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# Finite element comparison of single, bi-layered and three-layered tube hydroforming processes

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**Abstract**
In this paper, single, bi-layered and three-layered tube hydroforming processes were numerically simulated using the finite element method. It was found that the final bulges heights resulted from the models were in good agreement with the experimental results. Three types of modeling were kept with the same geometry, tube material and process parameters to be compared between the obtained hydroformed products (branch height, thickness reduction and wrinkling) using different loading path types. The results were also discussed.

## 1. Introduction

Tube hydro forming (THF) is an advanced and unconventional metal forming technology growing fast in many industries. Internal pressure with or without axial compressive loads is used to deform the tubes to conform the shape of given die cavity.

The main application of this method [1] has been found in manufacturing reflectors, household and kitchen appliances, aerospace, automotive and aircraft industries as well as manufacturing components for sanitary use.

Automotive industry applications can be seen in exhaust parts, camshafts, radiator frames, front and rear axles, engine cradles, crankshafts, seat frames, body parts and space frame. Throughout recent decades, it has been discovered that it is expensive and time consuming to design the metal forming processes using trial and error. The application of finite elements method has assisted engineers to efficiently improve the process development by avoiding cost and limitations of compiling a database of real world parts [2, 3].

Finite element analysis permits arbitrary combinations of input parameters including

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design parameters and process conditions to be investigated within limited expenses. Different finite element modeling studies have been reported in the literature. However, the 3D simulation method and non-linear analysis have been found to have the closest results to the experimental results [4].

A considerable amount of research concerning three-dimensional finite element simulation of single tube hydro forming process has been carried out through the last two decades. Two different loading patterns were numerically investigated by Ahmed and Hashmi [5].

They used a pressure predominant loading path and an axial predominant loading path and concluded that a pressure predominant path could give smoother deformation while a predominant axial load path may result in buckling or wrinkling. In another work, the same authors [6] used finite element simulations to identify locations and reasons for failure of a T-branch hydro forming process. It was found that tube would fail either by rupture at the branch top due to a dominant pressure or by buckling at the tube bend due to excessive axial loads.

Hydro forming of tubes in X and T dies was investigated by Ray and MacDonald [7] using finite element method. Numerical models were found to be valid when comparing numerical results with the experimental ones. Both modes of failure were numerically investigated.

However, in some special applications, there is a demand for bi-layered tubular components which can be produced by hydro forming. Bimetallic tubing which consists of two combined different layers gives combined properties of heat exchange, strength and corrosion resistance which cannot be provided by single tubes. Furthermore, it has been found that use of double-layered tubes with the same material and similar thickness of each layer (roughly one half of total design thickness) can make piping systems much safer for long-distance and high-pressure transportation [8].

A numerical investigation was done by Mac Donald and Hashmi [9] to study hydro forming of bimetallic tubes in a cross die in which a thin layer made of stainless steel was used to protect a copper tube. Islam et al. [10] used finite element simulations using implicit code ANSYS to explain stress distribution during bi-layered tube hydro forming. More recently, effect of geometrical factors on bi-layered tube hydro forming was investigated by Alaswad et al. [11] using integration of finite element modeling and designing experimental technique.

Finite element comparison of single and bi-layered tube hydro-forming processes was made by Abed Alaswad et al [12].

In this work, single, bi-layered and three-layered tube hydro forming processes were numerically simulated using finite element method.

The experiments were conducted to investigate validation of numerical models. Based on the proposed models, comparison of single, bi-layered and three-layered tube hydro forming was constructed. In this regard, three kinds of modeling were kept with the same tube and die geometries, tube and die materials and process parameters while different types of loading paths were applied (linear, internal pressure advanced and axial feed advanced loading paths) for three systems. Based on the resultant conclusions, a further discussion was made.

## 2. Finite element modeling

Finite element study was performed to model single, bi-layered and three-layered tube hydroforming processes using ABAQUS/Explicit 6.10.

In three cases, tubes of 120 mm length and 24 mm outer diameter were hydro formed in the T-branch die. Thickness of the single-layered tube

was considered 1.3 mm while it was 0.65 mm for each of inner and outer layers, which made the total thickness of the bi-layered tube the same as that of the single-layered tube. Also, it was considered 0.45, 0.45 and 0.4 mm for each of outer, middle and inner layers which made the total thickness of the three-layered tube the same as that of the single and bi-layered tubes.
The finite element model was built in three parts: (a) tube, (b) rigid die and, (c) rigid plunger. By taking advantage of symmetry, a 1/2th of the T-branch was modeled (Fig. 1, 2 and 3).

