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Effect of Annealing Temperatures on Formability of SS 304 tubes during Tube Hydroforming Process: A Numerical study

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Abstract: Tube hydroforming is an advanced manufacturing process which utilizes liquid medium to deform the tube with required shape. This method has an advantage of attaining uniform pressure throughout the tube at any time during the process. The main aim of the present study was to know the effect of different annealing temperatures on the tube hydroforming of SS 304 steel. Specimens were annealed with four different temperatures, viz., 100ºC, 150ºC, 200ºC and 250ºC. Annealed samples were tested to find the tensile properties in terms of yield strength, strength coefficient, strain hardening exponent, elongation and ultimate tensile strength. The evaluated mechanical properties were utilized to run the tube hydroforming simulations using finite element code. Effects of annealing temperatures on bulge height and thickness distribution of the bulged area of the tube was studied using FEM. Numerical simulations confirmed that the annealing temperatures had an effect on the bulge height and thickness distribution in the bulged zone of the tube.

Keywords: Annealing; tube hydroforming; formability; bulge height; thickness distribution

1. Introduction

Tube Hydroforming (THF) is a special manufacturing process used especially for the manufacture of aerospace and automotive components. Hydroforming process can be effectively used for light weight vehicle components since the application of light weight materials for vehicle manufacture reduces the vehicle weight. Basically, THF process works based on pressurized medium inside the tube specimen to produce the tube into required 3D shape. The internal pressure required to bulge the tube depends between yielding and bursting pressure along with the axial feeding to obtain the defect free product (Koç, 2008; Ng et al., 2018). The schematic illustration of the simple tube hydroforming process is shown in Fig.1. Application of the THF process for producing complicated shapes requires extensive research and development with more trial and error efforts. In THF process, still there are several problems that need to be addressed

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for attainment of defect free parts. Some researchers investigated on the effect of material properties, which has a significant influence on THF process (Manabe & Amino, 2002; Hwang & Lin, 2006; Lianfa & Cheng, 2006) and some researchers worked on the optimization of process parameters which are involved in THF process (Mirzaali et al., 2012; Abedrabbo et al., 2009; Yong et al., 2009; Seyedkashi et al., 2014).

Forming of high strength steels at room temperature is quite difficult due to their higher deformations and flow stresses (Grzegorczyk et al., 2019). Heat treatment of the samples before forming makes the forming easy with decrease in flow stresses with easy deformations. Moreover heat treatment makes the samples to relieve stresses such that forming can takes place easily and attains higher formability. Most of the forming industries use stainless steels of different grades for different applications due to their excellent properties. These steels can be hardened easily by cold working and also possesses non magnetic characteristics after the heat treatments. The applications of these steels are increased rapidly due to their properties like oxidation resistant and corrosion resistant even in organic acids, Due to this; these steels can be used in marine applications too. These steels possess high toughness even at high temperatures when these properties combined with magnetic properties their applications can be extended even more.

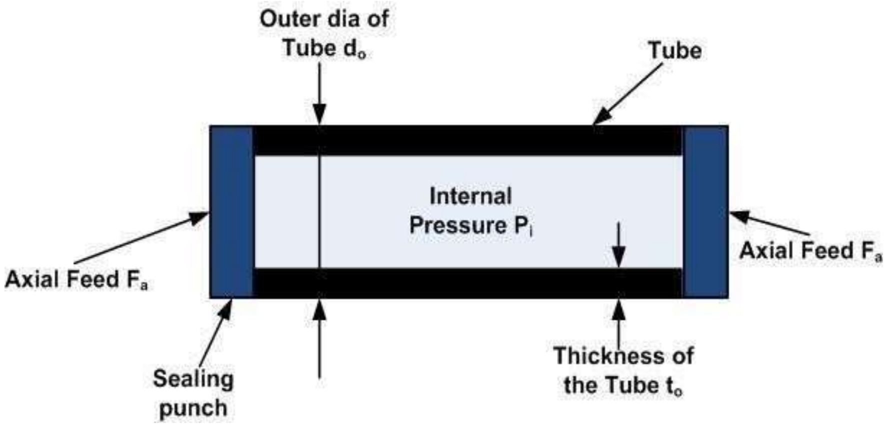

Fig. 1 - Tube under internal pressure and axial force (Koc, 2008)

