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Design and Optimization of Multistage Mandrel for Downhole Tubular Expansion

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Acknowledgment

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Abstract

Solid Expandable tubular (SET) a new invention was first presented to industries in early of 1999's, the new technology provides many solutions for unsolved problems, such as reducing the initial drilling diameter and replacing the telescoping drilling with mono-diameter drilling. Still, SET raise challenging problems, one of the problems is to make the tubular technology cost effective with conserve structure integrity for tubular. In present work a new multistage mandrel design has been introduced, the main objective of this paper is to design and optimize the shape and geometry of multistage mandrel by studying and understanding down-hole expansion parameters and develop finite element model in commercial finite element software ABAQUS. Simulations are preformed to study the effect of multistage mandrel on tubular mechanical properties, it is found that the expansion force can be reduce with multistage mandrel with increasing in residual stress, while the length shortening, and thickness reduction are found to be the same.

CHAPTER 1

INTRODUCTION

In the last decade a new technology was adopted by many oil and gas industries, this technology has opened a new prospect in oil and gas wells applications and gives alternative solutions for many unresolved problems. Expandable tubular technology which is expanding a down-hole tubular by a cone until its reach a specific diameter was first presented for oil and gas application in the early 1999's.

The traditional method of drilling oil and gas wells came with many limitation and problems, its begin by drilling a hole with large diameter, then installing a steel pipe knowing as casing with smaller diameter to fit into the hole, drilling continues using a smaller drill bit that fits inside the first casing, and required casing need to be smaller than the previous casing, this process continues until the required depth reached, eventually the diameter for the pipe will be very small comparing with initial drilling diameter, However, as oil and gas reserves are found at ever greater depths the costs of the traditional approach rise rapidly. While in the expandable tubular the down-hole tubular will be expand to nearly the initial diameter, by a cone - also known as mandrel – propagating through the tube, as the expanding rate increase as the productivity increase, expanding rate has limit depending on the material properties, in most applications expanding rate did not exceed 30% from the initial diameter of the pipe.

MOTIVATION:

The development of expandable tubular technologies is considered one of the most revolutionary technologies introduced in the oil and gas drilling and completion fields in past several decades. The successful expansion of a steel tube provided a unique challenge to engineering teams as the technology began development.

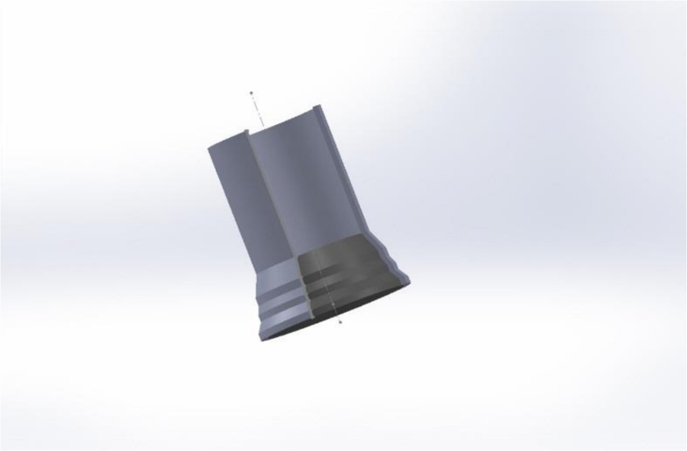


Figure 1: multistage mandrel-tubular system

There are many different techniques used to expand tubes, different variables governing the selection of expanding technique such as cost and time. Cost can be increase with increasing in the complexity of the mandrel shape, single stage mandrel shape can expand the tube for only one expansion ratio, a higher diameter mandrel needs to increase the expansion ratio, to expand with different expansion ration, multistage mandrel (Figure 1) shape has been designed to expand the tube with increasing stages diameter (16%, 20%, and 24%).

The modification in mandrel shape and geometry could lead to different expansion results. The main aim of this project is to design shape of multistage mandrel geometry to obtain the required expansion parameters.

OBJECTIVES:

1- Understand the parameters and details of down-hole tubular.

2- Develop finite element model of down-hole tubular and multistage mandrel and run the finite element simulations in commercial finite element software ABAQUS.

3- Analyze tubular expansion parameters and draw conclusions about each shape of mandrel.

4- Validate finite element model with the published experimental results of tubular expansion

5 – compare the result of multistage mandrel shape with single stage mandrel.

METHODOLOGY:

The activities of the project work is divided into four major phases and then further divided into sub-phases. The following discussion is dedicated to the project activities:

Phase 1: Literature Review Of Downhole Tubular Expansion.

In the first phase of project work, literature review has been done in the field of solid expandable tubular and down-hole tubular technology. The main purpose of literature review is to understand tubular expansion phenomenon and find the gaps in the existing work.

Phase 2: Finite element modeling for Downhole tubular and multistage mandrel shape.

In this phase, finite element model of down-hole tubular and multistage mandrel will be developed. this reflects the real tubular-mandrel system. The dimensions and experimental parameters are taken from published literature .

Phase 3: Model validation

In the third phase of the project, finite element model is validated through the experimental results from the published literature. The experiments are performed on a full-scale test rig; located at Sultan Qaboos University, Oman.

Phase 4: Finite element simulations: A parametric study of multistage mandrel geometry.

further simulations are performed in the fourth phase of project. These simulations are related to the parametric study of mandrel geometry. The main aim of this phase is to obtain an optimum geometry of mandrel through which, the required tubular expansion parameters can be achieved. Phase 4 is further divided into three sub-phases as

Phase 4.1: Variation of mandrel radius.

Phase 4.2: Variation of mandrel angle.

Phase 4.3: Variation of mandrel shape.

Chapter 2

LITERATURE REVIEW

2.1 REVIEW OF SOLID EXPANDABLE TUBULAR TECHNOLOGY

In tubular expansion, a mandrel is propagated through a string of down-hole tubular using hydraulic or mechanical force. The progress of the mandrel deforms the tubular to the desired inner and outer diameters, while preserving its integrity, as shown in Figure 2.

