ANALYSIS OF TUBE UPSETTING

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ABSTRACT

ANALYSIS OF TUBE UPSETTING

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Producing axi-symmetrical parts with holes from tubular stock by tube upsetting is a frequently used technique in industry. There are basically four types of tube upsetting process; external, internal, simultaneous internal and external upsetting, and expanding of tube. In general, tubular parts require more than one upsetting stage. In industry, generally trial-error methods, which require lots of time and effort depending on experience, are used for the design of stages. Wrong design causes failures during production. On the other hand, the problems, which are likely to be encountered in manufacturing, can be observed and solved in the design stage by using finite element analysis.

In this study, the finite element analyses of external, internal, simultaneous internal and external tube upsetting, and tube expanding processes have been realized. During the analyses, the part and the die geometries at the intermediate stages, which have been designed according to the proposed procedures, have been used. The stress and strain distributions and die filling actions have been observed during the process. The process design and die geometries have been evaluated according to the finite element results. It has been seen that the recommended procedures generally generate acceptable designs. In some cases, it has been noted that minor modifications may be required on the design.

Keywords: Tube Upsetting, Metal Forming, Hot Forging, Finite Element Analysis, Finite Element Method

ÖZ

BORU ŞİŞİRME İŞLEMİNİN ANALİZİ

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Endüstride delikli eksenel parçaların, boru malzemeden boru şişirme işlemi ile üretilmesi çok kullanılan yöntemlerden birisidir. Temel olarak boru şişirme işleminin dört çeşidi vardır; dışa doğru, içe doğru, aynı anda hem içe hem dışa doğru şişirme ve boru genişletme. Parçalar genellikle birden fazla şişirme aşama gerektirmektedir. Endüstride, aşama tasarımı için, deneyime bağlı olarak çok fazla zaman ve gayret gerektiren deneme ve yanılma yöntemleri uygulanmaktadır. Yanlış tasarımlar üretimde hatalara sebep olmaktadır. Diğer yandan, sonlu elemanlar yöntemi ile bu hatalar tasarım sürecinde farkedilip gerekli düzeltmeler yapılabilir.

Bu çalışmada, dışa doğru, içe doğru, aynı anda hem içe hem dışa doğru şişirme ve boru genişletme işlemlerinin sonlu eleman analizleri gerçekleştirilmiştir. Analizler sırasında, önerilen yöntemlere göre tasarlanmış ara aşamalardaki parça ve kalıp geometrileri kullanılmıştır. Şişirme işlemi sırasında boru üzerinde oluşan gerilmeler, yerdeğiştirmeler ve kalıpların dolumu gözlenmiş ve çıkan sonuçlara göre boru şişirme işlem tasarımının ve kalıp şekillerinin değerlendirmesi yapılmıştır. Önerilen yöntemlerin, genellikle kabul edilebilir tasarımlar doğurduğu gözlenmiş ve bazı durumlarda, ufak tasarım değişikliklerinin gerekli olduğu görülmüştür.

Anahtar Kelimeler: Boru Şişirme, Metal Şekillendirme, Sıcak Dövme, Sonlu Eleman Analizi, Sonlu Eleman Yöntemi

To My Family

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CHAPTER 1

INTRODUCTION

1.1 Hot Upset Forging

Forging processes can be classified according to their working temperature as cold forging, warm forging and hot forging. In cold forging, the process is performed at room temperature that is below the recrystallization temperature. In warm forging, temperature is just below or close to the recrystallization temperature. For steel, this temperature is between 750 – 950 °C. In hot forging, deformation is performed at a temperature above the recrystallization temperature which is 1150-1250 °C for steel.

Hot upsetting, which is also called hot heading, hot upset forging or machine forging, is basically a process for enlarging and reshaping the cross-sectional area of a bar, tube or other uniform sections, usually round. In its simplest form, hot upset forging is accomplished by holding the heated forging stock between the grooved female dies and applying pressure to the end of the stock in the direction of its axis by use of a heading tool, which spreads (upsets) the end by metal displacement [1]. A sequence of dies may be used to control the workpiece geometry gradually until it achieves its final shape.

Although hot upsetting originally was restricted to single-blow heading of parts such as bolts, present-day machines and tooling permit the use of multiple-pass dies that can produce complex shapes accurately and economically. The process now is widely used for producing finished forgings ranging in complexity from single headed bolts or flanged shafts to wrench sockets that require simultaneous upsetting and piercing [1]. Forgings requiring center or offset upsets may also be completed [1].

Because the transverse action of the moving die and longitudinal action of the heading tool are available for forging in both directions, either separately or simultaneously, hot upset forging is not limited to simple gripping and heading operations. The die motion can be used for swaging, bending, shearing, slitting and trimming. In addition to upsetting, the heading tools are used for punching, internal displacement, extrusion, trimming and bending.

In the upset forging process, the working stock is frequently confined in the die cavities during forging. The upsetting action causes the stock to fill the die impressions completely. Thus, a wide variety of shapes can be forged and removed from the dies by this process.

Upsetting processes are generally performed on horizontal forging machines. Their nominal rated capacity varies from 1250 to 22000 kN [1]. Pressure capacities required for the upset forging of carbon and low-alloy steels are about 400 MPa in simple shapes, whereas more complex shapes may require pressures of about 600 MPa [1].

A typical horizontal forging machine is shown in Figure 1.1. These machines are mechanically operated from a main shaft with an eccentric drive that operates a main slide, or header slide, horizontally. Cams drive a die slide, or grip slide, which moves horizontally at right angles to the header slide. The action of the header slide is similar to that of the ram in a mechanical press.

Power is supplied to a machine flywheel by an electric motor. A flywheel clutch provides for "stop motion" operation, placing movement of the slides under operator control.

Forging takes place in three die elements as given in Figure 1.2. Two gripper dies, one stationary and one moved by the die slide, which have matching faces with horizontal grooves to grip the forging stock and hold it by friction; and a heading tool, or "header", which is carried by the header slide in the plane of the work faces of the gripper dies [1]. The travel of the moving die is designated as the "die opening", and its timed relation to the movement of the header slide is such that the dies close during the early part of the header-slide stroke [1].

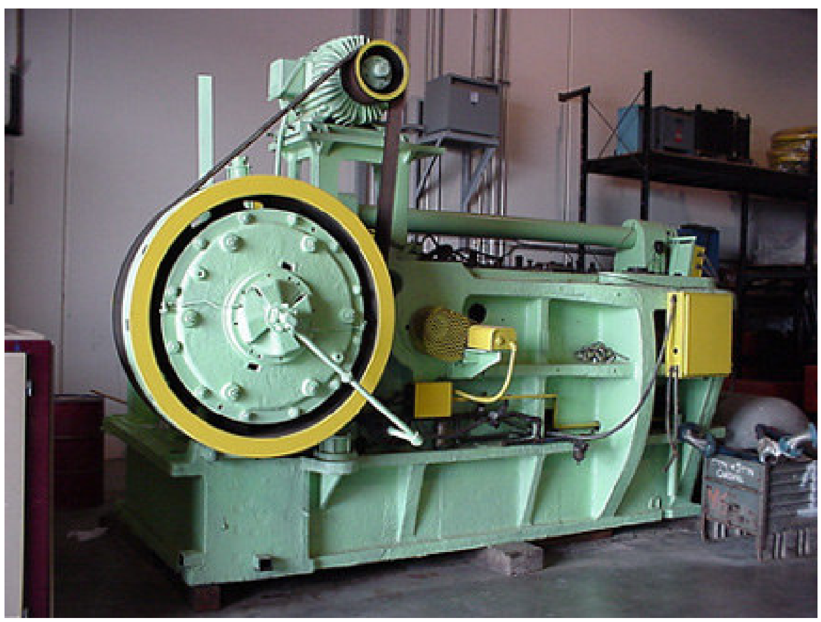


Figure 1.1. *A typical horizontal forging machine for hot upset forging [2]*

The die opening determines the maximum diameter of upset that can be formed on a given machine. The die station dimensions determine the number of progressive operations that can be accommodated in one set of dies.

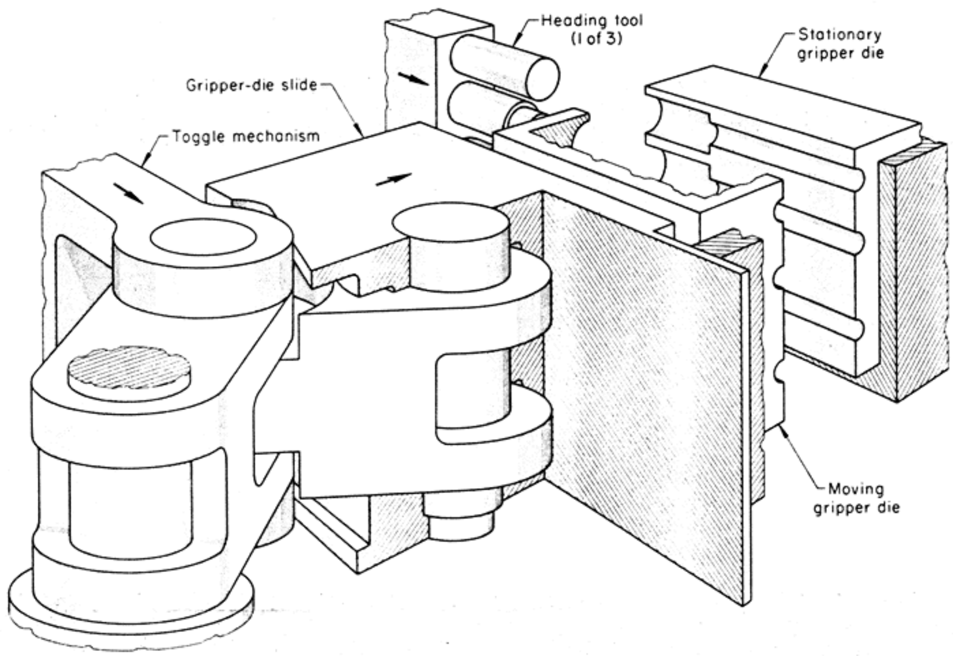


Figure 1.2. *Basic actions of the gripper dies and heading tools of an upsetter [1]*

The basic actions of the gripper dies and the header tools of an upsetter can be demonstrated by the three-station setup shown in Figure 1.2. The stock is positioned in the first (topmost) station of the stationary die of the machine. During the upset forging cycle, the movable die slides against the stationary die to grip the stock. The header tool, fastened in the header slide, advances toward and against the forging stock to spread it into the die cavity. When the header punch retracts to its back position, the movable die slides to open position to release the forging. This permits the operator to place the partly forged piece into the next station, where the cycle of the movable die and header tool is repeated. Many forgings can be produced to final shape in a single pass of the machine. Others may require as many as five passes for completion.