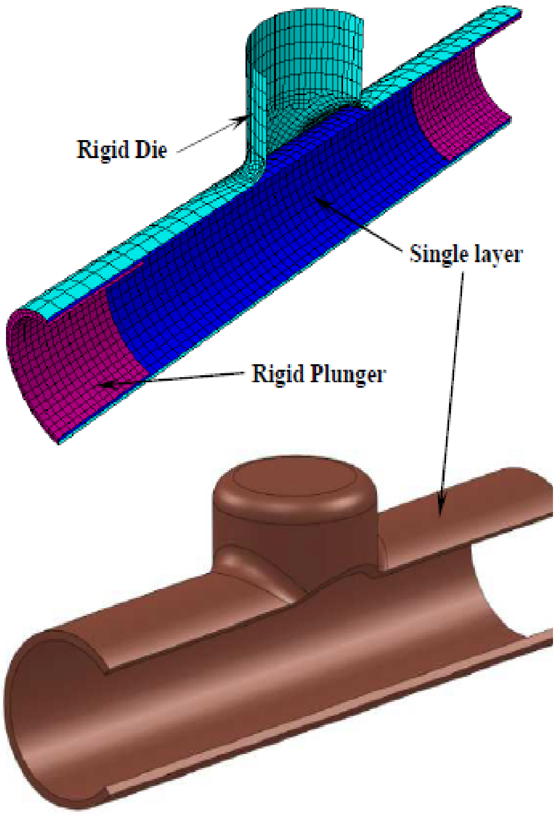


**Fig. 1.** Simulation of single-layered tube hydro forming.

The nodes at the symmetric edges were restrained in the appropriate directions while the nodes attached to the tube end were kept free for all degrees of freedom. The tubes were modeled using thin shell elements.

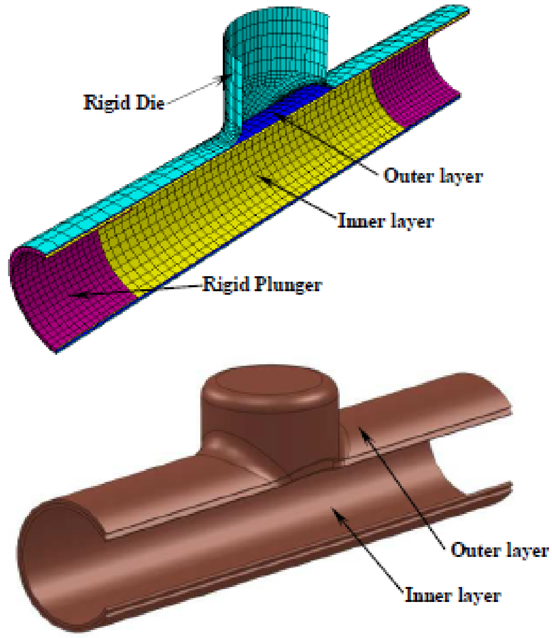


**Fig. 2.** Simulation of bi-layered tube hyro forming.

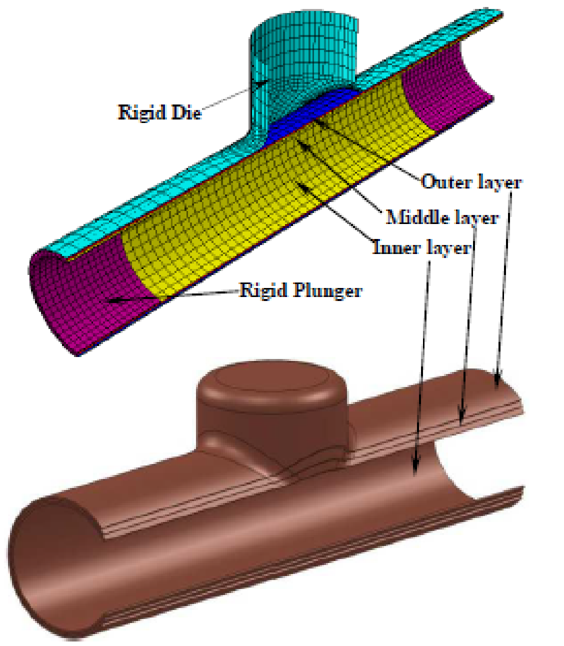


**Fig. 3.** Simulation of three-layered tube hydro forming.

Mesh sensitivity analysis was performed to determine effect of the number of elements used in tube modeling on the numerical results (Fig. 4).

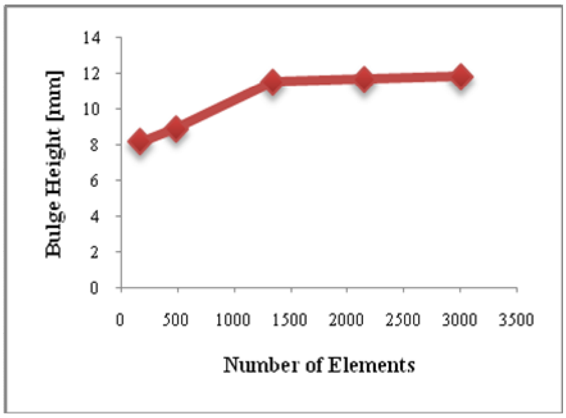


**Fig. 4.** Effect of number of elements on the bulge height of single tube hydro forming.

The contact between tube and each of the die and end plunger was modeled by an advanced automatic surface to surface contact algorithm with an elastic coulomb friction law and friction coefficient of 0.15.