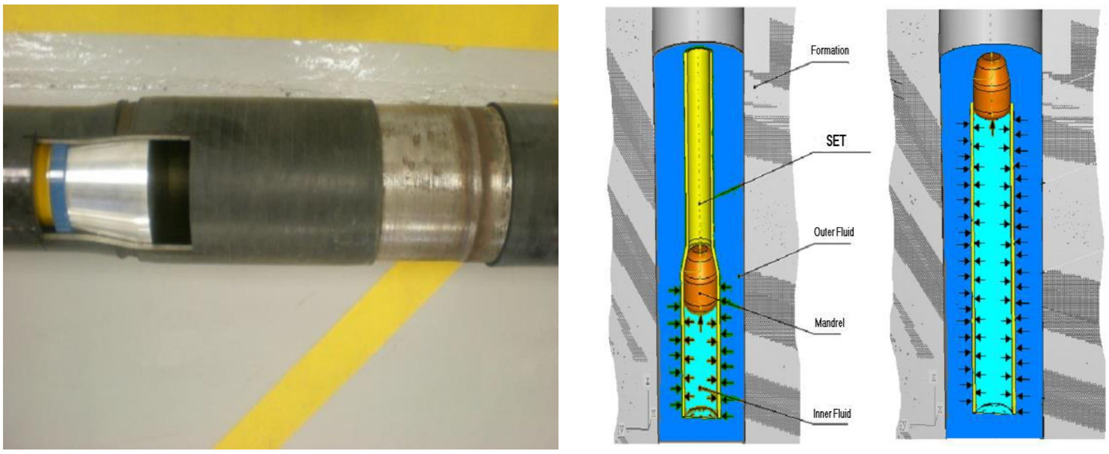


Figure 2 : single stage mandrel-Tubular mandrel system

The concept of expandable tubing is not new. The boiler manufacturers have been using expandable tubing as a core technology for many years. The notion of use of expandable tubing in down-hole applications dates from the late 1800's. The Russian oil and gas industry had utilized the idea for shutting off damaged zones. Over 700 applications had been recorded in the Former Soviet union by early 1990's [TatNIPIneft discussion 1992]. In late 1980's, Shell launched a research program for the development of a suitable solid pipe expansion system. However, the ease of expanding slotted pipe led to the potential use of the technology as a mean of maintaining borehole stability and as an alternative sand exclusion method. This classification of expandable tubular technology is termed as expandable slotted tubular. Here the expansion depends on the dimension and placement of slots and the size of expansion cone. Expansion up to 200 % of the original diameter can be achieved. The expansion process is based on bending the metal strips between two overlapping slots requiring small expansion forces, approximately 10 tons, depending on the number of shear screws pre-installed. The expansion forces for solid expandable tubular are enormous about 10-30 times that required for an average expandable slotted tubular. This technology is commercialized since 1997. The first commercial usage of expandable slotted tubing was as a sand exclusion mechanism. Applications of slotted expandable are the cemented expandable slotted liner and the expandable sand screen as means of down-hole sand control. Two successful applications of the cemented expandable slotted liner had been performed at Petroleum Development Oman in 2001. Hartgill reported the first successful gas production well in the world using a 4” expandable sand screen. The benefits of using expandable sand screen in terms of cost and production. al. reported a novel approach to slim well delivery using expandable sand screen. Critical issues of down hole expansion and wear of mandrel were addressed successfully. The substitution of expandable sand screen for the slotted liner in conventional slim design offered an added advantage of increased production from 3-1/2” to 4-3/4” expansion. The solid expandable were also used to isolate the zones producing only water leaving open the zone producing both oil and water.

The first test of solid expandable tubular technology was performed in 1993 by Royal Dutch Shell in The Hague. The results proved that the concept was viable. In this test, special automotive steel tubular of 4 inch diameter was expanded up to 22%. The tests were performed using joints of pipe that had been welded together. In 1998, Shell E&P and Grant Prideco made a breakthrough in developing expandable threaded connections making the technology practical for oilfield applications. With the visions to improve production in Shell Petroleum Development Company Nigeria by 20% in the short term coupled with the thrust to reduce environmental impact, most new wells favor utilizing expandable tubular technology. Over 150 wells were identified for this technology in the medium term with 3 wells selected as quick wins for the deployment of SET in 2001. However, in order to minimize the impact of oil exploitation to the environment such as reduced land uptake, efficient and effective waste management, etc., only horizontal sidetracks were favored. This was the first deployment of SET outside the Gulf of Mexico. The application also utilized a novel cementing technique “Settable Spotting Fluid” from Halliburton to minimize the risk of cross flow and low side channeling, a common situation in high angle application in the Niger Delta, which had resulted in an improved expandable casing process. Similar successful application of transforming conventional wells in mature basins to big bore producers using SET is reported in Malaysia. The concept involves installing and expanding a long section of 7 5/8”7 solid expandable tubular inside 9 5/8” casing. For a mature gas field offshore Sarawak where this concept was applied in a pilot well, yielded a production conduit with an internal diameter 24% larger than conventional tubular, a 61% increase in flow area, and a significant increase in well production. Results showed a 40-50% increase in well deliverability.

In the meantime, research on Solid Expandable Tubular continued on a limited scale. Potential benefits of the technology resulted in late 1998 and early 1999 in the launch of two joint venture companies dedicated to the development and implementation of expandable tubing products. Several papers, published during the last four years, describe the Solid Expandable Tubular Technology. Operators and researchers admit the simplicity of the technology, but agree that the process study and its implementation is complex and involve many fundamental mechanisms. described the system as a mechanical expansion device called mandrel or cone that propagates through a tubular either by pressure across the mandrel or by direct push or pull of mechanical force. The authors asserted that during its progress, the mandrel defines the new diameter of the tubular. They proved that the surplus or the gap between the mandrel outer diameter and the expanded tubular inner diameter is negligible.

Tests conducted by Steward, Marck and other researchers showed that the mechanical deformation increases the load bearing capacity of tubular but reduces the safety margin for failure. The task of striking a balance between increasing the load bearing capacity and reducing the safety margin, is extremely difficult. This is due to the inherent non-linearity present in the system. Various nonlinear effects are due to material non-linearity, contact and friction conditions, non-homogeneity of materials, and system instability. These irregularities, material non-linearity effects, contact conditions on the expandable tubular were thoroughly investigated using finite element method. The nonlinear conditions increase the difficulty in many ways. Particularly critical to the down-hole expansion process are:

- Mechanical properties of tubular such as burst strength, ultimate tensile strength, ductility, impact toughness, resistance to galling, wear, environmental cracking, etc.
- Manufacturing tolerance of the tubular.
- Tubular connection design.
- Mandrel shape.
- Lubrication between mandrel and tubular to be expanded.
- Springback phenomenon.
- Down-hole environment.

For a down-hole expansion process, the tubular must be able to expand to the desired diameter without fracturing, bursting or damaging. It must be able to maintain hydraulic capabilities to provide sufficient resistance against burst and collapse during service. The expanded tubular should have constant diameter and wall thickness over the whole length of expanded section and should maintain the integrity of expanded tubular connections. Another challenging task is to expand long sections at high rates.

Since the tubular, as well as the mandrel, experience high interfacial stresses, as the expansion proceeds, selection of mandrel material is also crucial. The shape of the mandrel also plays a critical role for successful completion of the expansion process. Knowledge of post expansion mechanical properties of tubular is very important for proper utilization during service. The variation in properties such as strength, ductility, impact toughness, collapse, burst, and environmental cracking for various tubular sizes have been done and compared to the same values for pre-expanded tubular. Studies on the effects of expansion on the mechanical properties of expanded tubular, hoop stress resilience during expansion, and the resistance of expanded tubular against sulfide stress cracking proved its viability for field applications.

Most of the applications reported for STE in literature indicate a maximum of 25% expansion in tubular outer diameters. Expansions greater than 20%, based on tubular inner diameter, have been accomplished. Simulations were carried out for expansion of 30% in inner diameter [19, 31]. However, most applications using 10.8 to 30 cm (4.25 to 13.375 inch) tubular required expansions less than 20%. So far, this technology has proven that casings can expand up to 25% of its original outer diameter with acceptable variations in many of the mechanical properties.

The solutions that the SET technology offers are presently based on analytical modeling, laboratory tests and limited large-scale field tests . It is impossible to test all the parameters that operators face in laboratory or through a large-scale field test. Extensive numerical modeling using finite element analysis (FEA) may provide answers for all the parameters involved, which are not possible through experiments. As a result, researchers have focused their attention on the effects of all parameters of interest using FEA to determine the viability and limitations of the technology. The use of finite element analysis shortened the time needed to develop a system that can address the operator’s major concerns. Decades of research work on cold drawing and extrusion is a proof of the concept but field readiness requires additional numerical and experimental testing. On the research paper of **"Effects of expansion rate on plasticity and structural integrity of downhole tubular"** Expansion tests for 174.6 mm inner diameter and 9.5 mm wall thickness tubular have been done for 16%, 20% and 24% expansion ratios. A finite element model for tubular-mandrel system has been developed using commercial software ABAQUS and has been validated through experimental observations. FE model is then used for simulations of tubular expansion to study the effects of mandrel velocity (strain rate) on post-expansion characteristics of tubular.

