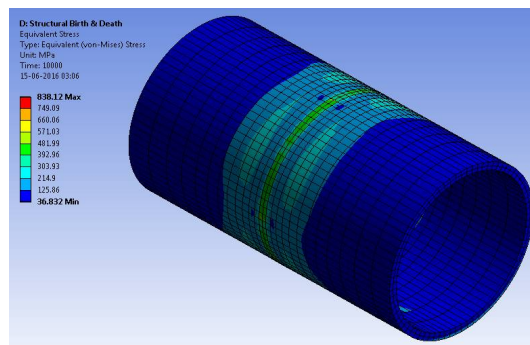


Figure 20 von Mises Stress Element Birth & Death

Figures 19 and 20 shows the von Mises stresses; both the methods show same stress values. Stress amplitudes are high at the weld region and HAZ. As von Mises stress is a derived quantity, further examination of direct stresses would give a better picture of the stress distributions. For this purpose, the axial and hoop stresses along the length of the cylinder are extracted at 45°, 135°, 225° and 315° respectively. Figure 21 indicates the locations of stress extraction on the cylinder for the analysis.

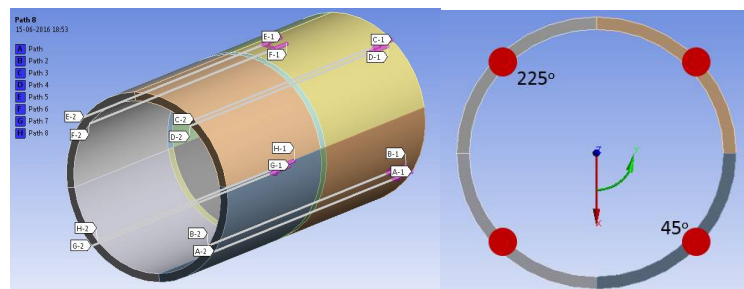


Figure 21 Stress extraction lines

Figures 22 and 23 show the hoop stresses on the cylinder at 45° line, at the cylinder outer and inner diameters respectively. Stresses for both the methods are presented below. The results indicate that the hoop stresses are tensile in the weld region and compressive in the vicinity of the weld (HAZ). The stresses are almost zero at the regions away from the weld. The results also show that the hoop stresses follow the same pattern and are almost equal for both Direct and Element Birth & Death technique.

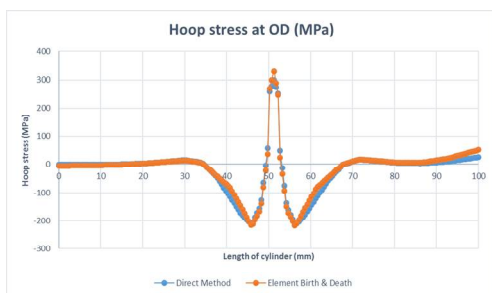


Figure 22 Hoop Stress along the outer diameter (45°)

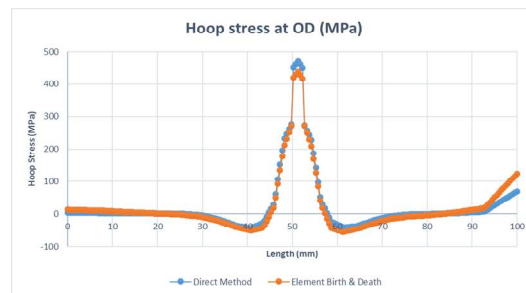


Figure 23 Hoop Stress along the Inner diameter (45°)

Figures 24 and 25 show the axial stresses at outer and inner diameters respectively; at the outer diameter the axial stresses are highly compressive at the weld region and are tensile at the locations away from the weld line. Though both the methods here show similar pattern, the stresses generated by using Element Birth and death technique higher compared to the Direct method. Compressive stress at the weld region is higher for the normal method at the outer diameter. The cylinder throughout the length experiences axial tensile residual stresses after cooling.