The coefficient of contact interface friction values used for the simulation was reported in [7] for hydro forming of Copper X and T-branch parts using the same die sets and lubricants as the ones used for the present experimental study. In case of bi-layered tube, the last contact parameters were used to define the interface between outer layer and die, and between both layers and the plunger while the interface between both layers was described by the same contact algorithm with friction coefficient of 0.57 as found in [10,11].

Another kind of contact parameter was defined with single surface contact entity. This was defined in the case of formation of wrinkles due to excessive axial feed, in which this contact definition would take care of self-surface contact.

Annealed standard copper (Cu 99.94%, P 0.02%) which was used in single-layered tube hydro forming experiment with the properties listed in (Table 1) was numerically used for single-layered tube and for both inner and outer layers in bi-layered tube hydro forming and for three inner, middle and outer layers in three-layered tube hydro forming [12].

Using the same material and thickness in three single, bi-layered and three-layered tube hydro forming was numerically assumed to compare the three systems.

A power law plasticity model was utilized for the copper material model (K = 0.4257, n = 0.2562). The material properties were obtained experimentally using a uni-axial tensile test. However, in the simulation, true stress strain data were calculated from the engineering stress strain data and power law plasticity models were fitted to the true stress–strain curve [7].

The rigid die and plunger were not fully modeled. Only the surfaces in contact with the layers were modeled using 3D thin shell elements. The die was constrained for all degrees of freedom while the plunger was constrained for all degrees of freedom, except for Z-translation; i.e. it was allowed to move along axial length of the tube.

In the non-linear analysis, the pressure load was applied as a surface load on the shell elements with the normal directing outward, assuming that the pressure acted on the tube inner surface while axial feed was applied to the plungers to feed the tube material. The relation between internal pressure and axial feed during the hydro forming process could be defined as the loading path.

In order to employ numerical models in the comparison study, an experimental study was required to examine validation of numerical models in terms of the investigated responses [12]. In the validation study, the loading paths used for the simulations were matched with the actual dynamic loading paths recorded during the hydro forming process.

**Table. 1.** Mechanical properties of single-layered tube.

| Mechanical properties | |
|---|---|
| Density (gm/cc) | 8.90 |
| Elastic modulus (GPa) | 119.86 |
| Poisson's ratio | 0.31 |
| Yield stress (MPa) | 116.00 |
| Ultimate tensile stress (MPa) | 260.00 |
| Strength coefficient (GPa) | 0.4257 |
| Work hardrning exponent | 0.2562 |

## 3. Experimental set up

The experiments were conducted on the tube hydro forming machine shown in Fig. 5 to form single and bi-layered T-branch components. The power source for the hydraulic system was a variable displacement piston pump driven by a 7.5 kW electric motor [11].

The set up consisted of a hardened steel die set with lower and upper die halves with T-branch cavities which were clamped using a hydraulic press attached to the upper die holder while the lower die part was rigidly fixed to the machine base. A LabVIEW system was used to set the axial sealing pressure, maximum forming pressure and maximum end axial feed [11].

In the experiments, after placing the tube in the cavity of the lower die, the upper die part moved down to close the die while axial plungers were pushed using horizontal pistons to seal the tube ends. As sealing of the tube took place, application of the internal pressure and the axial feed on the tubular blank would start.

During the experiments, the pressure values were recorded with an electronic pressure transducer and the end axial feed values with a linear variable displacement transducer. Values of forming pressure and end feed displacement were used for calculating the experimental load paths.

It was observed that initially the pressure increased steadily but, in the later part of the process, it kept varying or fluctuating due to the dynamic nature and high sensitivity of the pressure intensifier [11].