The mandrel velocity is varied from 5 to 25 mm/s. It is found that the mandrel velocity significantly affects the contact pressure at tubular-mandrel interface. It is also found that expanded tubular in all cases of expansion ratios and mandrel velocities is not stress free. The residual stress varies from 150 to 247 MPa, which is considered as high magnitude of stress. Failure of tubular due to excessive contact pressure, exceeds or close to ultimate strength, may result at 15, 20, and 25 mm/s mandrel velocities. Other velocities also affect the contact pressure but it remains within the allowable limits. Expansion of tubular at 16% expansion ratio (ER) with mandrel velocity of 20, and 25 mm/s yields the highest value of burst strength and lowest value of collapse strength as compared to other mandrel velocities. Similar trend is observed for 20% ER where maximum burst and minimum collapse strengths are found at 20, and 25 mm/s. At 24% ER, burst and collapse strengths are not much affected by mandrel velocity. This is due to the fact that at higher expansion ratio, tubular material is significantly strain hardening, so there is negligible change in thickness of tubular. It is important to note that the reduction in thickness will determine the acceptability of tubular installation in an oil well based on final burst and collapse strengths. And from the research paper of **"Experimental study of mechanical properties and residual stresses of expandable tubulars with a thread joint"** we read The variation of mechanical properties, microstructure, and deformation of J55 steel expandable tubular technology with a thread joint was investigated by experimentation in this study, and the results supplied theoretical support for application of expandable tubular technology. Based on the results, the conclusions can be summarized as follows: (1) For the microstructure of J55 steel, the pearlite phase surrounded by the ferrite phase observed in the unexpanded sample micrographs was uniformly distributed, and some coarse pearlite grains were present in the micrograph. Similarly the microstructure of expanded samples consisted of the ferrite and pearlite phase, but the pearlite grains were denser than in unexpanded samples. (2) An increase of hardness for the expanded tube was generated and it apparently resulted from work hardening, and the hardness in the middle surface exceeded the hardness of the outer and inner surface. (3) Work hardening was generated due to the expansion process, which increased the yield strength and ultimate strength while it decreased the elastic module of J55 steel. But the radial expansion had little effect on the ductility of the axial direction.

(4) The diameter of the expandable tube was increased with the wall thinned and the length shortened after the expansion. The expansion process contributed to the uniformity of the tube wall thickness. Another interesting result was that in the top zone and root zone of the box thread the depressed deformation was induced by expansion. (5) The presence of high residual

stresses in the thread joint was attributed to the irregular shape of the thread, and in the top zone and root zone of the box thread the residual stresses were relatively higher. This is because much wall thickness was lost from thread cutting on the top and the bending moment resulted when the expansion process acted in the root zone of the box thread. In order to acquire fine steel with high ductility and strength, more work concerning the metallurgical process needs to be developed for optimal steel. Moreover, further research with respect to expandable tubular technology should be developed with the aim of improving the application of this technology. ad little effect on the ductility of the axial direction.

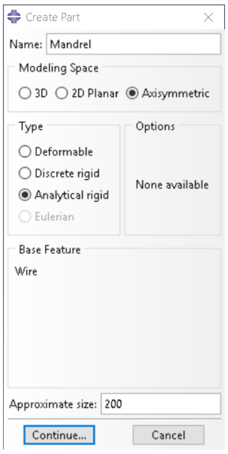
CHAPTER 3

FINITE ELEMENT MODEL OF DOWN-HOLE TUBULAR AND MULTISTAGE MANDRAL

Development of finite element model in commercial finite element software ABAQUS was done, the following section dedicate to the modeling of down-hole tubular and multistage mandrel, a step by step procedure shows the process of development the models.

3.1 Modeling:

The way of how the physical system can be modeled can significantly effects the result, and clearly can affect the computational time, as more as the model is complex, the computational time will increase, for the present work, tubular and mandrel have been modeled as 2D axisymmetric , a compression has been done in [24] between Two-dimensional axisymmetric and three-dimensional planar quarter symmetric, finite element models are developed using 4-node quadrilateral (C2D4R) and 8-node linear brick (C3D8R) elements, respectively, it is observed that the results are consistent for 2D and 3D models. Figure 1 and Figure 2 shows the procedure for creating the models, the objective is to calculate the tubular mechanical properties, therefore, the tubular modeled as deformable body, while the mandrel modeled as analytical rigid body. Figures 3 and 4, with Tables 1 and 2 shows the dimensions for models included in the geometrical optimization for the tubular and mandrel.



Name: Mandrel

Modeling Space: ○ 3D ○ 2D Planar ● Axisymmetric

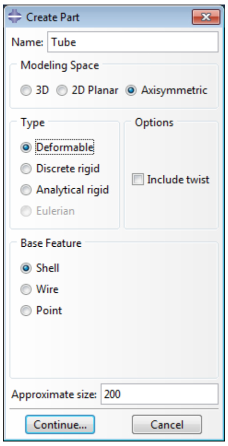
Type: ○ Deformable ○ Discrete rigid ● Analytical rigid ○ Eulerian

Options: None available

Base Feature: Wire

Approximate size: 200

Figure 3 create mandrel



Name: Tube

Modeling Space: ○ 3D ○ 2D Planar ● Axisymmetric

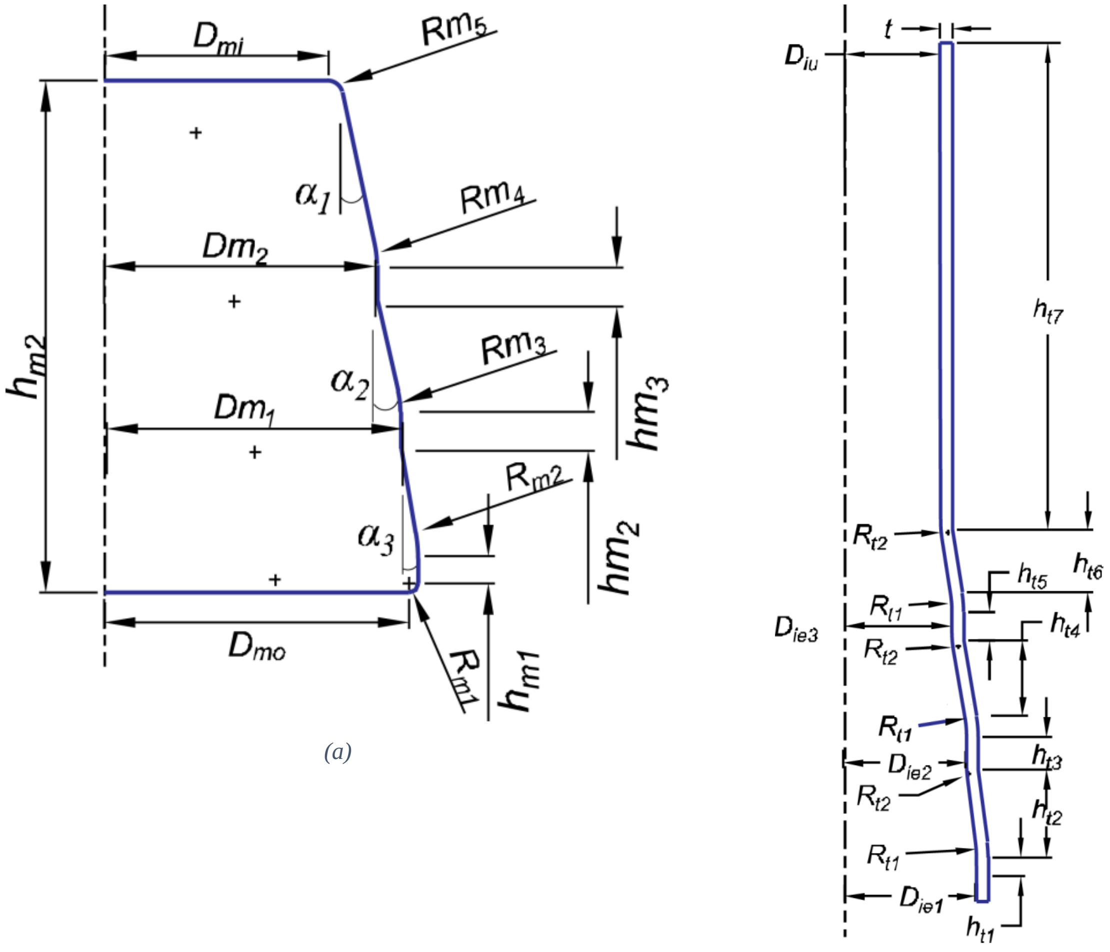
Type: ● Deformable ○ Discrete rigid ○ Analytical rigid ○ Eulerian