1.2. Tube Upsetting

The simplest definition of tube upsetting is the use of tube as an initial stock in an upsetting process. In many applications it is desirable and practical to use seamless tube as the stock for upset forgings, particularly for long forgings requiring a through hole. The use of tube, as the stock, reduces the weight and the number of operations. There are four types of tube upsetting [3] as shown in Figure 1.3. These are,

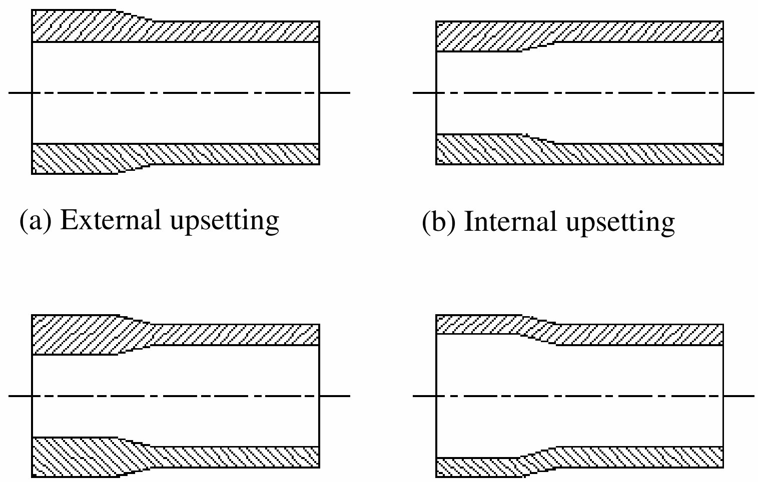
1. External Upsetting: External diameter of the tube is increased while the internal diameter is fixed.

2. Internal Upsetting: Internal diameter of the tube is decreased while external diameter is fixed.

3. Simultaneous external and internal upsetting: the external diameter of the tube is increased while the internal diameter decreases.

4. Tube expanding: external diameter of the tube is increased while the wall thickness stays constant.

In tube upsetting process, upset length and the obtainable increase in the wall thickness of tube are major process limitations. Upset length can be only controlled by proper design of dies and precise control of heated length. Therefore, a heating technique providing close control of temperature and heated length should be used. In order not to have buckling during upsetting, sequence design rules related with the allowable increase in wall thickness of a tube should be carefully observed. By applying process limitation of tube upsetting, great material saving and improved products can be obtained. Details of process limitations and the design rules are discussed on Chapter 2.



(a) External upsetting (b) Internal upsetting

(c) External and internal upsetting (d) Expanding of tube

Figure 1.3. *Types of tube upsetting [3]*

1.3. Developments in Tube Upsetting Process

In all types of forging operations, sequence design, design and manufacture of dies, and manufacture of the forged parts require experienced designers and operators, and time. In order to reduce these requirements, computer aided methods has been an attractive subject for lots of researches. In hot upsetting process, a number of researches [4-8] deal with operational sequence and die design for axi-symmetric solid round parts, where some of them consider also the hollow parts requiring piercing operations in addition to upsetting by using computer aided design techniques. A program, which uses a finite element technique to simulate the metal flow of the workpiece and provides the prediction of forging load, has been developed [9] based on the results of program developed by Gökler [7].

Because of difficulties in design and production, tube upsetting process was not commonly used although it has some advantageous on material saving and reducing the number of required processes. However, recent developments in Computer Aided Design / Computer Aided Manufacture / Computer Aided

Analysis (CAD/CAM/CAE) allow fast design and production. Interaction with the computer allows designers to optimize the process parameters by considering the design requirements and the process capabilities. Use of CAD/CAM provides design and manufacturing with a full control in a short time with a lower cost. A computer aided design program, which includes sequence and die design, has been developed [3, 10] for tube upsetting process. This thesis is mainly based on the results of the program developed by Karavelioğlu [3], where general forging recommendations and limitations had been concerned for tube upsetting. Two different sequence design procedures are proposed by Karavelioğlu [3]. However, the verifications of the procedures have not been attempted yet.

Recently, finite element analysis of upsetting processes has been attempted by a number of studies [11-17]. These studies deal with modeling, optimization and detailed analysis of the process. Although attention has been given recently to the finite element analysis of upsetting processes, analysis of tube upsetting process has not been attempted yet.

1.4. Scope of the Thesis

There are two procedures for sequence design of tube upsetting as discussed in the previous section. These procedures have been adapted to a CAD software by Karavelioğlu [3]. However, their verifications have not been attempted by experimental or computer simulation studies yet. Before performing experiments based on the CAD results, a finite element verification should be performed. By finite element simulations of the tube upsetting process, it is possible to observe flow behavior of the material. In this thesis, finite element analyses of tube upsetting processes are performed for four types which are external tube upsetting, internal tube upsetting, simultaneous internal and external upsetting, and tube expanding.

Industrially accepted sequence and die design recommendations are summarized in Chapter 2. The discussion about finite element approximation is available in Chapter 3. Finite element analyses for four different types of tube upsetting are presented in Chapters 4 – 7. In Chapter 4, the analyses of external tube upsetting for two alternative sequence design procedures are presented. Chapter 5, 6 and 7 include analyses for internal upsetting, simultaneous internal and external upsetting, and tube expanding, respectively. General discussion and conclusion on the obtained results are given in Chapter 8.

CHAPTER 2

DESIGN FOR TUBE UPSETTING PROCESS

2.1. Introduction

In almost all upset forging processes, firstly, the forging is designed. Dimensions of the initial workpiece are determined. Then, the number of stages in order not to have folds or buckles is determined. After designing the dies for all stages, the detailed analysis should be made by appropriate tools. The analysis can be performed by analytical methods or numerical methods such as finite element and finite volume methods. In this thesis, analyses are performed by finite element method.

2.2. Basic Design Considerations

The design of a forged part involves the allocation of machining allowances, parting line location (i.e. dividing plane between the header and gripper dies), determination of draft angles, fillet and corner radii [3]. In the design of forgings, draft angles should be applied in order to make the tool retraction easy. It is possible to find recommendations about draft angle at [18-21]. The draft and draft matching angles, with the parting line location are shown in Figure 2.1. DIN Standard [20] recommendations for draft angles are given in Table 2.1.

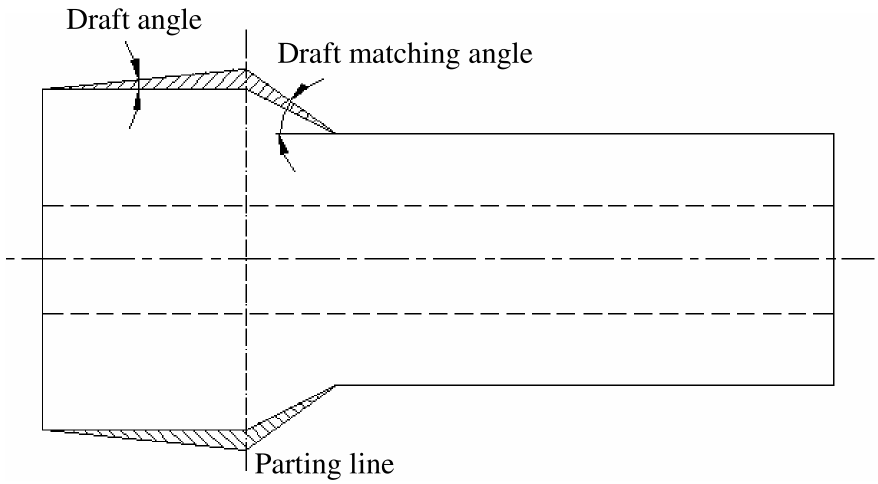


Figure 2.1. *Draft angle and draft matching angle [3]*

Table 2.1. *Draft angle recommendations for horizontal upsetters [20]*

Internal Surfaces			**External Surfaces**		
Slope	**Angle**	**Application**	**Slope**	**Angle**	**Application**
1:20	3°	According to depth	1:20	3°	In ram die
1:50	0-3°	Hole or recess	1:50	1°	Normal case
			-	0°	On jaw surfaces

In forged parts, sharp corners should be avoided in order to get rid of stress concentrations in the die. Corner and fillet radii applicable for hollow parts are shown in Figure 2.2. Recommendations for corner and fillet radii are available in Tables 2.2 and 2.3, respectively.