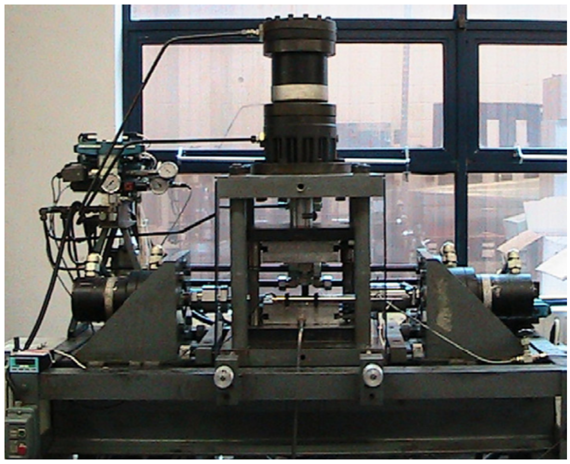

**Fig. 5.** Tube hydro forming machine [11].


**Fig. 6.** Hydraulic jacks (20 ton) used in tube hydro forming machine.

## 4. Numerical models validation

### *4.1. Single-layered tube hydroforming*

Hydro forming of a copper tube (L = 120 mm, OD = 24 mm ID = 21.4 mm) with the material properties listed in (Table 1) was performed using tube hydro forming machine.

In the finite element simulation, the experimental conditions were numerically simulated to compare the experimental results with the numerical ones and check the numerical models validation.
As stated before, loading path used for the simulation was matched with the actual dynamic load path recorded by the LabVIEW data acquisition system during the experiments (Fig. 7).

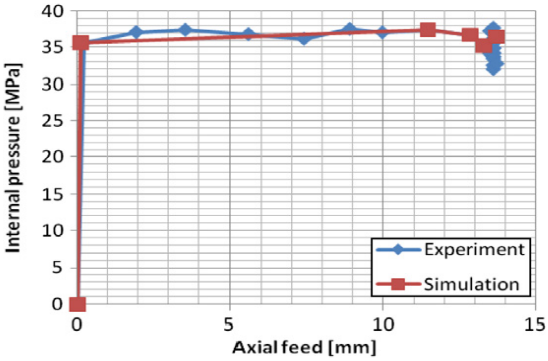


**Fig. 7.** Single-layered tube hydro forming loading path [11].

*4. 2. Bi-layered tube hydroforming*

Bi-layered tube hydro forming was conducted using the same hydro forming machine. In the experiment, copper tubular layer (L = 120 mm, OD = 22 mm, ID = 20.3 mm) was inserted in Brass tubular layer (L = 120 mm, OD = 24 mm, ID = 22 mm) with a loose fit. Material properties for both layers are listed in Table 2. During the hydro forming process, proper application of internal pressure caused tight fit between the inner and outer layers and deformed both of them in the die shape. In the finite element simulation, the same experimental conditions were applied. Materials of both layers were numerically modeled using bilinear kinematic hardening models with the same mechanical parameters described in Table 2. Furthermore, the applied loading path was simulated based on the experimental one (Fig. 8). A comparison between the experimental and numerical results could be used to check validation of numerical models.

**Table. 2.** Mechanical properties for two layers [11].

| Mechanical properties | Outer layer (annealed brass) | Inner layer (copper) |
|---|---|---|
| Density (gm/cc) | 8.8 | 8.98 |
| Elastic modulus (GPa) | 100 | 105 |
| Poisson's ratio | 0.33 | 0.33 |
| Yield stress | 980 | 220 |
| Tangent modulus ($m_t$) | 0.59 | 0.21 |

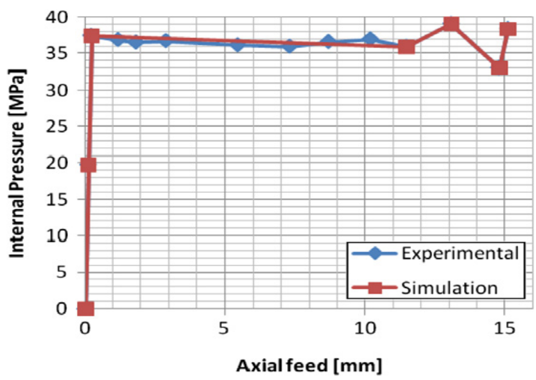


**Fig. 8.** Bi-layered tube hydro forming loading path [11].

In both cases, the branch surfaces were measured for the hydro formed experimental samples Figs. 9 and 11 using a coordinate measuring machine with accuracy level of 0.1mm [11]. The experimental readings were compared with the simulation results (Figs. 10 and 12). Numerical results were generally in good agreement with the experimental measurements.
Some differences were noticed between the experimental and numerical bulge profiles which could be attributed to the frequently changing boundary and friction conditions, the anisotropic material properties and the measurement errors of the experimental results.

However, for both cases, it is clear that experimental and numerical results tended to be closer at the final bulge height which was the investigated response in this study. Table 3 shows results of the final branch height with percentage deviation of simulation results with respect to the experimental ones. It was found that the maximum deviation in the branch height obtained from simulation was within ±5% of the experimental value which led to the validation of numerical models in terms of final bulge height.