Options: ☐ Include twist

Base Feature: ● Shell ○ Wire ○ Point

Approximate size: 200

Figure 4 create tube



(a)

(b)

Figure 5 Geometrical dimensions: a) mandrel ; b) tubular

Table 1 Gematrical parameters of tubular

Name	D_{to}	D_{t1}	D_{t2}	D_{ti}	h_t	h_{t1}	h_{t2}	h_{t3}	h_{t4}	h_{t5}	h_{t6}	h_{t7}	R_t	R_{t1}	t	a_1	a_2	a_3
Model-1	107.95	105.0	101.6	86.91	1309.65	104.67	18.38	103.76	18.24	103.75	84.1	868.93	10	10	9.25	8.57	9.85	9.85
Model-2	107.95	105.0	101.6	86.91	1224.65	104.68	18.71	18.57	18.24	103.75	84.1	868.93	10	10	9.25	8.25	9.85	9.85
Model-3	107.95	105.0	101.6	86.91	1071.38	8.75	21.19	7.68	24.93	11.87	115.32	868.55	20	20	9.25	7.17	7.16	7.16
Model-4	108.2	104.76	101.4	87.3	946.3	10.4	17.5	7.64	18.80	7.55	94.8	751.0	50	50	9.25	8.06	7.16	16.73
Model-5	108.2	104.76	101.4	87.3	946.3	10.4	17.5	7.64	18.80	7.55	94.8	751.0	52	52	9.25	8.06	6.48	10
Model-6	108.2	104.76	101.4	87.3	946.3	10.4	17.5	7.64	18.80	7.55	94.8	751.0	53	53	9.25	8.06	6.48	10
Model-7	108.2	104.76	101.4	87.3	946.3	10.4	17.5	7.64	18.80	7.55	94.8	751.0	50	3	9.25	8.06	6.48	10

Table 2 Geometrical parameters of multistage mandrel

Name	D_{mo}	D_{m1}	D_{m2}	D_{mi}	h_m	h_{m1}	h_{m2}	h_{m3}	h_{m4}	h_{m5}	h_{m6}	R_{m1}	R_m	R_{m3}	a_1	a_2	a_3
Model-1	97.94	104.9	101.5	68.34	449.86	94.6	18.27	103.74	18.26	103.09	88.98	10	10	10	9.83	9.8	15.09
Model-2	97.84	104.9	101.5	75.04	364.86	94.24	19.38	18.21	18.26	103.09	86.73	10	10	10	8.15	9.8	10.82
Model-3	105.8	104.9	101.5	59.17	201.5	6.75	21.15	7.49	24.76	11.72	112.26	2	20	10	7.16	7.16	16.73
Model-4	105.8	104.85	101.9	79.4	206.5	8.47	17.49	7.64	18.79	6.79	111.71	2	50	2	8.06	6.48	10
Model-5	105.8	104.85	101.9	79.4	206.5	8.47	17.49	7.64	18.79	6.79	111.71	2	52	2	8.06	6.48	10
Model-6	105.8	104.85	101.9	79.4	206.5	8.47	17.49	7.64	18.79	6.79	111.71	2	53	2	8.06	6.48	10
Model-7	105.8	104.85	101.9	79.4	206.5	8.47	17.49	7.64	18.79	6.79	111.71	2	50	2	8.06	6.48	10

3.2 MATERIAL MODULES:

The tubular is made of high strength low-alloy steel with the following major alloying elements (weight percent): 0.23% C, 1.34% Mn, 0.23% Si, 0.01% Ni, 0.121% Cr, and 0.065% Mo. It has high yield, 610 to 641 MPa, and ultimate tensile strengths, 706 to 728 MPa. The stress-strain behavior of tubular material (Figure7 and Table 3) is obtained from uniaxial tensile tests [27]. Since the tubular is subjected to large permanent deformation, elastic-plastic material model is used to simulate tubular expansion process with isotropic yielding and hardening conditions. Other material properties include modulus of elasticity E = 234000 MPa, Poisson's ratio υ = 0.30, and density ρ=7.8x10-6 (kg/mm3). The mandrel made of hardened tool steel D6 and assumed to be rigid body.

Table 3 applied stress with corresponding strain

Yield stress MPa	Plastic strain
642.424	0
654.545	3.789927
661.472	7.208979
673.593	11.640635
687.446	19.168384
701.299	27.385732
716.883	39.044177
723.81	49.359749
729.004	59.337834
729.004	67.958534
727.273	77.965838
720.346	88.684665
713.42	97.334789
706.494	104.605013
692.641	115.008464
677.056	124.384224
661.472	132.380979

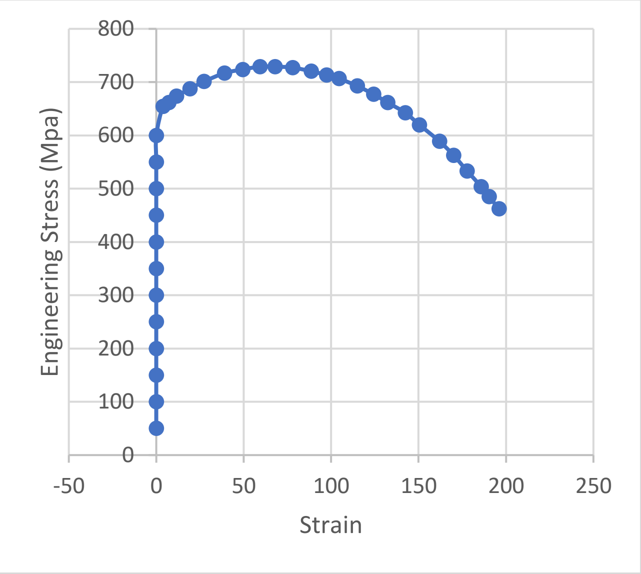
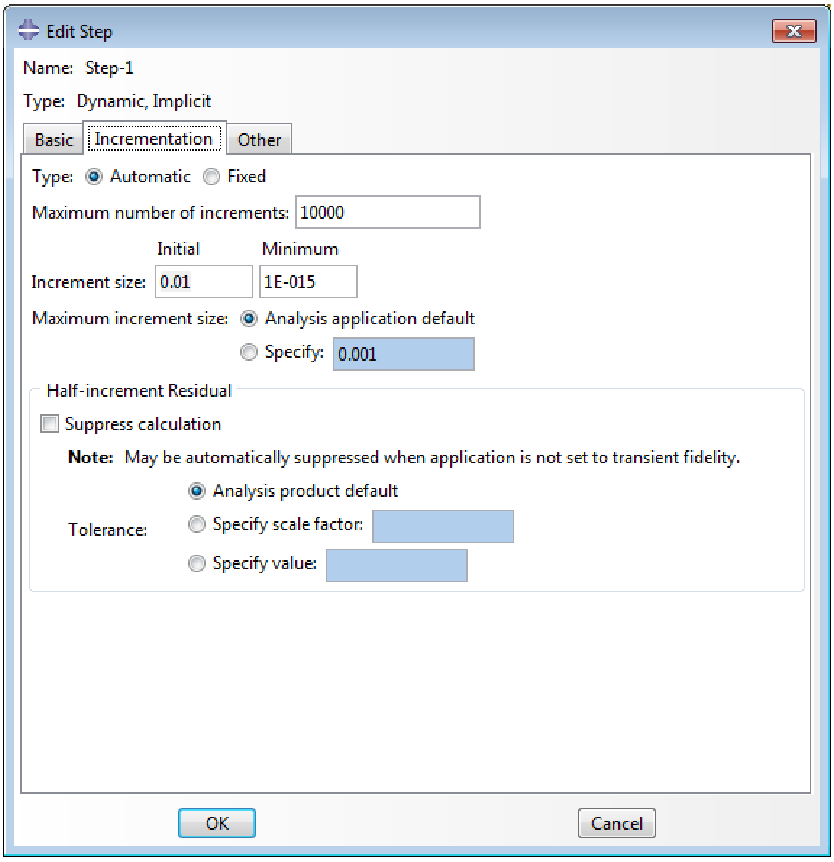


Figure 6: Stress strain behavior of tubular material subjected to uniaxial tensile load

3.3 STEP MODULE:

The selection of step type will determine the type of analysis that will be performed to the simulation, it is important to select an appropriate step type to perform the analysis, in the present work a dynamic implicit step type is chosen, Figure 8, increment size will depend on the detention of initial selected value, minimum value, and the smallest element size in the mesh elements.