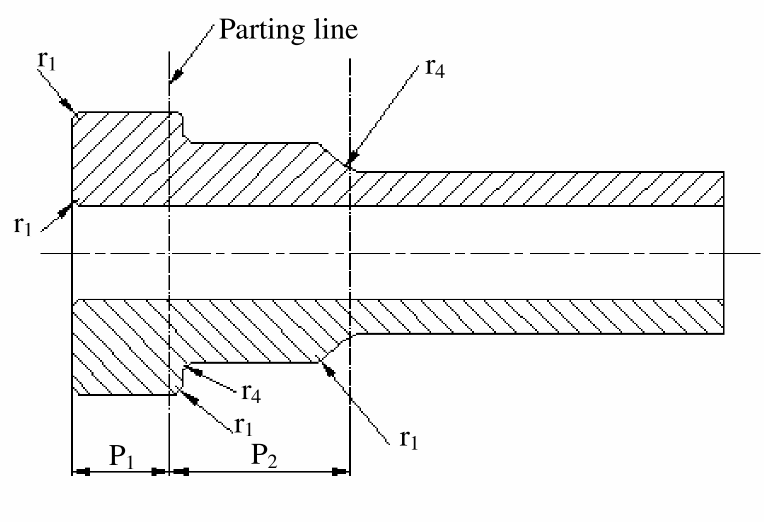


Figure 2.2. *Corner and fillet radii [3]*

Table 2.2. *Recommendations for corner radius [20]*

Greatest distance from parting line to the edge of upset region (i.e. greater one of P_1 and P_2 in Figure 2.2) (mm)	**Corner radius, r_1 (mm)**
0-25	2
26-40	3
41-63	4
64-100	6
101-160	8
161-250	10
251-400	16
401-630	25

Table 2.3. Recommendations for fillet radius [20]

Shank Diameter (mm)	Fillet Radius, r_4 (mm)
0-25	2
26-40	3
41-63	5
64-100	8
101-160	12
161-250	20

In hot upsetting, the stock is heated before it is put into the first die. Heating of the tube stock requires a higher degree of control than for solid bar stock. The length of tube to be deformed is the only portion that should be heated, in order to prevent deformation beyond the upset region. For almost all type of tube upsetting, a sharp transition between heated and unheated portions must be maintained to minimize the material that may be displaced into the tube at the rear of the upset region [1]. Precise location of this sharp transition is of major importance in internal upsetting cases, since there is no practical means for limiting the upset length by means of dies or heading punch. In addition to the controlling of heated length, which directly affects the upset volume, the heat must be kept from running back beyond the upset region by applying fast heating methods [1].

Induction heating, which has been successfully adapted for use in upset forging, is the most appropriate heating method providing minimum scale formation, and controlling the heated length of the stock precisely. The fast heating rate, which also minimizes scale formation, the accuracy of temperature control, and the adaptability to the localized heating, make induction heating particularly useful in the forging of similar parts on a mass production basis. During the determination of the tube length to be formed, scale losses must be taken into account and compensated. Recommendations for scale allowances are available in the literature [18] and shown in Table 2.4. If the forging requires more than one heating stage, scale allowances should be increased to 1.5-2 times the recommended value. As seen from the table, scale formation is the lowest in induction heating. In available finite element analysis packages, scale formation is not included. Therefore, scale allowance will be considered before performing the finite element analysis.

Table 2.4. *Recommendations for scale allowances [18]*

Furnace	Scale Allowance
Oil box	4%
Oil continuous	3%
Gas Box	3%
Gas continuous	2.5%
Electric	1.5%
Induction	1%

If the designed tools allow flash formation (Figure 2.3), volume of the initial stock should be increased to compensate the material loss due to flash formation. Recommendations for the flash width, f_w, and thickness, f_t, are given in Table 2.5.

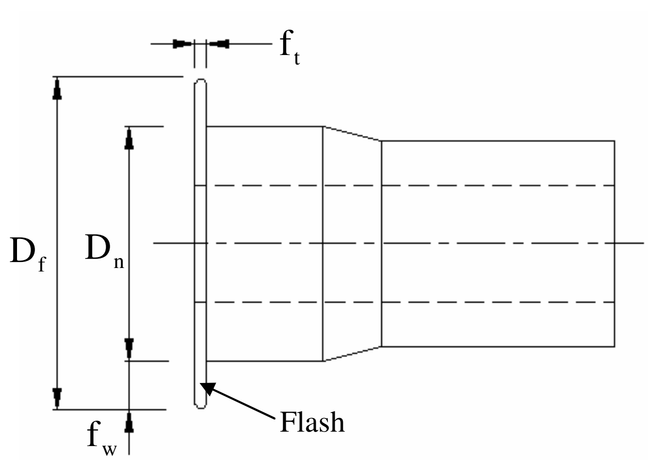


Figure 2.3. *Flash Notation [3]*

Table 2.5. *Recommendations for flash dimensions [18]*

	Maximum Diameter (mm)				
	0-20	**21-80**	**81-160**	**161-260**	**261-360**
Flash Width (mm)	5	8	12	14	16
Flash Thickness (mm)	0.8-1	1-1.5	2-2.5	3-3.5	3.5-4

For the hot tube upsetting process, expansion of the stock in heating should be considered in die design. 1.5% expansion allowance is recommended in various publications [18, 19, 21-23]. In order to allow progressive cooling of the forged part during forming, the dimensions of the die cavities should be reduced by about 0.15% [17, 21] per stages.

2.3. Process Limitations

Process limitations of tube upsetting mainly involve the control of upset length and the determination of obtainable increase in cross-sectional area. In order to prevent injurious fold or buckling during upsetting, the ASM Metals Handbook [1] suggests four rules. These are,

1. To prevent the buckling in single-blow flanging, the length of unsupported working stock to be upset should be less than or equal to 2.5 times the wall thickness of the stock.

2. In external upsetting, the wall thickness of the tube can be increased to a maximum of 1.5 times the original wall thickness in one pass as shown in Figure 2.4.

Maximum Wall Thickness Ratio:

$$WTR_{MAX} = \frac{t_{i+1}}{t_i} = 1.5 \tag{2.1}$$

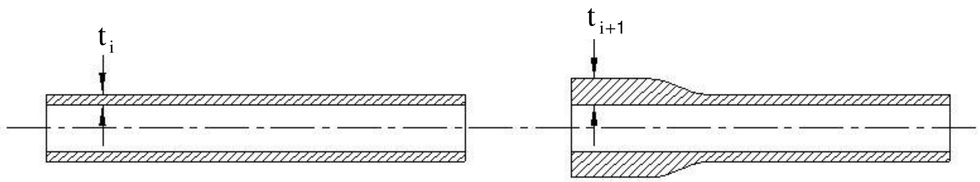


Figure 2.4. *Wall thickness change during external upsetting*

3. In internal upsetting, the wall thickness of the tube can be increased to a maximum of twice its original wall thickness in one pass shown in Figure 2.5.

   Maximum Wall Thickness Ratio:

   $$WTR_{MAX} = \frac{t_{i+1}}{t_i} = 2 \qquad (2.2)$$

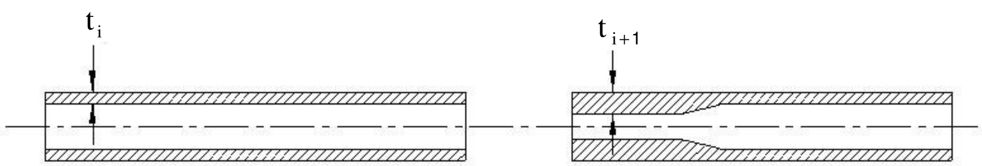


Figure 2.5. *Wall thickness change during internal upsetting*

4. In simultaneous external and internal upsetting, the wall thickness of the tube can be increased to a maximum of 1.5 times the original wall thickness in one pass as shown in Figure 2.6.

   Maximum Wall Thickness Ratio:

   $$WTR_{MAX} = \frac{t_{i+1}}{t_i} = 1.5 \qquad (2.3)$$

Detailed discussion on process limitations from various publications is available in the Karavelioğlu’s study [3].

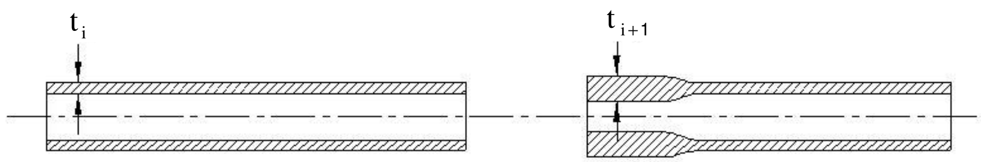


Figure 2.6. *Wall thickness change during simultaneous internal and external upsetting*

2.4. Sequence Design Procedures

The sequence design procedure mainly involves the calculation of allowable increase in wall thickness for a particular upset region in a single stage and determination of the outer limit for external upsetting and the lower limit for internal upsetting case.

There are two alternative procedures for the sequence design which were discussed by Karavelioğlu in his study [3]. The first one is the use of constant increase in wall thickness and the second one is the modified and extended version of the procedure suggested by Russian Forging Handbook [3, 19].

2.4.1. Procedure I

The procedure covers the following steps [3]:

1. The overall wall thickness ratio of a particular upset region, WTR_o, is calculated as follows;

$$WTR_o = \frac{t_{max}}{t} \tag{2.4}$$

where,

t_{max} : the maximum wall thickness to be obtained in the upset region,

t : wall thickness of the initial tube.

If the overall wall thickness ratio, WTR_o, is less than or equal to the allowable wall thickness ratio, WTR_a, the particular upset region can be forged into the final shape in one operation.

2. If the overall wall thickness ratio is greater than the allowable thickness ratio, more than one operation is necessary. The theoretical number of operations, n_t, required for forging the upset can be calculated as;

$$n_t = \frac{\log WTR_o}{\log WTR_a} \tag{2.5}$$

If n_t is calculated as a noninteger value, the required number of operations, n, is equal to the smallest integer number greater than n_t. In such cases, the wall thickness ratio for the final operation can be small. However, forging can be performed with the same number of operations by applying an equilized wall thickness ratio smaller than the allowable. The equilized wall thickness ratio, WTR_e, is calculated as follows:

$$WTR_e = (WTR_o)^{1/n} \tag{2.6}$$

According to the choice of the designer, WTR_a or WTR_e can be considered during the sequence design.