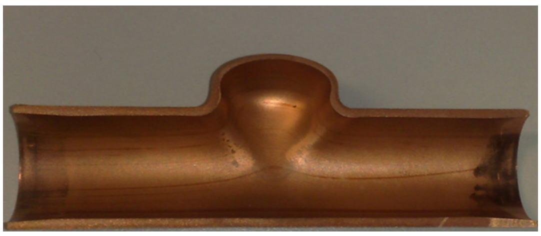

**Fig. 9.** Experimental result of T-type single-layered tube hydroforming [12].

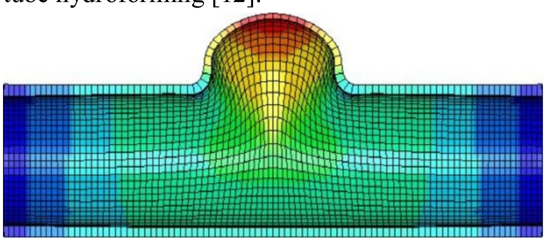

**Fig. 10.** Numerical simulation result of T-type single-layered tube hydroforming [12].

## 5. Types of loading paths

With the aim of performing the proposed comparison, different loading path types were applied to three systems and the process formability under each applied loading path was investigated.

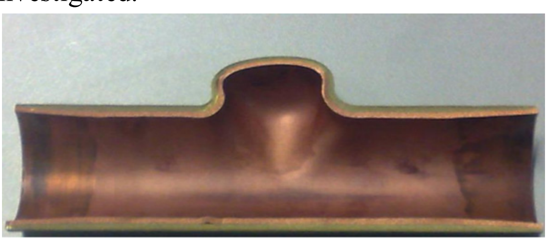

**Fig. 11.** Experimental result of T-type bi-layered tube hydro forming [12].

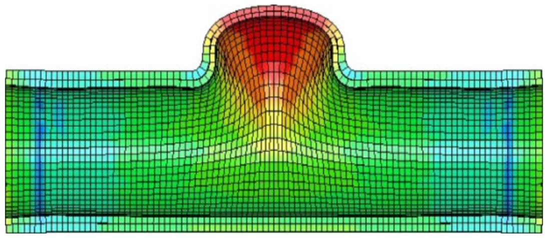

**Fig. 12.** Numerical simulation result of T-type bi-layered tube hydro forming [12].

**Table. 3.** Final bulge height comparison (experiment, simulation results and present FEM).

| Hydroforming system | Single layer | Bi-layered |
|---|---|---|
| Branch height (Experiments) (mm) | 11.505 | 9.638 |
| Branch height (Simulation) (mm) | 11.615 | 10.050 |
| Present FEM (mm) | 11.517 | 9.704 |
| Percentage deviation (%) | -1 | -4 |

In T-branch tube hydro forming, obtaining a high protruded bulge, good wall thickness distribution with no significant wrinkling in the hydro formed part is mostly preferred by engineers and manufacturers.

One of the factors which significantly influences process formability is loading path type selection which determines the relationship of internal pressure and axial feed during the process.