Edit Step

Name: Step-1

Type: Dynamic, Implicit

Type: ● Automatic ○ Fixed

Maximum number of increments: 10000

Increment size: Initial 0.01 Minimum 1E-015

Maximum increment size: ● Analysis application default

○ Specify: 0.001

Half-increment Residual

☐ Suppress calculation

Note: May be automatically suppressed when application is not set to transient fidelity.

Tolerance: ● Analysis product default

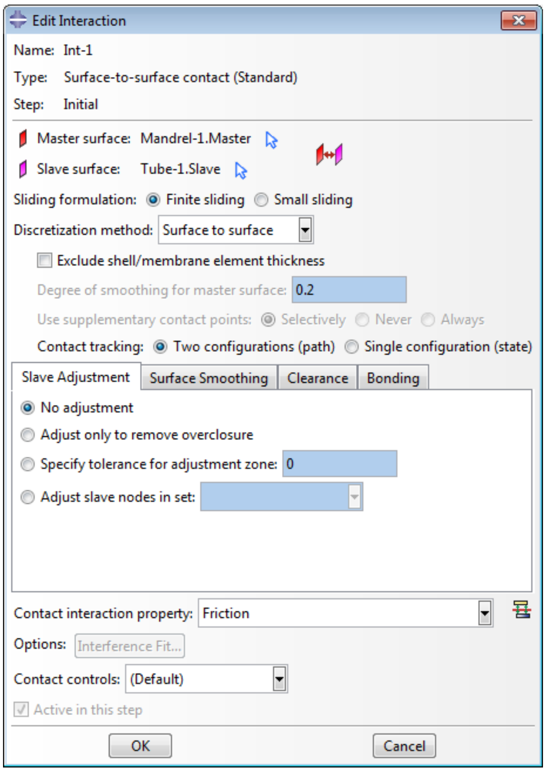
○ Specify scale factor:

○ Specify value:

Figure 7 step module option

3.4 INTERACTION MODULE

The contact interaction conditions at the tubular-mandrel interface are described through Coulomb friction model, where coefficient of friction is taken as 0.07 as shown in Figure 9; provided by the manufacturer as mentioned in [27]. Relatively low value of coefficient of friction is taken due to the fact that mandrel outer surface is highly polished while tubular is coated by special lubricating layer from inside. The interaction type has been defined as surface to surface contact as shown in Figure 8.



Edit Interaction

Name: Int-1

Type: Surface-to-surface contact (Standard)

Step: Initial

Master surface: Mandrel-1.Master

Slave surface: Tube-1.Slave

Sliding formulation: ● Finite sliding ○ Small sliding

Discretization method: Surface to surface

☐ Exclude shell/membrane element thickness

Degree of smoothing for master surface: 0.2

Use supplementary contact points: ● Selectively ○ Never ○ Always

Contact tracking: ● Two configurations (path) ○ Single configuration (state)

Slave Adjustment | Surface Smoothing | Clearance | Bonding

● No adjustment

○ Adjust only to remove overclosure

○ Specify tolerance for adjustment zone: 0

○ Adjust slave nodes in set:

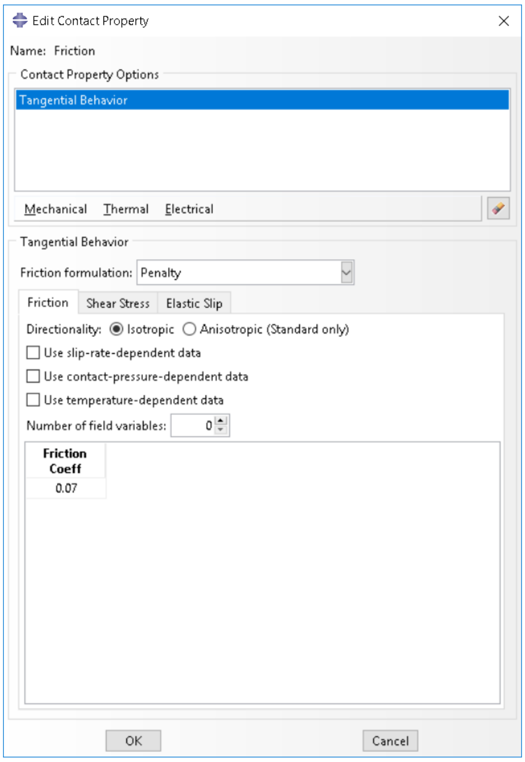
Contact interaction property: Friction

Options: Interference Fit...

Contact controls: (Default)

☑ Active in this step

OK Cancel



Edit Contact Property

Name: Friction

Contact Property Options

Tangential Behavior

Mechanical Thermal Electrical

Tangential Behavior

Friction formulation: Penalty

Friction | Shear Stress | Elastic Slip

Directionality: ● Isotropic ○ Anisotropic (Standard only)

☐ Use slip-rate-dependent data

☐ Use contact-pressure-dependent data

☐ Use temperature-dependent data

Number of field variables: 0

Friction Coeff
0.07

OK Cancel

Figure 8: interaction type surface to surface contact

Figure 9 : contact property with penalty friction formulation

3.5 BOUNDARY CONDITIONS

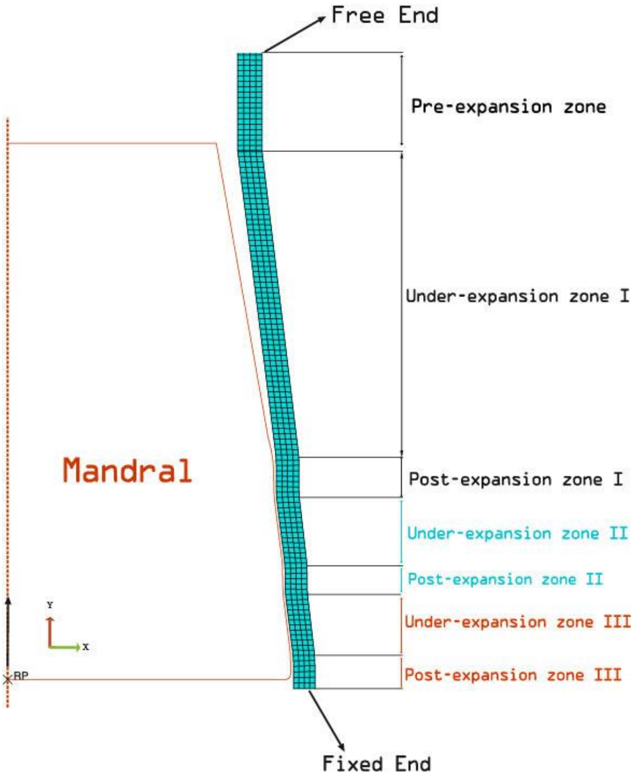
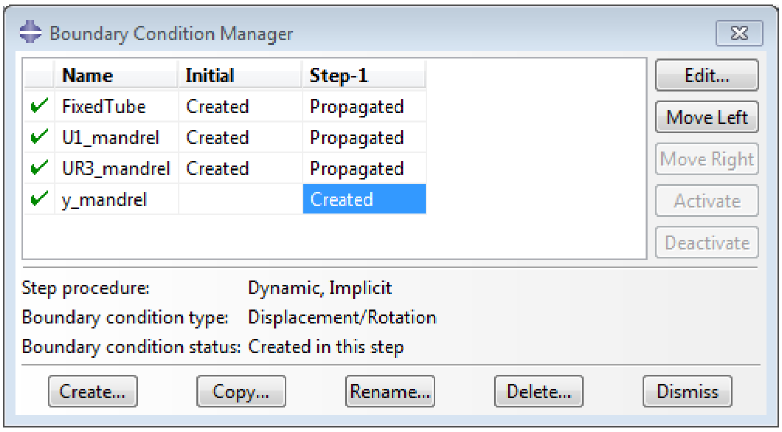


Figure 10 : Finite element model of multistage mandrel-tubular system

The tubular boundary condition can be defined as Fixed-Free displacement boundary condition, as show in Figure 11, the upper free end allow the tubular to shorten as a result of the expansion. All boundary condition for mandrel are fixed except translation in the direction of the tubular, as shown in Figure 11. These Boundary condition have been applied to the all simulation.