3. It is assumed that all the scale is removed either before or during the first operation. Therefore, volumes of the subregions remain constant during the sequence design. If the part will be forged with flash, volume of the subregion adjecent to the parting line will include the flash allowance as shown in Figure 2.7.

4. The limits for the outer and inner profile of current stage, OL_i and IL_i respectively, are determined as follows;

i. For external tube upsetting (see Figure 2.7):

$$IL_i = d_o \tag{2.7}$$

where,

d_o : the inner diameter of the initial tube.

$$OL_i = d_o + WTR \cdot (OL_{i-1} - d_o) \tag{2.8}$$

For the first operation, OL_o is equal to the outer diameter of the initial tube, D_o, as shown in Figure 2.7.

ii. For internal tube upsetting;

$$OL_i = D_o \tag{2.9}$$

$$IL_i = D_o - WTR \cdot (D_o - IL_{i-1}) \tag{2.10}$$

where, the outer diameter of the initial tube, D_o, is kept constant, and for the first operation IL_o is equal to d_o.

iii. For internal and external tube upsetting simultaneously;

The upsetting ratio U_r, the ratio of the increase in the outer diameter to the decrease in the inner diameter, is determined by considering the final shape of the upset region as shown in Figure 2.8.

$$U_r = \frac{D_u - D_o}{d_o - d_u} \tag{2.11}$$

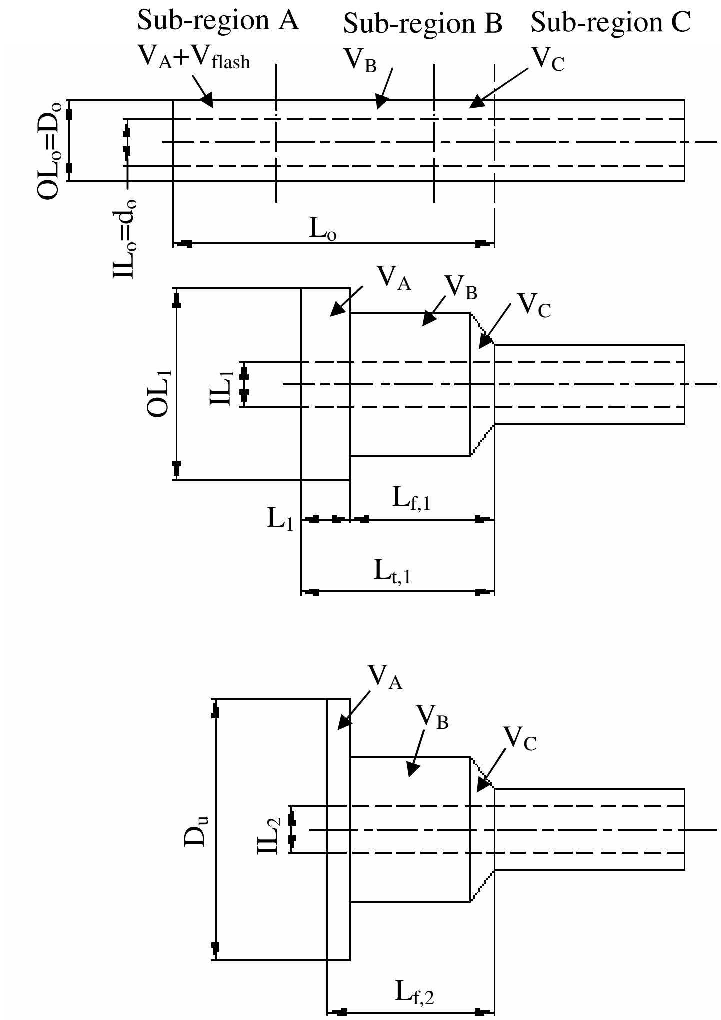


Figure 2.7. *Volume constancy along the upset region and shape design for intermediate stages [3]*

This ratio is kept constant for all stages to obtain a gradual increase in the outer diameter and a gradual decrease in the inner diameter. The outer and the inner profile limits for the current stage, OL_i and IL_i, are calculated by solving the following two equations simultaneously.

$$U_r = \frac{OL_i - D_o}{d_o - IL_i} \tag{2.12}$$

$$OL_i - IL_i = WTR \cdot (OL_{i-1} - IL_{i-1}) \tag{2.13}$$

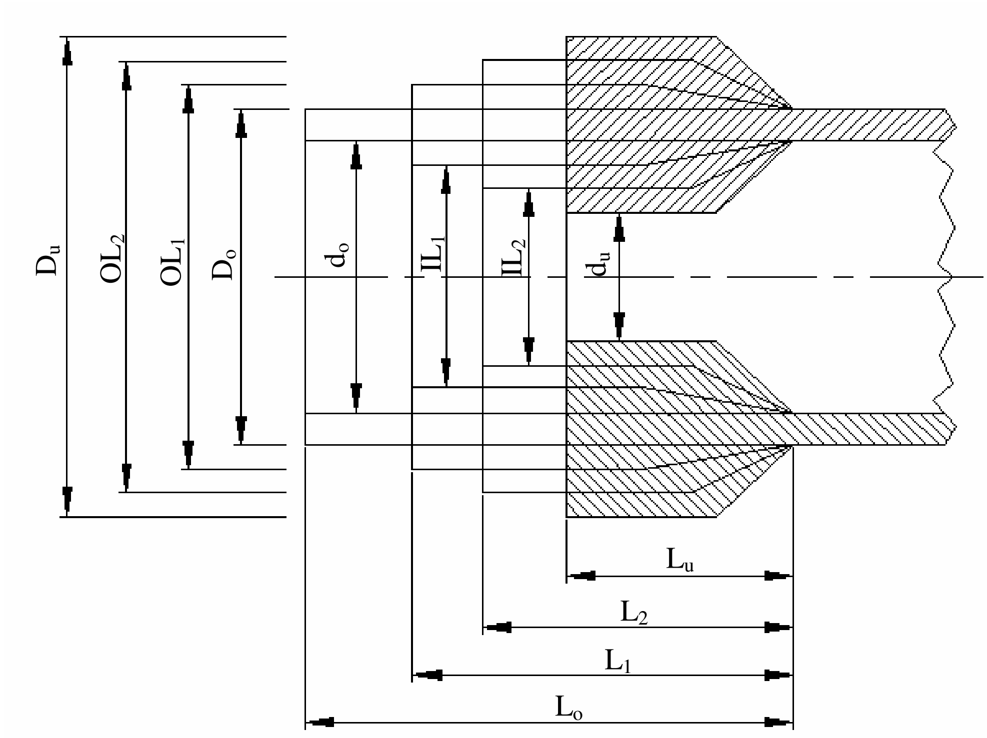


Figure 2.8. *Determination of outer and inner profile limits for simultaneous external and internal upsetting [3]*

5. If the determined limits for the outer and inner profiles of the upset region allow for production of the required geometry, then the upsetting can be completed in the current stage.

6. The subregions with required geometry exceeding the determined limits at the current stage, is included in the upset region of the following stage. The outer and inner diameters of the right and left extremities of these subregions at the current stage, $D1_i$, $D2_i$, $d1_i$ and $d2_i$ (Figure 2.9) are determined by using the calculated profile limits. The diameters are taken to be equal to the relevant limits if their required dimensions is out of the limits. The lengths of these subregions, L_j, at the current stage are determined by considering their volumes, V_j, which are kept constant throughout the operational sequence. The length of a particular subregion, j, at the current stage, i, is calculated with the following expression:

$$L_{j,i} = \frac{V_j}{\frac{\pi}{12}\left[\left(D1_{j,i}^{\ 2} + D1_{j,i} \cdot D2_{j,i} + D2_{j,i}^{\ 2}\right) - \left(d1_{j,i}^{\ 2} + d1_{j,i} \cdot d2_{j,i} + d2_{j,i}^{\ 2}\right)\right]} \quad (2.14)$$

The subregions which remain in the determined limits of the current stage, reach their final dimensions. This procedure, from step 2 to step 6, is repeated until the limits which allow for the required dimensions of the all subregions, are obtained.

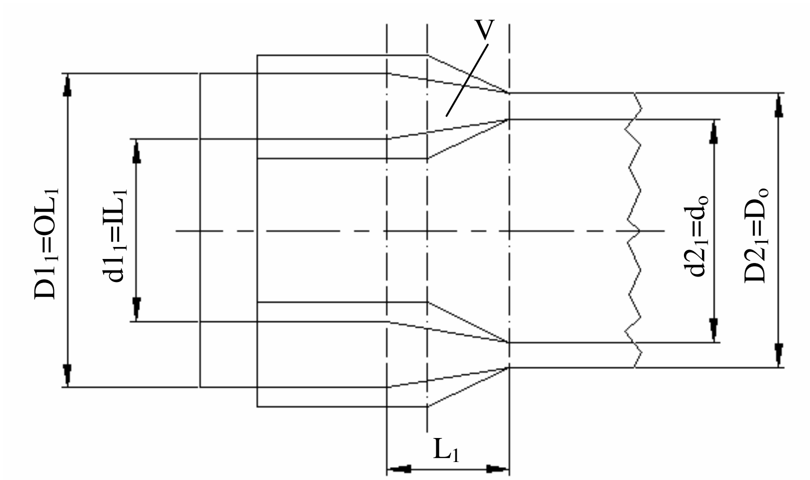


Figure 2.9. *Determination of the geometry of intermediate stages [3]*

2.4.2. Procedure II

The sequence design procedure, which is suggested by Russian Forging Handbook [19] for tube upsetting, has been modified and extended by Karavelioğlu [3]. The extended procedure is as follows [3]:

1. The equivalent diameter at the previous stage, $d_{e,i-1}$, is calculated at the cross-section with maximum area as follows:

$$d_{e,i-1} = \left(OL_{i-1}{}^{2} - IL_{i-1}{}^{2}\right)^{1/2} \tag{2.15}$$

where, for the first stage, outer limit, OL_o, and inner limit, IL_o, are equal to the outer and inner diameter of the initial tube respectively.