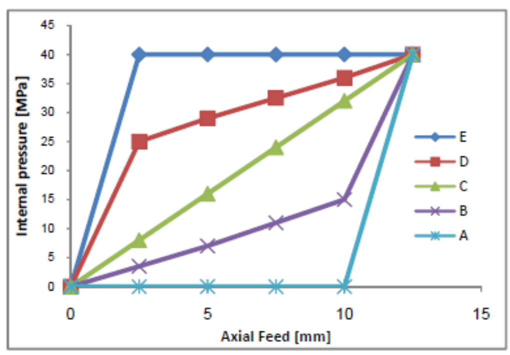


**Fig. 13.** The applied loading paths in tube hydro forming [13].

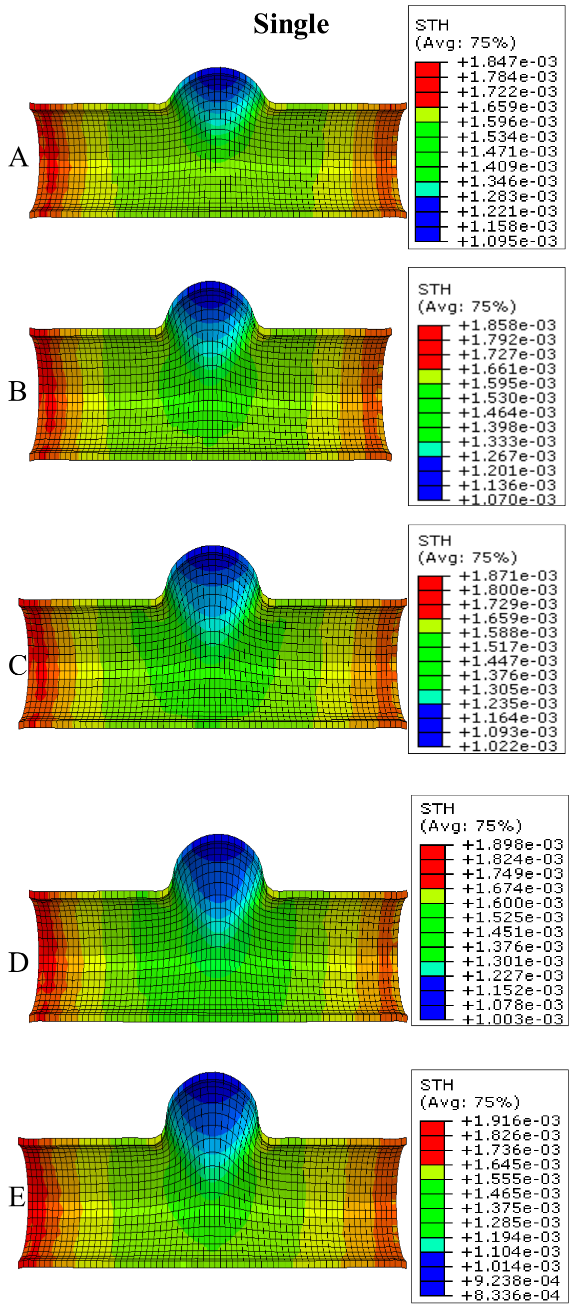


**Fig. 14.** Single hydro formed parts under different loading paths (A-E).

Applied loading paths which are shown in (Fig. 13) can be categorized in three types. The first type which is loading path (C) represents linear relationship between the internal pressure and axial feed. Loading paths (D and E) are classified as pressure advanced type in which the hydraulic pressure is raised to a certain magnitude before the axial pushing while A and B stand for the loading paths which guarantee big increase of axial feeding before the internal pressure [14, 15].

For the comparison reason, all the studied loading paths were chosen with the same maximum internal pressure and total axial feeding values.