	Name	Initial	Step-1
✓	FixedTube	Created	Propagated
✓	U1_mandrel	Created	Propagated
✓	UR3_mandrel	Created	Propagated
✓	y_mandrel		Created

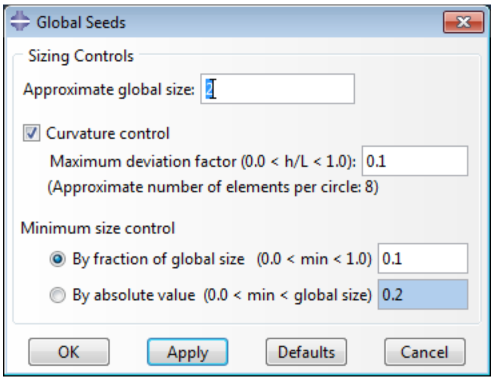
Step procedure: Dynamic, Implicit
Boundary condition type: Displacement/Rotation
Boundary condition status: Created in this step

Figure 11: boundary conditions

FixedTube	at the lower end of the tubular with all Degree of freedom equal zero.
U1_mandrel	at the center of the mandrel, the displacement along x-axis equal zero.
UR3_mandrel	at the center of the mandrel, the rotation about z-axis equal zero.
y_mandrel	at the center of the mandrel, the displacement along y-axis depending on the length of the tubular

3.6 DISCRETIZE THE MODEL: MESHING

The element type used for discretize the tubular is (CAX4R) which is a 4-node bilinear axisymmetric quadrilateral as shown in Figure 13, the total number of element is counted to be 2366 elements, a mesh optimization has been done to investigate the effects of increasing number of element on the residual stress, the result found to be there is significant increase in the computational with no much different in residual stress. The mandrel modeled as analytical rigid, therefore, it is not intended to be meshed. Figure 12 the global seed definition of Discretization.


Global Seeds

Sizing Controls

Approximate global size: 2

☑ Curvature control

Maximum deviation factor (0.0 < h/L < 1.0): 0.1

(Approximate number of elements per circle: 8)