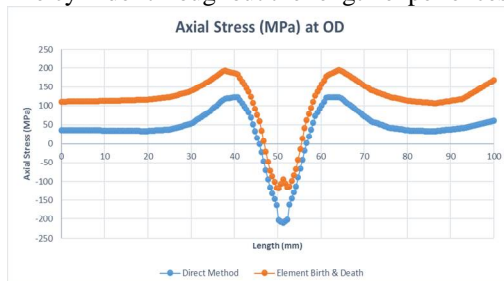


Figure 24 Axial Stress along the outer diameter (45°)

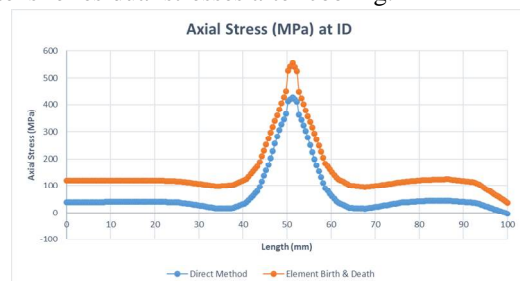


Figure 25 Axial Stress along the Inner diameter (45°)

Similarly, the hoop and axial stresses are presented for 225° line in the figures 26 to 29. Figures 26 & 27 show the hoop stress pattern is same for both methods. The weld region shows tensile high tensile stresses; its vicinity has compressive stresses. Region far from weld is mostly free from hoop stress.

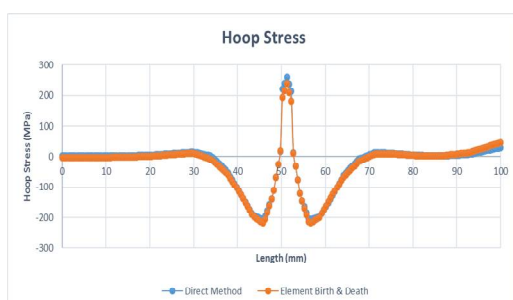


Figure 26 Hoop Stress along the outer diameter (225°)



Figure 27 Hoop Stress along the Inner diameter (225°)

Axial stresses are shown in figures 28 & 29; stress pattern is similar for both the methods. The stresses at 225° line show the same behaviour as 45° line as explained above.

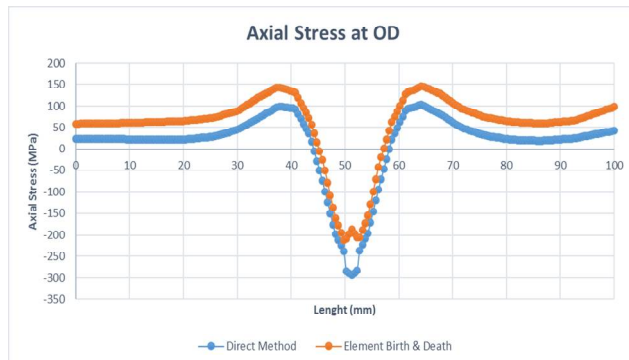


Figure 28 Axial Stress along the outer diameter (225°)

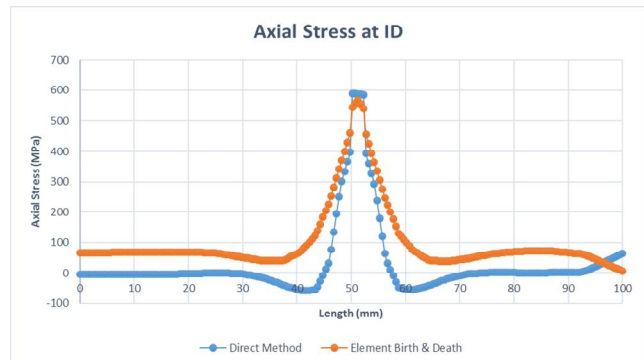


Figure 29 Axial Stress along the Inner diameter (225°)

V. CONCLUSION

The above study shows that peak residual von Mises stress is almost same with any of two techniques explained above. The hoop stresses extracted along the length of the cylinder show a very good match for the both techniques. The weld region shows high tensile stresses at both outer and inner diameters. The heat affected zone in the vicinity of the weld shows compressive stresses. The axial stress pattern looks very similar for both the techniques; however, the Direct method underestimates amplitude of residual tensile stresses over the length of the cylinder. At the outer diameter the residual axial stresses are compressive in nature. Stress pattern along the stress extraction line suggests that the stresses developed are not entirely different for both the techniques.

The deformations after cooling or residual deflection is higher at the weld region when Element Birth and Death technique is implemented. The direct method underestimates the both axial and hoop deflections in the weld region.

Solving the model with Direct method is much easier than implementing Element Birth and Death. The later method requires use of spring elements and convergence controls to bring the model to equilibrium. Owing to the difficulty in Element Birth & Death technique, a judicious choice should be made by the analyst among the two methods based on his objective.

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