Zribi et al., (2013) investigated on inverse approach for determining the flow stress parameters by designing tube hydroforming test setup with suitable parameters variations. Tests were conducted both experimentally and numerically to evaluate the flow stress characteristics and concluded that both the results are in good agreement with each other. From their work, the flow stress behavior is predicted accurately to know the plastic deformation of the tube. Mirzaali et al., (2012) investigated on the pressure and loading paths of the tube hydroforming process to improve product quality by optimizing the process parameters using ANSYS/LS-Dyna. Optimization is carried out on simulated annealing algorithm by incorporating the code in ANSYS and the obtained optimal process parameters are validated by conducting experiments on copper tubes. Alaswad et al., (2011) investigated on the bi layered tube hydroforming by numerical simulations using finite element code for the production of X-shaped components in order to model the responses- bulge height, wrinkle height and thickness distribution using response surface methodology. FEM results are validated with the experimental results and concluded that the developed models can be further used for the prediction of the bi-layered tube hydroforming process. Seyedkashi et al., (2013) derived an analytical model for hydroforming of dual layered tube both analytically and experimentally.

The derived model is in good agreement with experimental results and the derived model predicted the results like internal pressure required to bulge the tube and their wrinkling behavior accurately. Zhuang et al., (2012) investigated on the localized thinning of the micro tube which undergone the hydroforming both numerically and experimentally. The work concluded that the failure modes of micro tube hydroforming are different with the macro tube hydroforming under similar conditions. Finally the work resulted in localized thinning in micro tube hydroforming have a significant effect on microstructure and grain distribution of tube material. Hashemi et al., (2013) investigated on the warm hydroforming of aluminum alloy tube and its effects on thickness distribution. From their work, it was concluded that the increase in temperature increased the formability of the tubes and also improved the thickness distribution of the bulged area. Fatemi et al., (2013) investigated on the formability of tube hydroforming of both copper and aluminum tubes by considering the effects of heat treatment along with tube material and their microstructure. From their work, it was confirmed that strength coefficient and strain hardening exponent are the two major parameters which effect the formability of the tube since these alters the microstructure of the tube material at different temperatures and attains different strength coefficient and strain hardening exponent.

As per the conducted literature survey, a very little amount of work has been carried out on tube bulge forming considering the mechanical properties. The novelty in the present work is the consideration of annealing temperatures.

The effects of annealing temperatures on mechanical properties are evaluated using tensile tests. Based on curve fitting method, the tensile test data are converted into required mechanical properties as per the Hollomon law. The obtained mechanical properties are utilized for carrying out tube hydroforming simulations such that the effects of mechanical properties are investigated.

2. Materials and method

2.1 Work piece material

The chemical composition of the SS 304 is shown in Table 1. From as received SS 304 tubes of 1 mm thickness, the tensile test specimens were cut according to ASTM E8 standard dimensions using gas cutting machine. The dimensions of the tensile test specimens are shown in Fig.2. A total of five samples were cut from five different tubes each of it at same 0^{o} rolling direction. Out of five samples, four samples were heat treated in an electrical furnace. The samples were heated at 100ºC, 150ºC, 200ºC and 250ºC in the furnace and the samples of respective temperature were kept constant for 30min inside the furnace. Later, the samples were cooled at room temperature.

Table 1 - Chemical composition of SS 304 material

Elements	Cr	Ni	Mn	C	Si	S	Al	Cu	Fe
SS 304 (wt. %)	18.91	8.44	1.79	0.015	0.483	0.03	-	0.043	Balanced