Minimum size control

● By fraction of global size (0.0 < min < 1.0) 0.1

○ By absolute value (0.0 < min < global size) 0.2

Figure 12 Global seeds

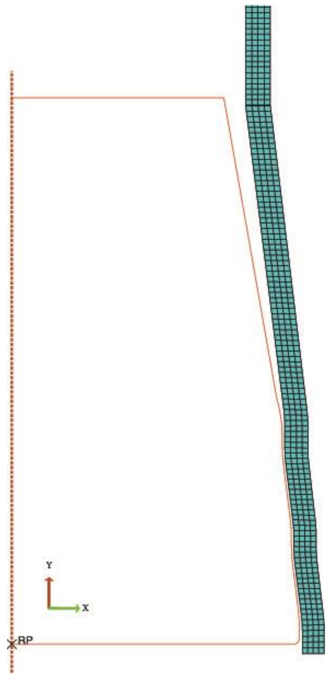


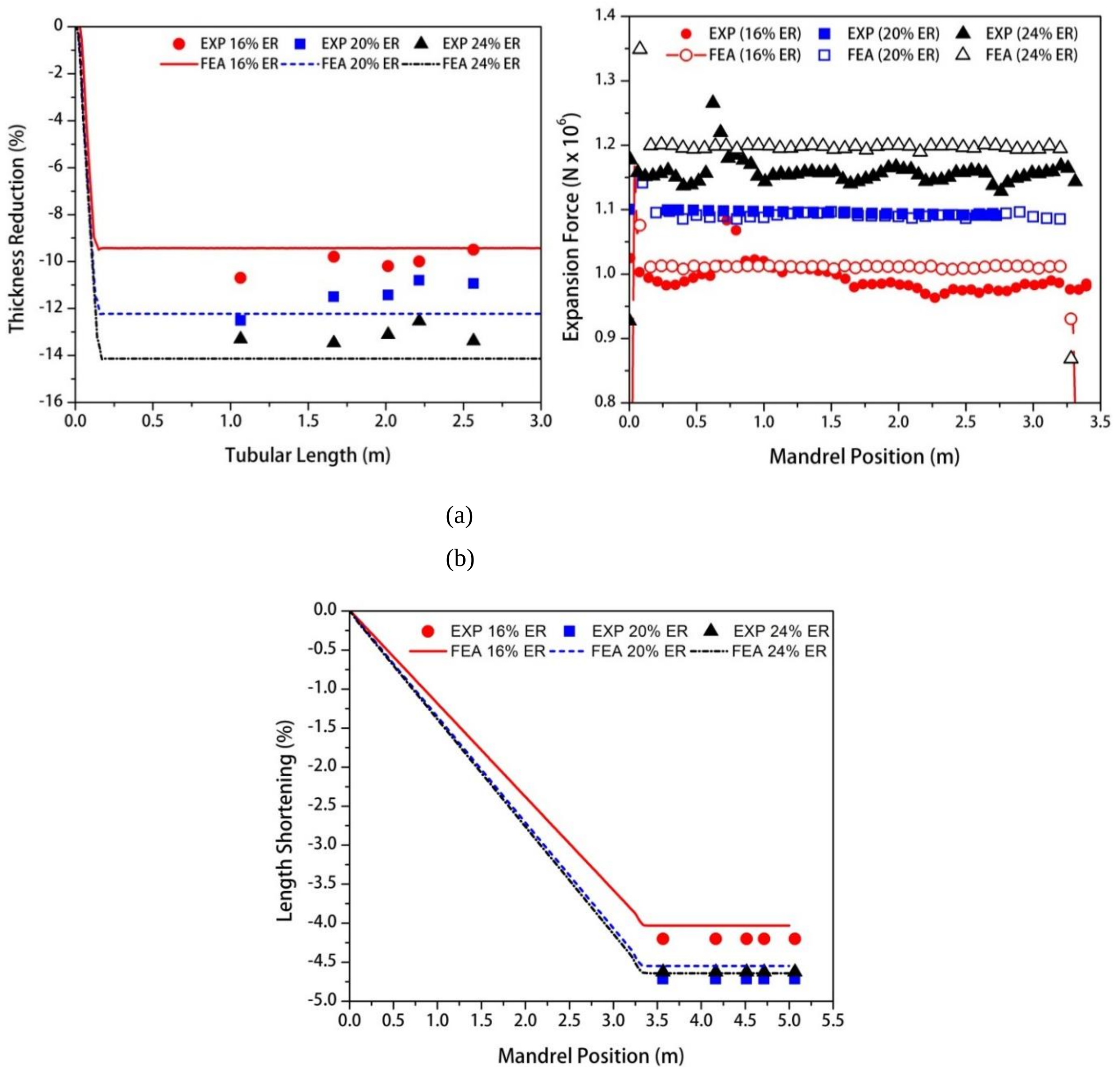
Figure 13: Discretization of tubular

CHAPTER 4

FINITE ELEMENT SIMULATIONS

4.1 MODEL VALIDATION:

As shown in [27], The comparisons of experimental and finite element simulation results are shown in Figure 5(a-c). Simulation results are in good agreement with experimental observations. For expansion force, simulation results are showing almost similar trend as experiments for 16 and 20% expansion ratio while slightly overestimating for 24% expansion ratio with maximum absolute relative error of 3.33 %. The possible reason of this difference may be the difference in material response. Solid tubular are normally manufactured through hot extrusion process which may induce defects in a material and the overall strength of a material reduced. In simulations, homogeneous and defects free material is considered, so the overall resistance of a material against expansion is higher which ultimately results in higher expansion force. Another possible reason could be the increase in tubular temperature, as observed during expansion experiments. It is noted that the temperature of a tubular increases up to 70 degree Celsius. This affects strength of tubular material and ultimately reduces expansion force. Tubular average wall thickness, before and after expansion, is measured at ten points; pair of two at five different locations (X_i, $i = 0, 1, 2, 3, 4$), as shown in Figure 1. Similarly, length shortening of tubular is calculated by measuring relative change in distance between the points (X_i, $i = 0, 1, 2, 3, 4$). In thickness reduction, absolute average relative errors (difference between experimental and simulation results) are 0.486%, 1.230%, and 0.837%, while in length shortening, these are 0.002%, 0.935%, and 0.775%, for 16%, 20%, and 24% ER, respectively. It is obvious that the finite element model is predicting results very close to the experimental values. After this validation, FE model is used for further numerical simulations to study the effects of mandrel velocity (strain rate) on post-expansion structural integrity.



(a)

(b)

(c)

Figure 5: Experimental and simulation results for 16%, 20%, 24% ER; (a) expansion force; (b) thickness reduction; (c) length shortening

4.2 FINITE ELEMENTS SIMULATIONS

Finite element simulations are preformed to investigate the effects of multistage mandrel on different tubular post-expansion parameters, these parameters include, contact pressure, residual stress, equivalent plastic strain**,** thickness reduction, and length shortening.

A geometrical optimization for mandrel design has been done to reach the optimum mechanical properties, the following table show the different mandrels that has been modeled with the corresponding properties.

Contact Pressure:

Contact pressure is an important parameter needs to be study, if the contact pressure at tubular mandrel interface exceed the Ultimate strength a failure may occur, contact pressure may affected by coefficient of friction as it is studied by Pervez et al [22]. the study shows there is a direct relation between contact pressure and coefficient of friction, and the effect of coefficient of friction on the thickness reduction studied by Pervez et al [23] and showed that the thickness reduces more as coefficient of friction increase, Therefore, the increase in contact pressure can result a higher thickness reduction. The following figure shows the variation of contact pressure with respect to the distance along tubular mandrel interface.

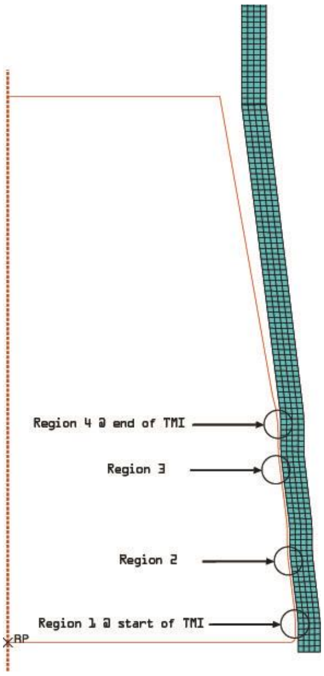


Figure 14 : Regions for contact pressure

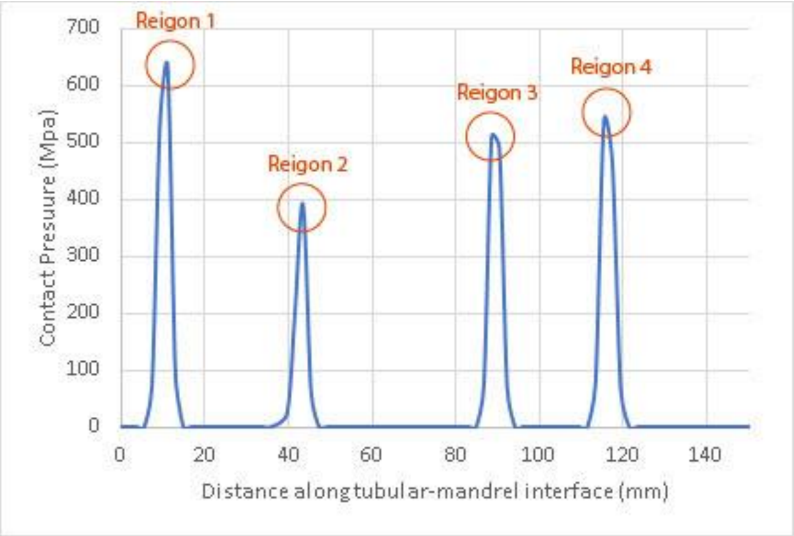


Figure 15 Contact pressure vs distance

It is appearing from this figure that significant amount of pressure developed between tubular and mandrel at four locations due to the staging of the mandrel, the maximum contact pressure of 650 MPa is noticed at region 1. A geometrical optimization was done to investigate the effect of mandrel geometry on the value of contact pressure between tubular and mandrel, the following table shows the geometrical value with corresponding contact pressure value.

Table4 variation contact pressure

Model No.	Total Mandrel height (h_m) (mm)	Mandrel Fillet Radius (R_m), (mm)	Max. Contact Pressure (MPa)
1	449.86	10	1.63×10^3
2	364.86	10	1.45×10^3
4	206.5	10	1.42×10^3
7	206.5	50	640

It is clear from Table 4 that, the contact pressure depends significantly on the size of the mandrel and mandrel fillet radius, it is found that, the optimum value for contact pressure can be estimate at 206.5 mm total mandrel height, and 50 mm fillet radius.

Equivalent Stress Distribution At The Inner Surface

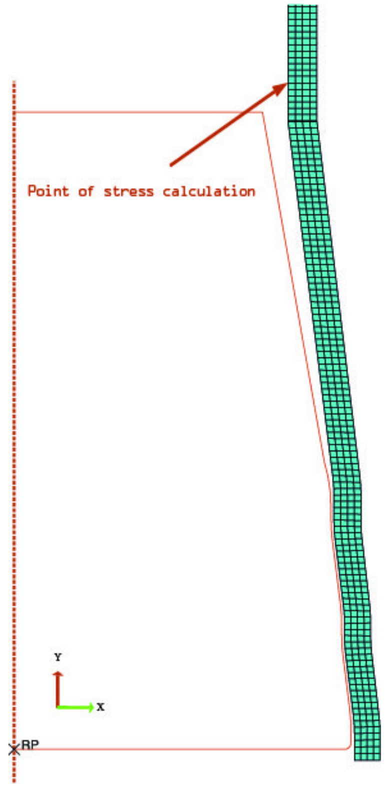


Figure 16 point of stress calculation

Figure 17 equivalent stress optimization for different models

As shown in Figure 17, the maximum equivalent stress for model 4 is 750 MPa, while in model 1 and 7 the maximum equivalent stress is 640 MPa, for model 7 the equivalent stress decrees to 360 MPa, while in model 1 decrease to 480 MPa and 230 MPa for model 4, Figure 17 clearly show that, the optimum model is model 7. The higher amount of stress in expansion zone needed to overcome the yield strength, in the chosen point Figure 20 the residual stress decrease to 360 MPa, which considered high magnitude of stress, the residual stress may reduce burst and collapse strength of tubular [27], which make the calculation of residual stress in the tubular before implementing it into application essential.

As a comparison with single stage mandrel [27], the residual stress estimated to be equal to 247 MPa for 24% expansion ratio, it is appear that, the staging on mandrel interface can effects the residual stress by increasing it, while the maximum amount of equivalent stress exceed 720 MPa, which may cause a material failure, therefore, multistage mandrel can significantly decrease the maximum equivalent stress.