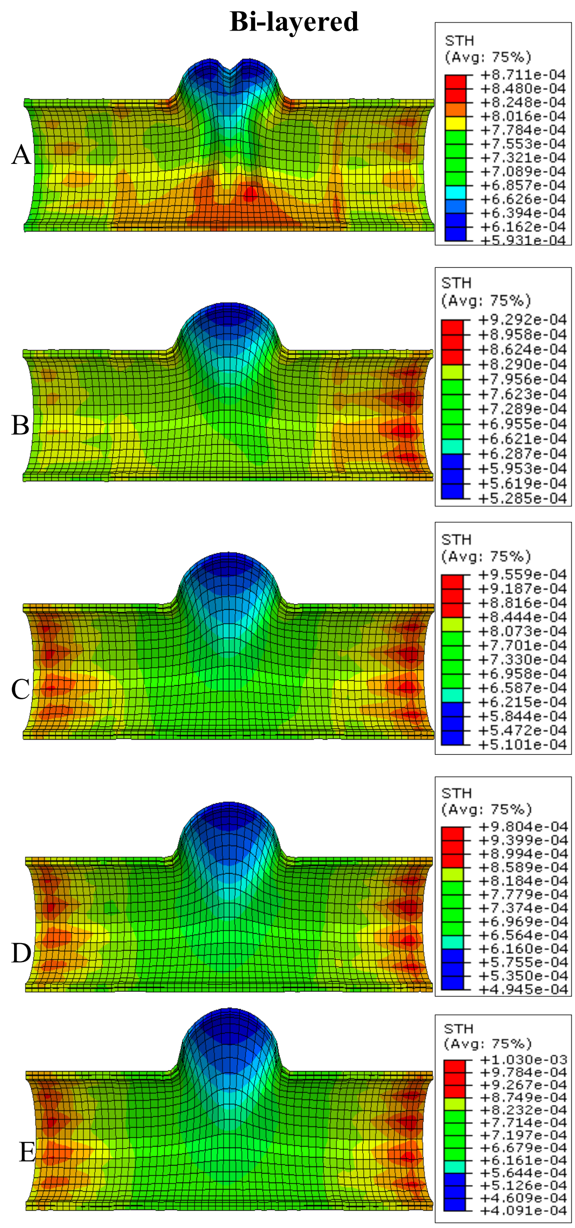


**Fig. 15.** Bi-layered hydro formed parts under different loading paths (A-E).

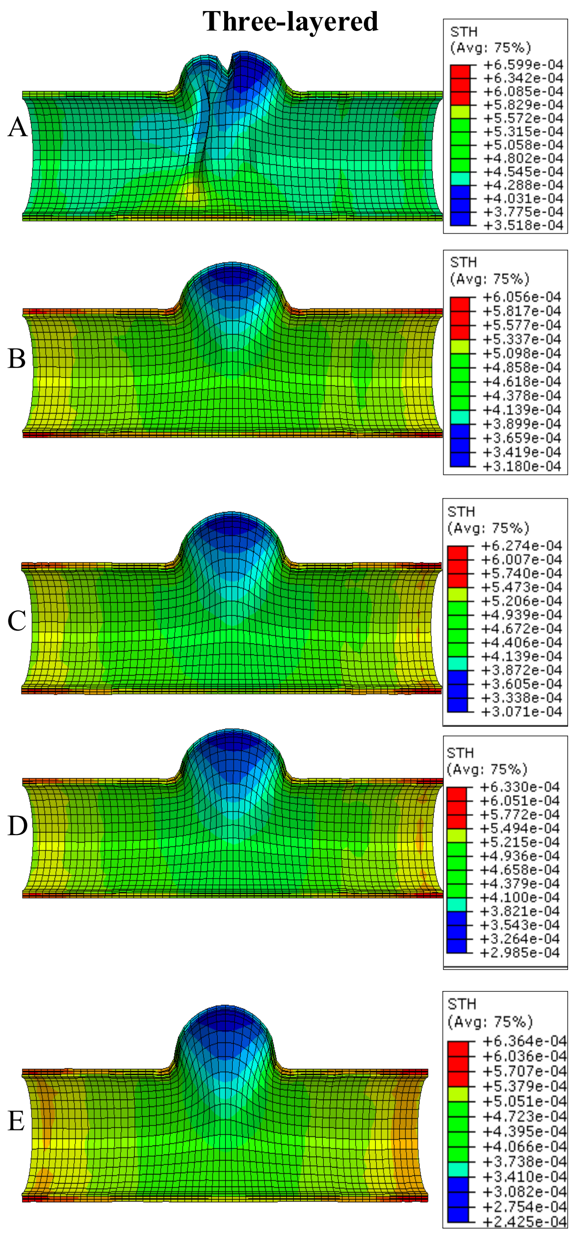


**Fig. 16.** Three-layered hydro formed parts under different loading paths (A-E).

## 6. Results and discussion

Single, bi-layered and three-layered hydro formed parts resulted by applying each loading path are shown in Fig. 13. Based on the numerical results, bulge heights and wall thickness reduction were recorded for three types of single, bi-layered and three-layered tube hydro forming and compared to each other in Figs. 14, 15 and 16 [15].

According to Figs. 13 and 17, it can be noticed that, for three types of single, bi-layered and three-layered tube hydro forming, pressure advanced loading paths (D and E) guaranteed the best process formability since high bulges with accepted wall thickness reduction ratios were gained.

In bi-layered tube hydro forming, applying high internal pressure in advance led to early combination of inner and outer layers and deformation of both in the die recess. However, by applying this type of loading paths, bi-layered and three-layered hydro formed bulges were found slightly lower than the single-layered one because of the internal friction taking place between both and the three layers before the combination.

Applying linear and axial feed advanced loading paths (C, A and B) resulted in low bulges for three systems. In bi-layered tube hydro forming, applying such loading paths delayed the combination of inner and outer layers which allowed both layers to feed separately before the layers merging.

The feed applied to the inner layer would give an extra pressure to the outer layer which resulted in the protruded bulges slightly higher than those obtained from single tube hydro forming.

By comparing wall thickness reduction of single, bi-layered and three-layered hydrof ormed branches (Fig. 18), it can be observed that, when loading paths were applied, thickness reduction percentage of the bi-layered and three-layered hydro formed parts were bigger than what was obtained from the single-layered tube hydro forming. This was because of the internal friction which took place between the layers before their combination.

Based on the numerical results, Von misses stress at the top node of branch in single, bi-layered and three-layered tubes are shown and compared to each other in Fig. 19.

As can be seen, the maximum stress in the layers was lower than tensile strength of materials. Then, tubes in the applied pressure could be completely formed in hydro forming die without the bursting [14].

No significant wrinkling was detected when applying loading paths (B, C, D and E) in three types of single, bi-layered and three-layered tube hydro forming. On the other hand, loading path (A) was responsible for forming wrinkles in the hydro formed products due to including application of the biggest part of axial feeding under the applied small internal pressure (Fig. 13).

However, a late and sudden rise of internal pressure was applied before the process ending. Single, bi-layered and three-layered hydro formed parts resulted from applying loading path A, as shown in Fig. 20.