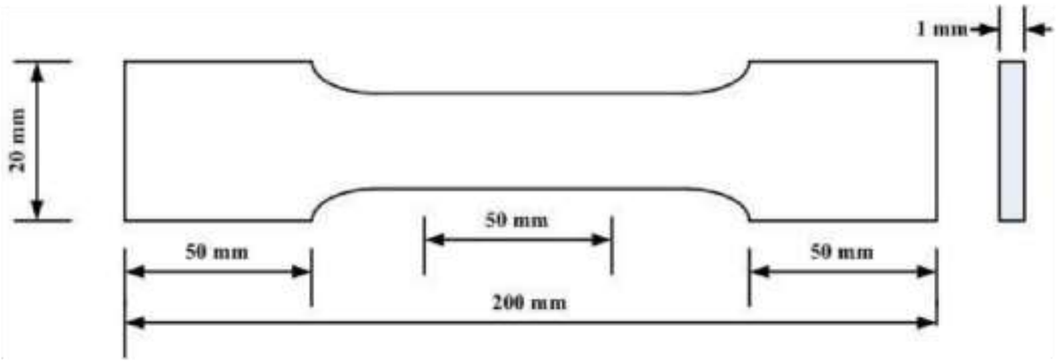

Fig. 2 - Dimensions of the tensile test specimen

2.2 Tensile Testing

All the Heat-treated specimens with a gauge length of 50 mm, oriented at 0 degrees were tested on an INSTRON 3369; a computer controlled Universal Testing Machine (UTM). All the tests were carried out at a strain rate of 0.01mm/sec at room temperature with 50% relative humidity and 5 samples were tested each of different annealed temperatures. The tensile test curves of all the five samples are plotted in Fig. 3. From the fig. 3, it is observed that by annealing, decrease in yield strength and ultimate tensile strength. Increase in elongation was observed up to 150ºC, further increase in temperature decreased the elongation. Increase in elongation leads to increase in strain hardening exponent up to a temperature of 150ºC. Moreover, increase in annealing temperature reduced the strength coefficient when compared to as received condition. The study proved that the annealing of the test specimens reduced the yield strength and ultimate tensile strength of the metal for all temperatures. This is because of once the yield strength of the test specimen is reached; load increases drastically by attaining a plastic hardening and holds the constant value over a large elongation interval (16% to 35%). This is well known that load decreases for larger deformation levels because of the reduction in transversal area at the necking zone. The load vs displacement data obtained from UTM is converted into true stress-strain curve and this true stress-true strain curves were fitted by the Hollomon power law to get the required mechanical properties for carrying out numerical simulations. The Hollomon law is defined in Eq.1.

$$\sigma = K\varepsilon_n \qquad (1)$$

Whereas K is the strength coefficient and n is the strain-hardening (or work-hardening) exponent. The corresponding parameters are presented in Table 2. For attaining higher formability and defect free products, the material should have high yield strength to ultimate tensile strength ratio and also should have high elongation which was reported by Kalpakjian & Rajgopal (1982). Keeping this in view, investigations were carried out on annealing of SS 304 specimens to improve the formability by achieving the required mechanical properties.

2.3 Numerical Simulations

Finite element simulations are used in the metal forming area in order to optimize the process variables. Basically there are many process variables in any of the metal forming area, so optimization of these process variables are necessary to obtain defect free product by minimizing cost and time. Metal forming area consumes lot of time for performing trial and error tests to attain sound product, such that most of the material, time and cost is wasted. To overcome this problem, implementation of FEM simulations in this area is mandatory such that the design of tools and process variables can be altered based on the obtained results from simulations. There are many commercially available codes for carrying out the metal forming simulations. The FEM software used in the present study is PAM-STAMP 2G. The tools required for carrying out the tube hydroforming simulations were modeled in CATIA V5R21. The modeled tools were imported into the analysis software PAM-STAMP 2G and surface mesh was generated over the tools. The assembled tool setup is shown in fig. 4 (a) and the meshed tube is shown in fig. 4 (b). The tube thickness is exceptionally low when compared to its length and diameter, so the tube is generally modelled as a shell element. Tube was meshed with elastic-plastic quadrilateral shell elements of Belytschko –Tsay with a mesh size of 2 in order to attain accurate results as it takes very less computational time (Ganesh, 2011; Suresh & Regalla, 2014). Die and axial plungers were considered as rigid bodies, whereas tube was considered as deformable body. A uniform surface pressure was applied to the tube inner surface to simulate the tube hydroforming process using fluid cell concept. The coefficient of friction was kept constant value of 0.1 between the outer surface of the tube and the inner surface of the dies by employing the Coulomb's law. The input material properties for the tube material (SS 304) were found by the tensile tests using UTM as explained in the previous section. The material properties used for carrying out the simulations for different heat treatment temperatures are shown in Table 2. All the simulations were carried out by applying Hills 1948 yield theory with Hollomans flow stress characteristic as explained in the previous work of the author (Reddy et al., 2018; Omer et al., 2015).