Expansion Force

Figure 18 expansion force)

Figure 20 shows the variation of expansion force with respect to the mandrel position, maximum magnitude of expansion force is found to be equal to 1.4 MN for model 7, while for model 4 the maximum expansion force reach to 1.7 MN and for model 2 reach to 1.82 MN. It obvious that model 7 gives the least expansion force. The disturbance in the chart due to the dynamic effect of the expansion process, it can be eliminated when the process simulates as quasi static.

In single stage mandrel the expanding force reach to 1 MN for 16%, 1.09 MN for 20%, and 1.19 for 24% [27], approximately 3 MN to expand the tubular to 24%, comparing with multistage mandrel the required expanding force needed to expand the tubular to 24% is equal to 1.4 MN. The reduction in expanding force has great influence on reduction in cost.

Equivalent Plastic Strain at Inner Surface

The PEEQ (equivalent plastic strain) is calculated from the component plastic strain, in the Figure 12 shows the variations of equivalent from 0 (no yielding) at start, to 0.3 (yielded 3%) then constant until end of the tubular, PEEQ is a scalar variable that is used to represent the material's inelastic deformation. When the value of PEEQ is greater than zero that’s mean the tubular is yielded.

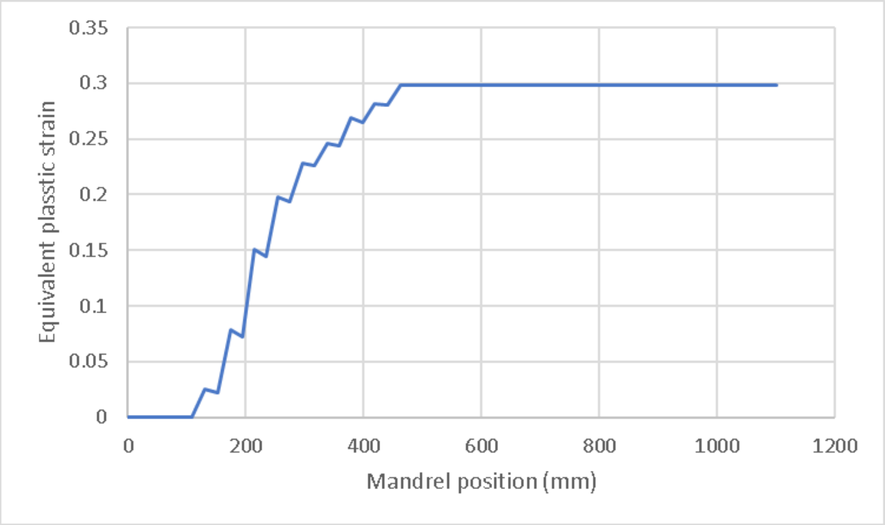


Figure 19 equivalent plastic strain vs mandral postion

Variation Of Thickness And Length Shortening

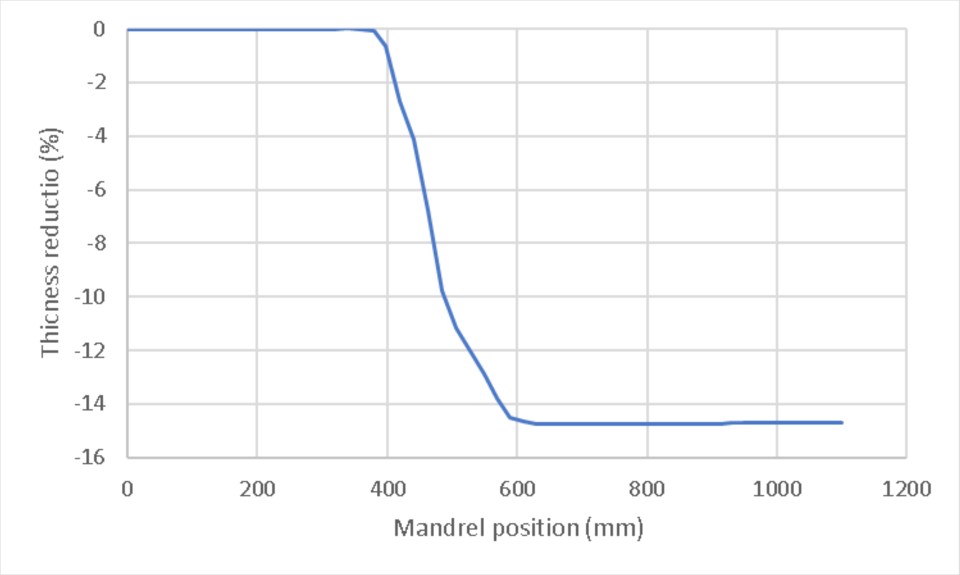


Figure 20 thickness reduction vs mandral position

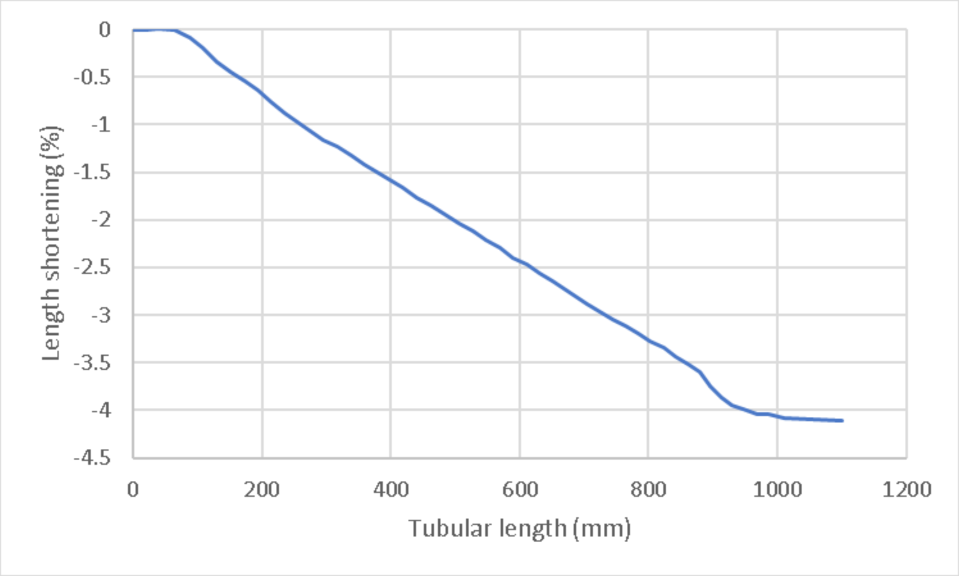


Figure 21 Length shorting vs tubular length

Figure 25 and Figure 26 shows the reduction in thickness and length shortening of the tubular respectively, tubular thickness before and after the expansion ware measured at three different locations, and an average value of thickness reduction was calculated. It appear form the figure that the reduction has maximum value of 14% from the original thickness. The shortening in the tube length reach 4% from the original length.

For single stage mandrel the thickness reduction for 24% expanding is equal to 14%, which is nearly the same thickness reduction in tubular with multistage mandrel, while the length shortening for singe stage is equal to 4.6%, while the length shortening for multistage expanding is equal to 4.1%.

Chapter 5

Conclusion

The tests expansion for 174.6 mm inner diameter and 9.5 mm wall thickness tubular have been done for multi stage expansion.

Geometrical optimization was done to investigate the effects of expansion with multistage mandrel, a finite element models for tubular and multistage mandrel have been developed using commercial software ABAQUS.

The tubular-mandrel system has been validated through experimental observation. Simulations for expansion process have been performed for different multistage mandrels, it is found that, the maximum contact pressure for optimum mandrel size and fillet radius reach 640 MPa, where the maximum equivalent stress found to be 630 MPa, which is less value comparing with 24% single expansion that found equal to 720 MPa. The expansion force for multistage mandrel found equal to 1.4 MN, which can consider cost effective comparing with single stage with three expansions processes (16%, 20%, and 24%).

Other properties (plastic equivalent strain, length shortening, and thickness reduction) are founds approximately equal to single expansion process.

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