2. Length of the region to be upset at the current stage is calculated as follows (see Figures 2.7 and 2.8):

$$L_{i-1} = L_{t,i-1} - L_{f,i-1} \tag{2.16}$$

where, $L_{t,i-1}$ is the total length of the upset region at the previous stage and $L_{f,i-1}$ is the total length of the sub-regions which have been fully formed in the previous stages. For the first operation, L_0 is equal to the initial length of the upset region as shown in Figure 2.7.

3. The upset length to the equivalent diameter, F, and the outer limit to the inner limit, R_d, ratios are calculated with the following expressions:

$$F = \frac{L_{i-1}}{d_{e,i-1}} \tag{2.17}$$

$$R_d = \frac{OL_{i-1}}{IL_{i-1}} \tag{2.18}$$

4. K factor is calculated by considering the type of tube upsetting to be performed in the current stage as follows;

For external upsetting and expanding:

$$K = 0.4 + R_d \qquad (2.19)$$

For internal upsetting:

$$K = 0.8 + 2R_d \qquad (2.20)$$

For external and internal upsetting in the same stage:

$$K = 0.6 + 1.5R_d \qquad (2.21)$$

5. The limit value, F1, is determined by using the following expression;

$$F1 = \frac{K(OL_{i-1} - IL_{i-1})}{2d_{e,i-1}} \qquad (2.22)$$

6. If F is less than or equal to F1, further upsetting stages are not required and the particular upset region can be fully formed in the current stage. Otherwise, the maximum equivalent diameter obtainable in the current stage is calculated as follows:

$$d_{e,i} = C\, d_{e,i-1} \qquad (2.23)$$

where,

$$C = \sqrt{2 - 0.03\sqrt{(35 - F1)^2 - (35 - F)^2}} \qquad (2.24)$$

7. The limits for the outer and inner profiles of the particular upset region are determined by considering the obtainable equivalent diameter in the current stage, $d_{e,i}$ and the type of tube upsetting.

For external upsetting;

The limiting value for the outer profile, OL_i, is calculated as follows:

$$OL_i = \left(d_o{}^2 + d_{e,i}{}^2\right)^{1/2} \tag{2.25}$$

The limiting value for the inner profile remains equal to the inner diameter of the initial tube, d_o.

For internal upsetting;

The limiting value for the inner profile, IL_i, is calculated as follows:

$$IL_i = \left(D_o{}^2 + d_{e,i}{}^2\right)^{1/2} \tag{2.26}$$

The limiting value for the outer profile remains equal to the outer diameter of the initial tube, D_0.

For simultaneous external and internal upsetting;

The ratio of the increase in outer profile to the decrease in inner profile, U_r, is kept constant as in the procedure I. the following two equations are solved simultaneously to calculate OL_i and IL_i.

$$U_r = \frac{OL_i - D_o}{d_o - IL_i} \tag{2.27}$$

$$d_{e,i}{}^2 = OL_i{}^2 - IL_i{}^2 \tag{2.28}$$

For expanding of tube;

For expanding, in which the wall thickness, t, is kept constant, OL_i and IL_i are calculated solving the following expressions simultaneously.

$$OL_i - IL_i = 2\,t \tag{2.29}$$

$$d_{e,i}^{\;2} = OL_i^{\;2} - IL_i^{\;2} \tag{2.30}$$

8. If the required dimensions of all the portions remain in the determined limits, the upset region is fully formed at the current stage. Otherwise, the shape of the upset region at the current stage is determined as discussed in Step 6 of Procedure I, and the procedure should be restarted to determine whether the particular upset region can be fully formed in the succeeding stage or not.

The difference between the two procedures is that the constant wall thickness ratio is used for all upsetting stages in Procedure I. However, in Procedure II, different wall thickness ratios can be obtained depending on the geometry of the forging.

2.5. Die Design for Tube Upsetting

After the sequence design procedure is completed, the dies for preforming and finishing stages can be designed. There are three basic types of tube upsetting dies [3]. These are classified according to the cavity types on header tools or gripper dies. In the closed die upsetting processes, cavities can be on gripper dies, header tool or both. Selection of the die type according to their cavities completely depends on the sequence design and location of parting line. The cavity types can be described as follows.

1. Die cavity in header tool only (Figure 2.10)
2. Die cavity in both header tool and gripper dies (Figure 2.11)

3. Die cavity in gripper die only

   a. For flashless forging (Figure 2.12)

   b. For forging with flash (Figure 2.13)