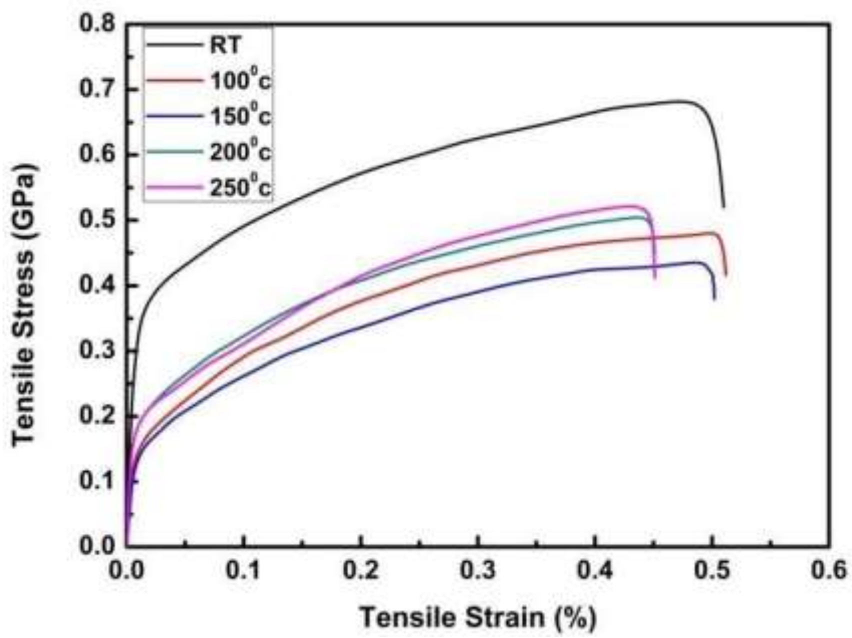

Fig. 3 - Tensile Stress-Strain curves at different heat treatment temperatures

Table 2 - Mechanical Properties of SS 304 sheets

Heat treatment temperature	R_0	R_{45}	R_{90}	σ_y (MPa)	E (GPa)	K (MPa)	n
As received				360		1417	0.403
100ºC				342		1072	0.381
150ºC	1.08	0.96	1.05	325	210	1041	0.376
200ºC				351		1285	0.395
250ºC				349		1199	0.385

3. Results and Discussion

Tube bulge tests simulations were carried out with different annealing temperatures. The parameters which are considered to know the effect of formability in tube hydroforming of SS 304 tubes are yield strength, strain hardening index (n) and strength coefficient (k) based on the literature (Fratini et al., 2004). The parameters are considered based on the annealing temperatures and their corresponding tensile test data. The influence of these considered parameters on the tube bulge were studied numerically. Bulge height and thickness distribution in the bulge area was observed and is explained below.