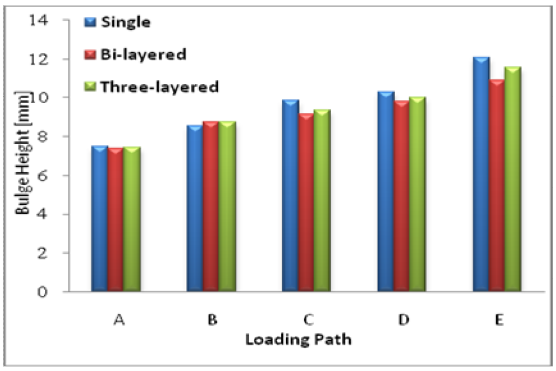


**Fig. 17.** Bulge height comparison between single, bi-layered and three-layered tube hydro forming.

Comparison between these three types indicated that bi-layered and three-layered tube hydro forming was more sensitive to wrinkling and buckling than hydro forming of single-layered tubes, which was because the maximum internal pressure applied at the end of the process was not able to calibrate the formed wrinkle in the bi-layered and three-layered hydro formed parts while the single-layered offered less resistance against the wrinkle calibration.

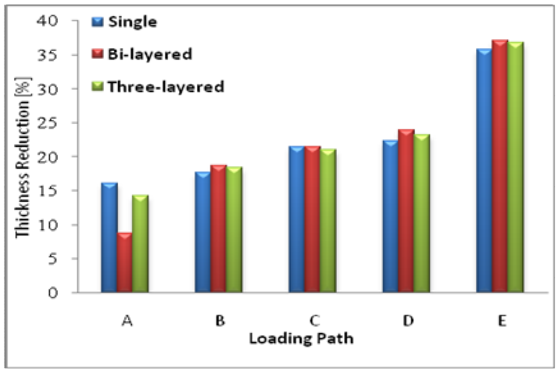


**Fig. 18.** Thickness reduction comparison between single, bi-layered and three-layered tube hydro forming.

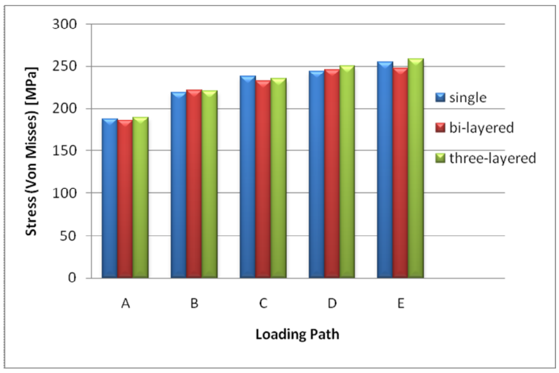


**Fig. 19.** Comparison of Von misses stress between single, bi-layered and three-layered tube hydro forming.

## 7. Conclusions

Finite element models were conducted for single, bi-layered and three-layered tube hydro forming. Validation of numerical models was experimentally investigated. Different loading path types were applied to three types of single, bi- layered and three-layered systems and the process formability under each applied loading path was investigated.

Loading paths D and E which included the application of internal pressure before the axial feeding were found to improve formability of three systems (Maximum branch height).

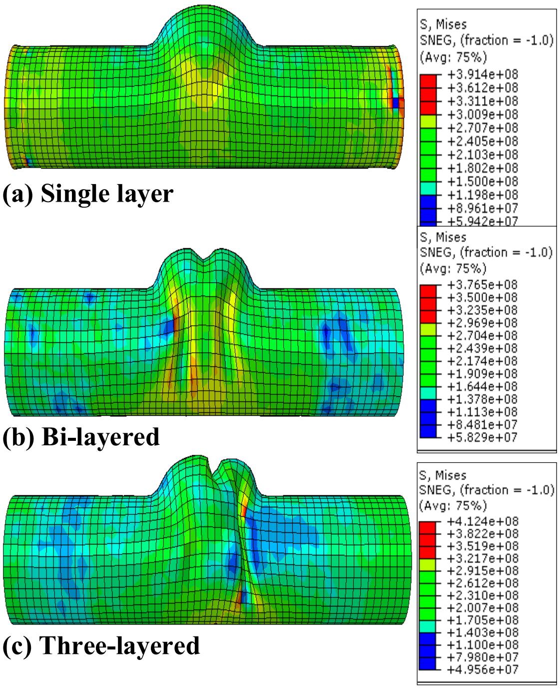


**Fig. 20.** A comparison of (a) single tube hydro forming, (b) bi-layered tube hydro forming and (c)three-layered tube hydro forming under loading path (A).

However, by applying this type of loading paths, bi-layered and three-layered hydro formed bulges were found slightly lower than the single-layered one while bi-layered and three-layered hydro formed bulges produced when applying linear or axial feed before loading paths C, A and B were found higher than the single-layed ones.

Comparison between single-layered, bi-layered and three-layered hydro formed components indicated that bigger wall thickness reduction was found in the bi-layered and three-layered hydro formed parts when one of the loading paths A, B, C or D was applied. Nevertheless, better wall thickness distribution was reported in the bi-layered and three-layered hydro formed parts when loading path E was applied (maximum branch height).

On the other hand, it was observed that the bi-layered and three-layered tube hydro forming process was more sensitive to wrinkle formation than the single-layered tube hydro forming process (Fig. 20).

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