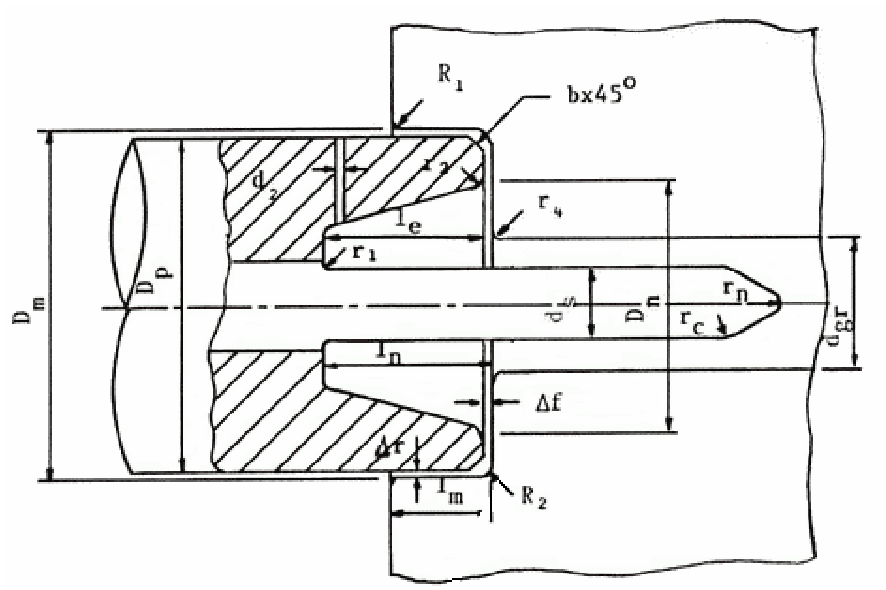


Figure 2.10. *Die cavity in header tool [3]*

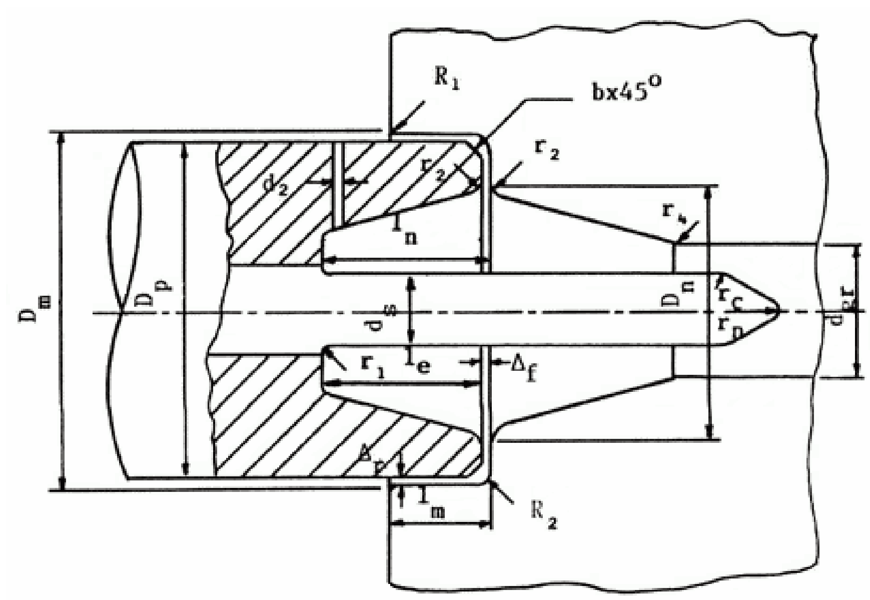


Figure 2.11. *Die cavity in both header tool and gripper dies [3]*

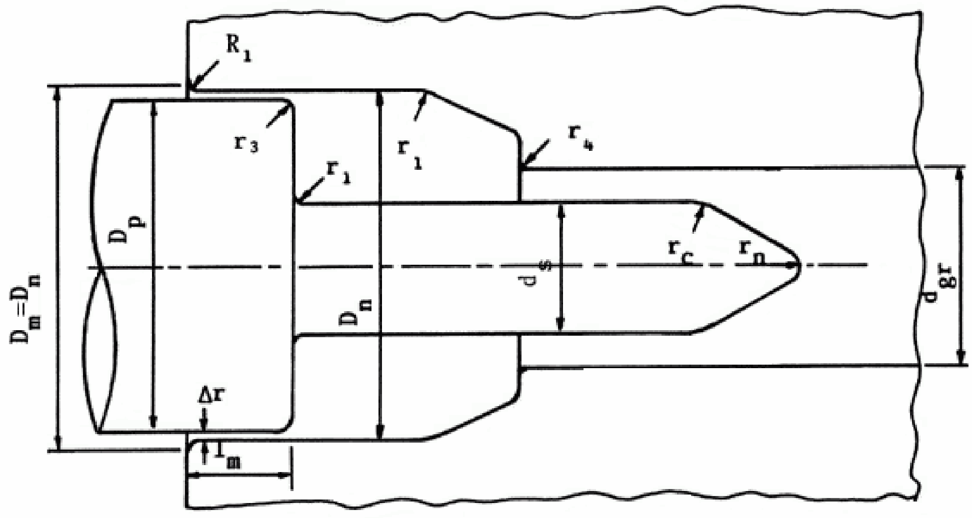


Figure 2.12. *Die cavity in gripper dies for flashless forging [3]*

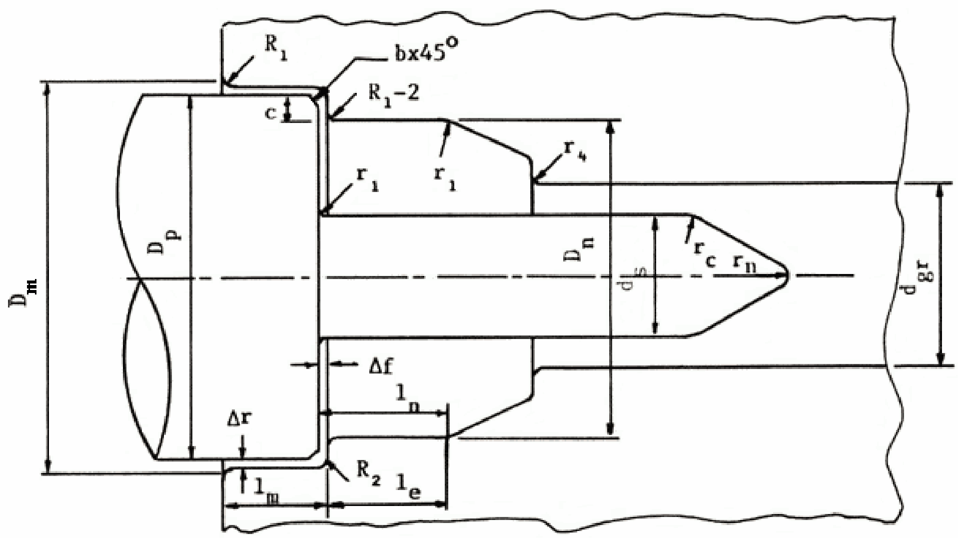


Figure 2.13. *Die cavity in gripper die for forging with flash [3]*

The recommendations for the die parameters are available in [3]. In the die design for hot tube upsetting process, 1.5% expansion allowance is used [18, 19, 21-23]. If the forging requires more than one stage, expansion allowance should be reduced 0.15% per stages [7, 21]. The wall thickness of the forging is controlled by the pilot of header tool. The length of the pilot should be long enough to support the heated zone of the workpiece before the deformation starts. Additionally, suitable draft angle should be added as discussed in Section 2.2.

The type and hardness of the tool material depend mainly on the production rate and the complexity of the shape to be produced. Production rates vary with the size of material to be forged and process automation. Utilizing automatic feed, production rate can be increased to a high numbers such as 6000-7000 pieces per hour. At high production rates the tool is used at high temperatures for a long period of time. Therefore, wear problems is likely to occur. After a period of time, the tool is worn-out and become nonfunctional. Therefore, die inserts are widely used. In several publications [3, 22], material selection for the die and die inserts are discussed in details.

CHAPTER 3

FINITE ELEMENT METHOD IN FORGING

3.1. Introduction

It is possible to analyze forging processes by analytical methods. However, for complex parts and environmental conditions, it is either very difficult or impossible to analyze the processes by the closed solutions. Hence, in these situations, it is necessary to apply numerical methods for the solutions. Finite element analysis is the most powerful method applied in numerical solutions of forging problems.

In the finite element approach, a continuum is approximated as finite number of sub-domains connected to each other at finite number of points. These sub-domains are called as elements and the points are called as nodes. The displacements within the element are approximated in terms of nodal displacements. Resulting equations can be linear or non-linear depending on various factors. In linear equations, stiffness is independent of the displacement in contrast to nonlinear equations which are resulted by material, geometrical or contact nonlinearities.

Finite element analysis of a hot forging operation is a large strain – large displacement problem, with thermo-mechanical coupling. In such an analysis there are different procedures for solving nonlinear equations; rigid-plastic formulation, elastic-plastic formulation, etc. In elastic-plastic material model, besides plastic deformations, elastic deformations are also considered in order to determine residual stresses and springback. In this study, elastic-plastic material approach and updated Lagrangian Method are used to describe the kinematics of material flow. In the updated Lagrangian Method, current configuration is used as reference. Hence, it is more convenient to use updated Lagrangian method in metal forming simulations in which there exist large deformations and displacements [24].

3.2. Finite Element Analysis of Tube Upsetting

In tube upsetting process, generally, initial workpiece and the final product have axi-symmetric geometries. In the literature [13, 14], for almost all of the upsetting simulations of axi-symmetric parts, axi-symmetric elements have been used. In this study, the complete tube upsetting process is modeled by axi-symmetric elements. However, during the gripping of workpiece by moving and fixed gripper dies, the temporary deformation on the shank is not axi-symmetrical. Hence, the effect of modeling the gripping action by axi-symmetric assumption is examined separately in Appendix A. The results have shown that the axi-symmetrical analysis can be used with acceptable accuracy.

In this study, MSC.Superform analysis software is used. The analysis is performed with following steps as in the other available software:

1. Modeling and mesh generation,
2. Assigning material properties,
3. Applying initial conditions,
4. Applying boundary conditions,
5. Defining contacting bodies,
6. Defining re-meshing criterion,
7. Defining load-cases.

After these steps, the solution process is applied for all subsequent forging stages.

3.2.1. Modeling and Mesh Generation

In finite element analysis, mesh generation and element selection play an important role on the solution.

In axi-symmetric analysis of tube upsetting process, axi-symmetric triangular ring elements (Types 2 and 156) and quadrilateral axi-symmetric ring elements (Types 10, 82, 116 and 119) are available in the MSC.Superform software [25]. Element type 2 is suggested for simulation of elastic tool and element type 156 for rigid-plastic material formulation [25]. Types 116 and 119 are not recommended for non-linear analysis. Type 82 is a reduced integration element in which analysis output is given only at the center of the element. However in Type 10, which is a fully integrated element, analysis output is given at the four Gaussian points as shown in Figure 3.1. Therefore, element type 10 is selected for axi-symmetric analysis of tube upsetting.

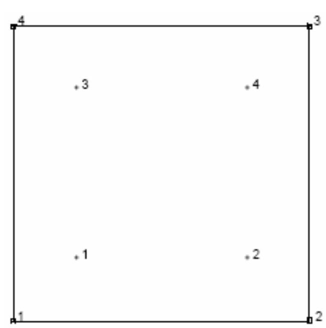


Figure 3.1. *Integration point for element type 10 [25]*

In three dimensional analysis of the gripping action, there are mainly two element types available; tetrahedron and hexagonal elements. MSC.Superform provides two tetrahedron (Type 134 and 157) and four hexahedral (type 7, 84, 117 and 120) element choices. Types 157, 84 and 120 elements are suggested by [25] for rigid-plastic material formulation which is not applicable for the subject of the thesis. Type 134 elements use linear interpolation functions, the strains are constant throughout the element. It results a poor representation of shear behavior and requires a fine mesh to obtain an accurate solution [25]. Therefore it is not preferred in this study. When the remaining element types (7 and 117) are compared, type 117 is not found to be as good as type 7 in the analysis of nonlinear material behavior [25]. Therefore, element type 7 has been preferred in three dimensional analysis of gripping. This element has 8 nodes as shown in the Figure 3.2.

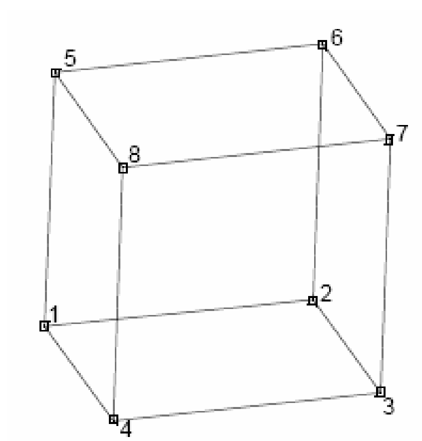


Figure 3.2. *Element type 7 [25]*

3.2.2. Material Properties

In the analysis with thermo-mechanical coupling, it is required to use the mechanical properties which change with temperature. Hence, variation of stress-strain relation with temperature and thermal properties like conductivity and specific heat are required. In this study, C35 carbon steel alloy is used as workpiece material. All of the thermal properties and variation of mechanical properties with temperature are given as input to the finite element program.

Since the dies are assumed as rigid, there is no need to define the die material for the analysis.

3.2.3. Initial Conditions

In this study, the only required initial condition is the temperature. Room temperature, which is 25 ˚C, has been assigned to all nodes of the workpiece as initial condition in the analyses. The die surfaces are taken as 300 ˚C.

3.2.4. Boundary Conditions

The shank side of the workpiece is loaded radialy to model the gripping die forces. The friction between the die and the workpiece holds the stock against the punch load. Additionally, thermal boundary conditions are defined in order to simulate heating of the workpiece. Edge heat fluxes are applied to the outer edges of the finite elements at the part of the workpiece which is supposed to be heated.