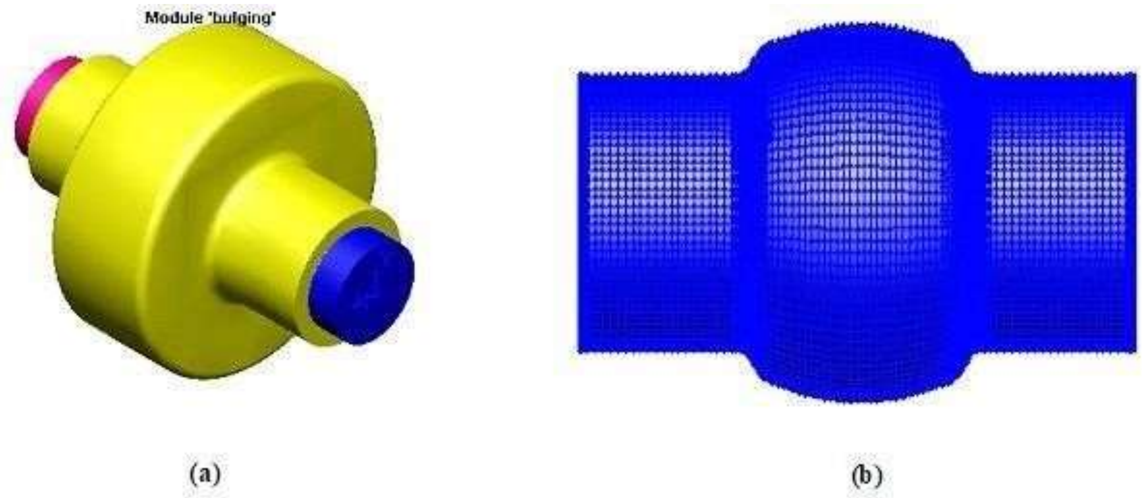

Fig. 4 - (a) Assembled setup of THF, (b) Mesh over bulged tube

3.1 Bulge Height Evaluation

The most important material parameters which have considerable effect on bulge height are yield strength, strain hardening index (n) and strength coefficient (k). The effect of these parameters on the bulge height is studied numerically in the present study. Bursting of the tubes leads to the increase in the tube diameter in local area which produces a nonuniform bulge in the tube especially in the hoop direction. During the bursting phenomenon the failure place remains unchanged in the tube diameter in perpendicular direction. So this phenomenon is useful for evaluating the bulge height of the bulged tube before fracture. From fig. 5, it is observed that the bulge height is little higher for 150ºC annealing temperature than the other annealing temperatures and as received condition. At 150ºC, increase in strain hardening took place as is observed in table 2. Increase in strain hardening exponent attains higher limit strains such that the formability of the tubes/sheets increases. This makes the tube to bulge higher and bulge height increased. Whereas at 250ºC, the strain hardening exponent is less when compared to other annealing temperatures such that it attained lesser bulge height. Lower strain hardening exponent attains lesser formability.

Heat treatment of the sample increases the grain size up to a particular range and moreover it decreases with increase in volume fraction. As the strain hardening exponent also increases with increase in heat treatment temperature and higher strain hardening leads to attain higher bulge height as observed from fig. 5. Many other studies also support the present study in terms of relation between the formability and strain hardening index. Increase in strength coefficient and strain hardening index improved the formability of the sheet metals as observed by related peers in their study (Pranavi et al., 2014; Reddy et al., 2019). Effect of materials and die geometries also effect the formability and the study was carried out to know their influence on the dome height and thickness distribution in the literature (Reddy et al. 2016). Frictional coefficient in the THF process affects the bulge height and thinning of bulged tube as is evident from the literature study (Reddy et al. 2020).

3.2 Thickness Distribution

Fig. 6 represents the thickness distribution of the hydroformed tube obtained from numerical simulations. Simulations were carried out at different annealed temperature cases and the difference in their thickness distribution is shown in fig. 6. Annealing the specimens with different temperatures induces the thermal softening phenomenon at various temperatures and these make an impact on the thickness distribution. Friction between the tools and work pieces also make an impact on thickness distribution, but in the present case the frictional coefficient is considered constant. Maximum thinning of the bulged tube takes place at 100ºC as the strain hardening exponent at that temperature is higher when compared to room temperature. Thickness distribution of the bulged area becomes uniform up to 150ºC, but further increase in temperature has uneven distribution of thickness. This concludes that the strength coefficient and strain hardening exponent has an impact on thickness distribution since strain hardening exponent is higher for 150ºC. In tube bulging, the flow of the material is highly concentrated in deformation zones. Increasing the annealing temperature not only softens the material but also necking and thinning of the material takes place in rapid pace when compared to lower temperatures.

Maximum thinning was taken place at 100ºC and the bursting of the tube taken place rapidly at this temperature. Thinning decreases by increase of the annealing temperature as can be observed from fig. 6. In the case of tube hydro bulging, annealing of tube improves the thickness distribution. Higher annealing temperatures attained lesser thinning of the bulged zone of the tube since the higher temperature induces the thermal softening phenomenon. The thickness distribution of the bulged tube explains one of the formability characteristics of the tube material. Higher thinning of the material during forming leads to the failure of the specimens. Moreover, the serviceability of such formed parts is also less and possesses less strength and the chances of failures of the parts will be more. It was observed from the simulation results that thickness distribution in hoop direction of the hydroformed part is uniform before fracture of tube. Further increase in the internal pressure made the tube sample starts necking and fracture takes place at the centre of the tube due to high hoop stress at that position.