3.2.5. Contacting Bodies

In order to simulate the cooling of the hot workpiece by free convection to environment during the upsetting process, a film coefficient for convection is assigned to the workpiece to obtain heat flux to the environment. The formulation between the heat flux and the film coefficient is given in Equation 3.1.

$$q = h(T - T_{\infty}) \tag{3.1}$$

where,

q: heat flux (W/m^2)

h: thermal convection film coefficient ($W/m^2\,°C$)

T: workpiece temperature (ºC)

T_∞: Environment temperature (ºC)

It can be seen from the literature [25] that there are two friction models which are commonly used in the forging simulations. The one of them is the Adhesive Friction or Coulomb Friction model, which is preferred for cold forming processes. It is given as

$$\sigma_{fr} \leq -\mu \cdot \sigma_n \tag{3.2}$$

where,

σ_n : Normal stress

σ_{fr} : Tangential (friction) stress

μ : Friction coefficient

The other one is the shear friction model as given below.

$$\vec{f}_t \leq \frac{m \cdot \sigma_y \cdot \vec{t}}{\sqrt{3}} \tag{3.3}$$

where,

$\vec{f}_t$: tangential force (N)

σ : Flow stress of the material being deformed

m : friction factor

$\vec{t}$: unit tangential vector in the direction of the relative velocity.

The shear friction model is generally used for the friction modeling in hot regions. In the finite element analysis of the tube upsetting process, the shear friction model has been used.

3.2.6. Re-meshing Criterion

In bulk metal forming processes, workpiece is exposed to high deformation. Consequently, the finite elements of initial workpiece experience high distortion during the analysis. High distortion of element may cause the analysis to fail. Therefore, elements should be examined and then re-meshed periodically in order prevent high distortion. Additionally, finer mesh could be required at the part of the workpiece, where contact occurs. In MSC.Superform software, there are some predefined re-meshing criteria. In this thesis, the overlay technique is selected for re-meshing.

CHAPTER 4

THE ANALYSIS OF EXTERNAL TUBE UPSETTING

4.1. Introduction

In this study, finite element analysis of external tube upsetting is presented. C35 carbon steel is used as material in all of the analyses. Poison's ratio of the material is taken as 0.3 and the density is assigned as 7.85×10^{-9} tons/mm^3. In order to include thermal expansion and contraction of the material, temperature dependent thermal expansion coefficient (mm/mm/ºC) is given as shown in Figure 4.1. The specific heat (mm^2/s^2/ºC) and conductivity (tonne-mm/s^3/ºC) of the material, as a function of temperature, are shown in Figure 4.2 and Figure 4.3 respectively. Additionally, Young's Modulus at different temperatures are shown in Figure 4.4. The flow stress of the material mainly depends on the temperature and the strain rate. In forging operations, the obtainable strain rate is about 1/s. Flow stress-strain curves at different temperatures for the strain rate of 1/s are shown in Figure 4.5.

Dies are modeled as the velocity controlled rigid tools. In the axi-symmetric analysis of the process, temperature of the header and the gripper dies are assigned as 300 ºC.

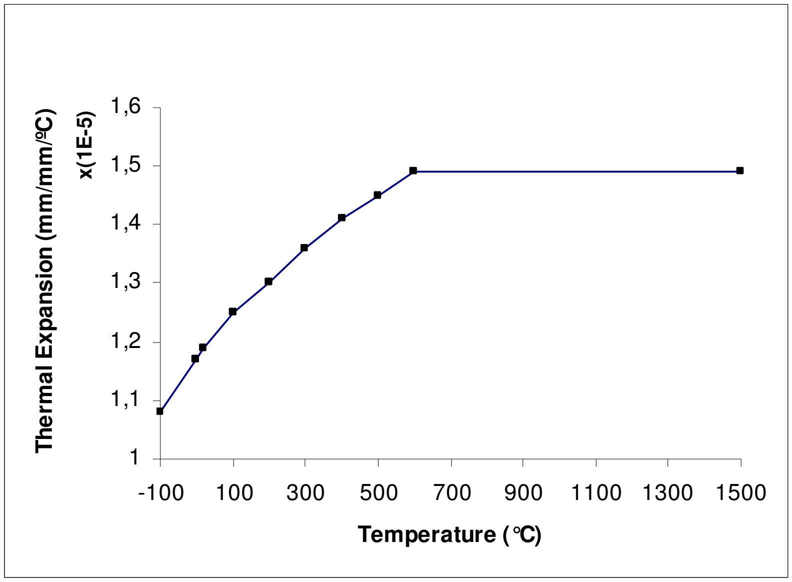


Figure 4.1. *Thermal expansion versus temperature graph [26]*

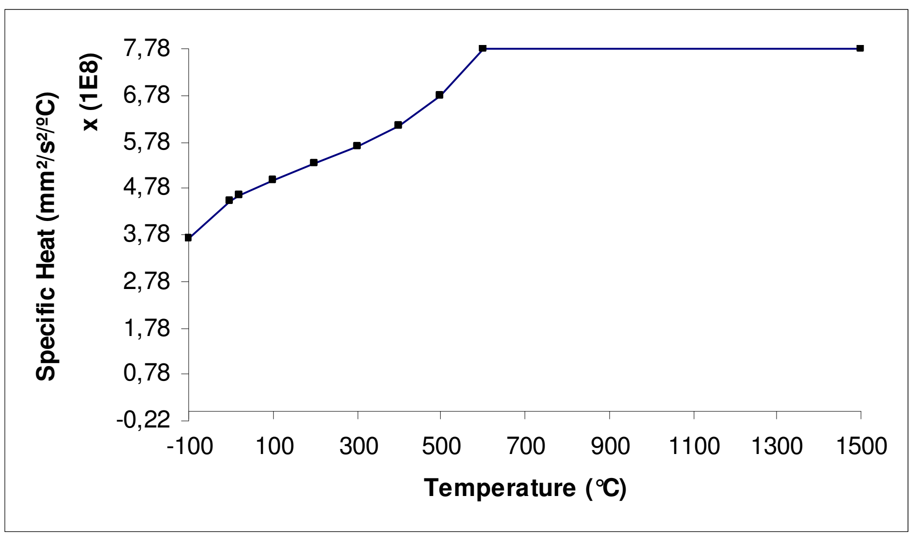


Figure 4.2. *Specific heat versus temperature [26]*

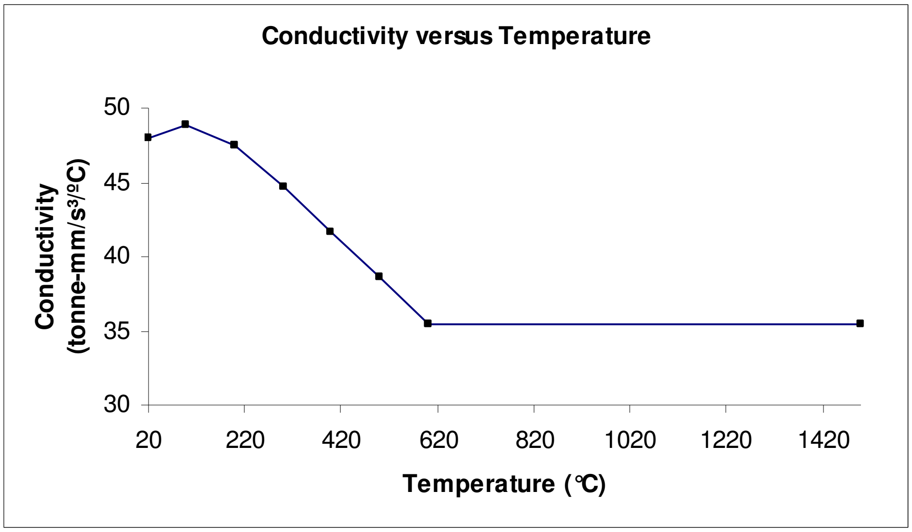


Figure 4.3. Conductivity versus temperature [26]