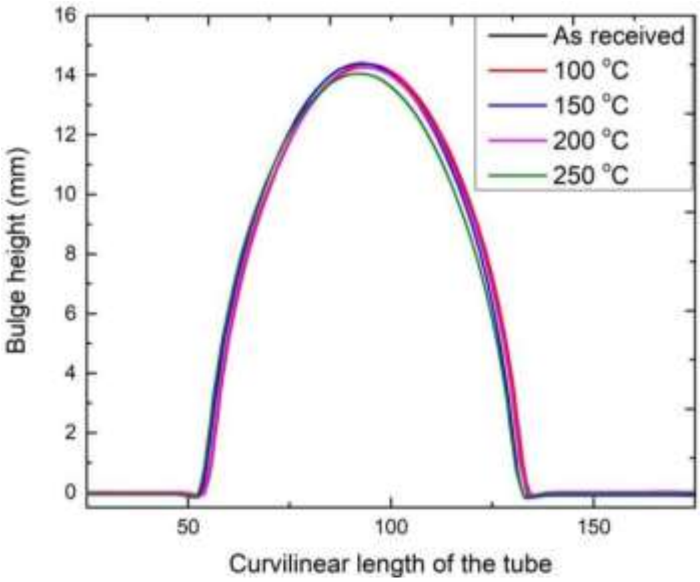

Fig. 5 - Effect of heat treatment temperature on bulge height

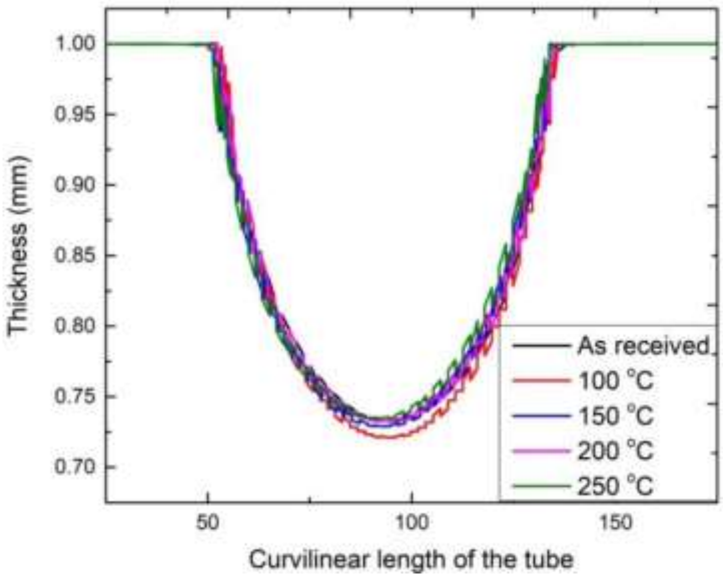

Fig. 6 - Effect of annealing temperature on thickness distribution

3.3 Bursting of tubes in hydroforming

Bursting is called as a fracture in the formed tube and hence it cannot be improved and origins necking so that the thickness reduction is considered as an important parameter to be measured. Hence the Percentage thickness reduction is selected as a Quality characteristic. The thickness distribution of the bulged tube is shown in fig. 6. Bursting of the tube in the tube hydroforming of SS 304 metal is shown in fig. 7. Almost all the annealing conditions and as received condition, the tube burst in a similar fashion. The red zone over the bulged part of the tube represents the bursting of the tube. The bursting of the tube mainly depends on the process parameters and the die design. Bursting of the tube does not depend on the material parameters as is confirmed by the present study. Highest bulge height is attained for an annealing temperature of 150ºC. Beyond 150ºC annealing temperature lowered the bulge height due to the decrease in strain hardening exponent and strength coefficient. When compared to as received tubes, increase of annealing temperature up to 150ºC can reduce the early bursting of tubes, such that the bulge height increased before bursting. Moreover nonhomogeneous bulging is observed for an annealing temperature of 250ºC as observed from fig. 5.

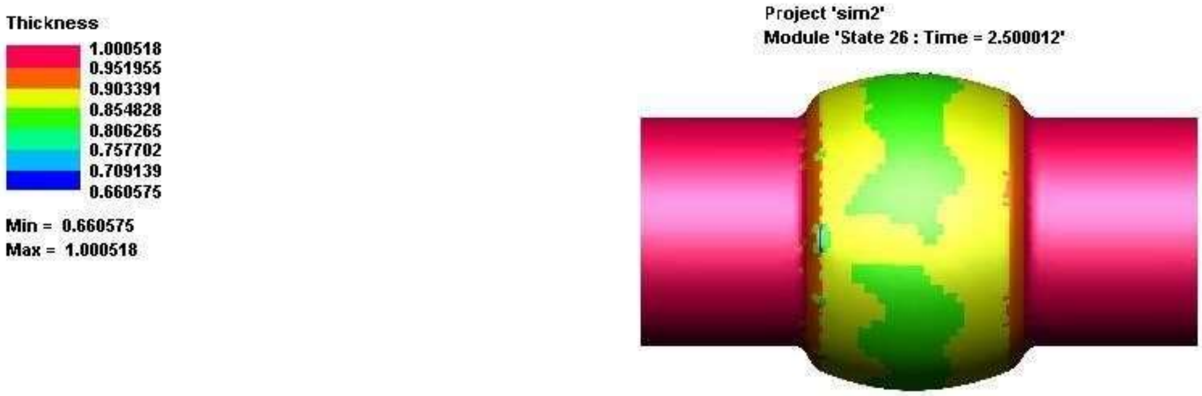

Fig. 6 - Thickness distribution of the bulged tube during hydroforming

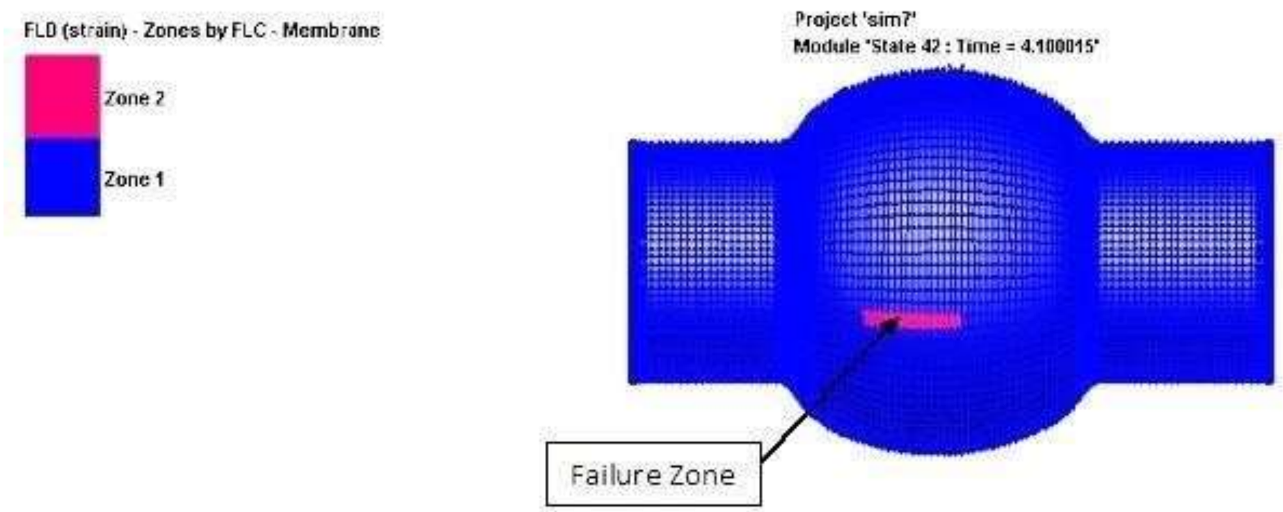

Fig. 7 - Bursting of the tube in tube hydroforming of SS 304

4. Conclusions

Numerical study on tube hydroforming process was studied on SS 304 tube metal. The effect of annealing temperatures on bulge height and thickness distribution of tube hydroforming process was investigated. The following conclusions were drawn from the present case study:

1. Annealing temperatures effected the bulge height and thickness distribution in the bulging zone.
2. Annealing temperature of 150°C attained highest bulge height when compared to as received condition and other annealing temperatures.
3. Uniform thickness distribution of the bulging zone is observed for a annealing temperature of 150°C is observed from the present work.
4. Annealing of the tubes altered the mechanical properties like strength coefficient, elongation and strain hardening exponent. All the properties were improved as far as forming is concerned up to a temperature of 150°C.

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