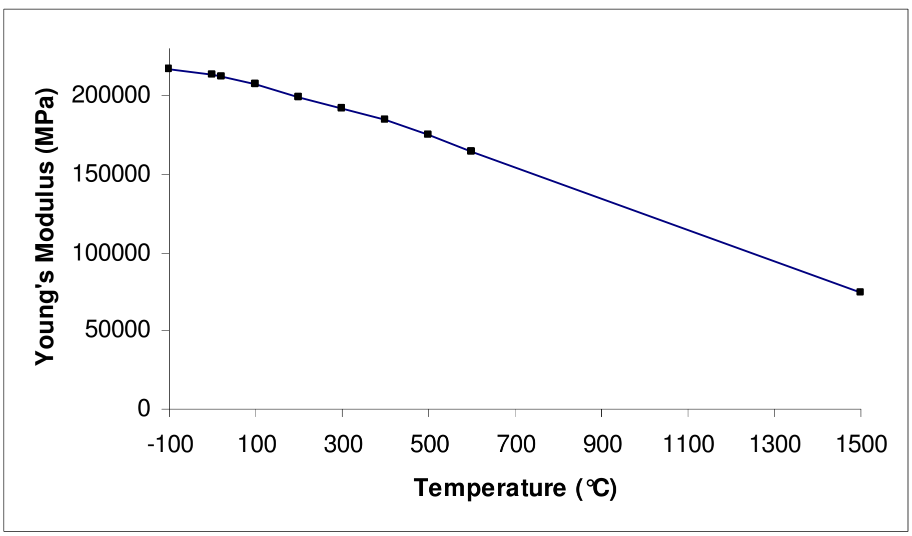


Figure 4.4. *Young's Modulus versus temperature graph [26]*

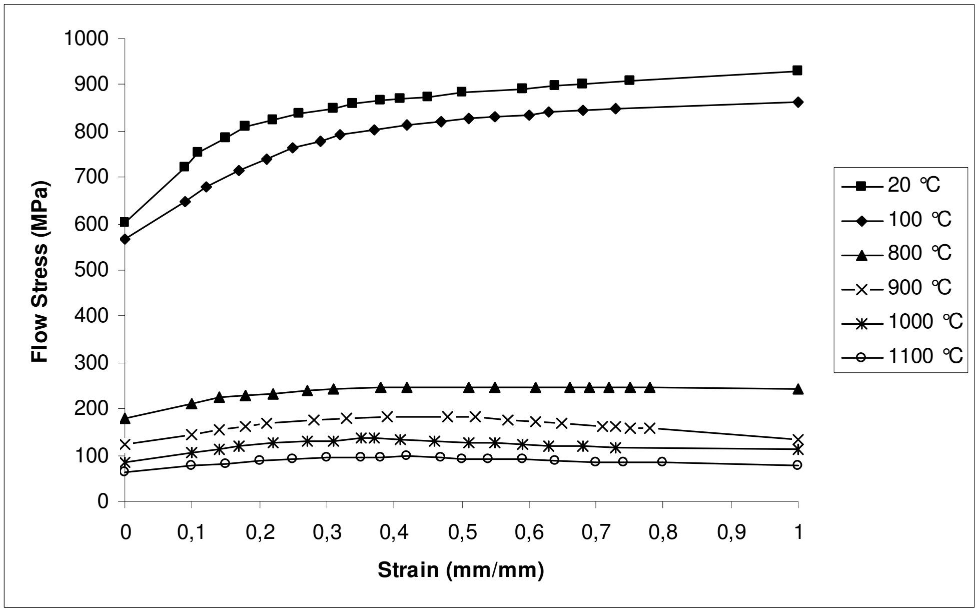


Figure 4.5. *Flow stress-strain curves for 1/s strain rate [26]*

4.2. Case Study 1: External Upsetting

The sequence and die design of the part, shown in Figure 4.6, was performed by Karavelioğlu [3]. As seen from Figure 4.6, the part requires external tube upsetting only.

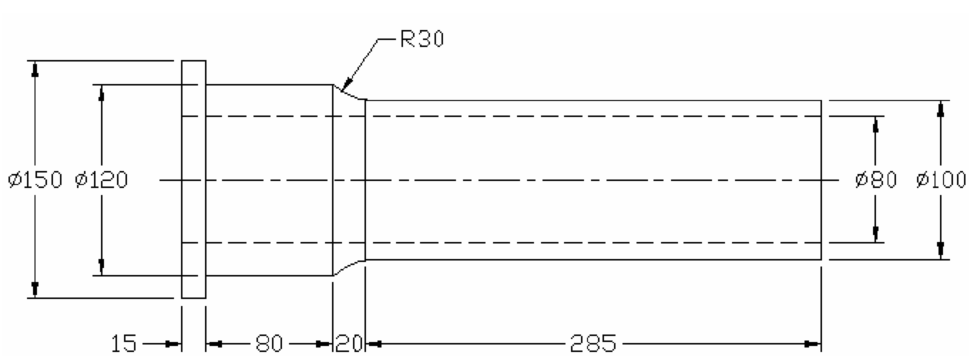


Figure 4.6. *A part flanged at one end [3]*

4.2.1. Sequence and Die Design for Procedure I

The sequence and die design of the part are performed according to the Procedure I described in Chapter 2. The shape of the final product determines the dimensions of the undeformed tube used in upsetting operation. The outer diameter of the undeformed tube should be equal to the smallest outer diameter of the final part, and the inner diameter of the deformed tube should be equal to the smallest inner diameter of the final part. Therefore, the undeformed initial tube should have 100 mm outer and 80 mm inner diameters.

The forging is divided into three sub-regions as shown in Figure 4.7. The volumes of these sub-regions A, B and C are calculated as 189674 mm^3, 502655 mm^3 and 79001 mm^3, respectively. Length of the initial tube is determined as 586.01 mm by using volume constancy as shown in Figure 4.8. While determining the initial tube length, the flash volume and the draft angle is also included. Flash width, f_w, and flash thickness, f_t, are taken as 12 mm and 2.5 mm, respectively, according to Table 2.5. The flash volume is calculated as 46880 mm^3 and added to the volume of sub-region A. Then, the total volume of sub-region A becomes 236554 mm^3 including the flash.

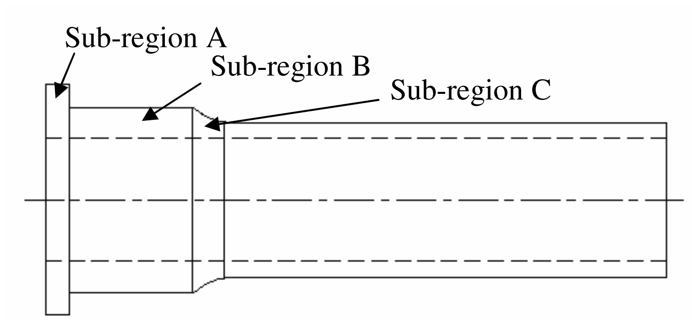


Figure 4.7. *Sub-regions of the tubular part*

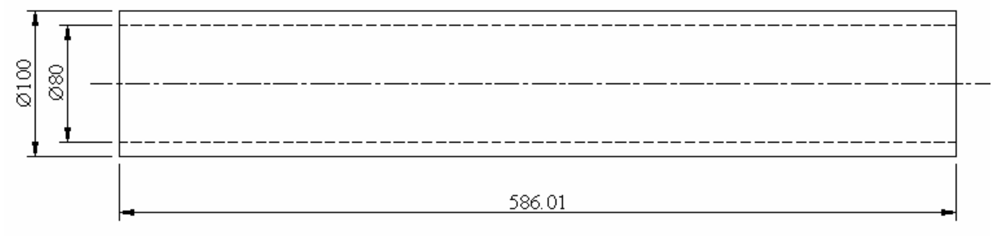


Figure 4.8. *Required initial tube for upsetting*

By applying sequence design rules, shape of the tube at the intermediate stages can be determined. Number of stages is calculated as 4 and the equalized wall thickness ratio is 1.37 for all stages. The shapes of the part with the cold dimensions (i.e. at room temperature) at intermediate stages are shown in Figures 4.9 to 4.12.

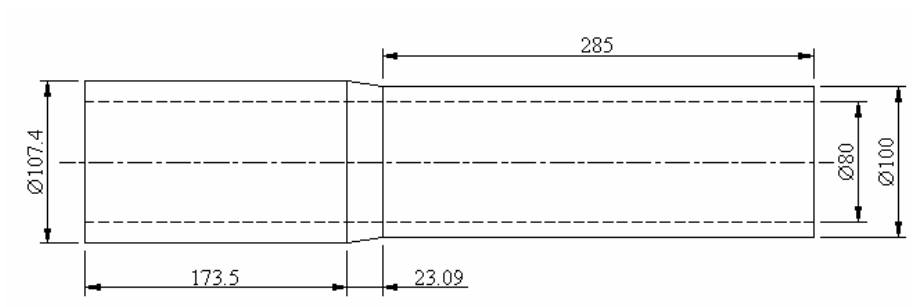


Figure 4.9. *Shape of part for stage 1 [3]*

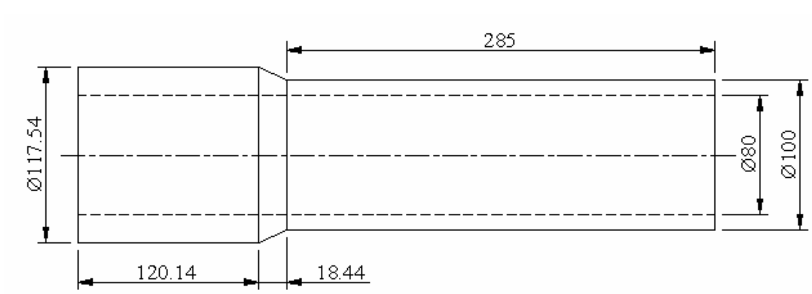


Figure 4.10. *Shape of part for stage 2 [3]*

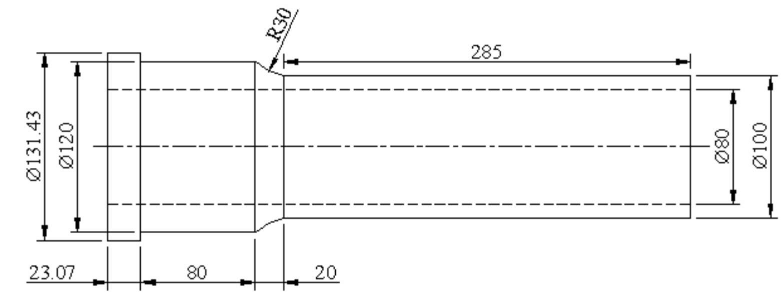


Figure 4.11. *Shape of part for stage 3 [3]*

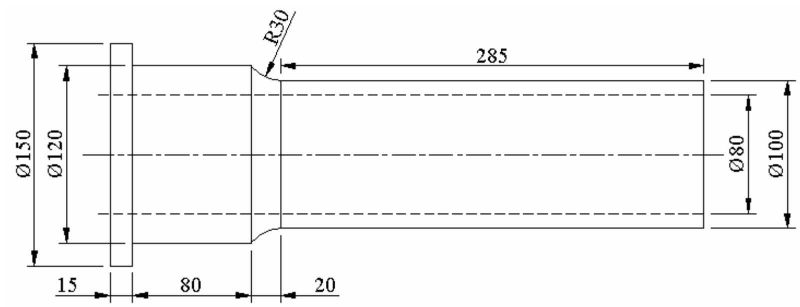


Figure 4.12. *Shape of part for stage 4 [3]*

Design of Karavelioğlu [3] for header tools and gripper dies are shown in Figures 4.13 - 4.16. In the die design of first stage 1.5% contraction allowance is used for the die dimensions. However, in the consequent stages, contraction allowance is decreased by 0.15% to allow progressive cooling as discussed in Chapter 2. Therefore, 1.35%, 1.2% and 1.05% contraction allowances are used for the second, third and fourth stages.

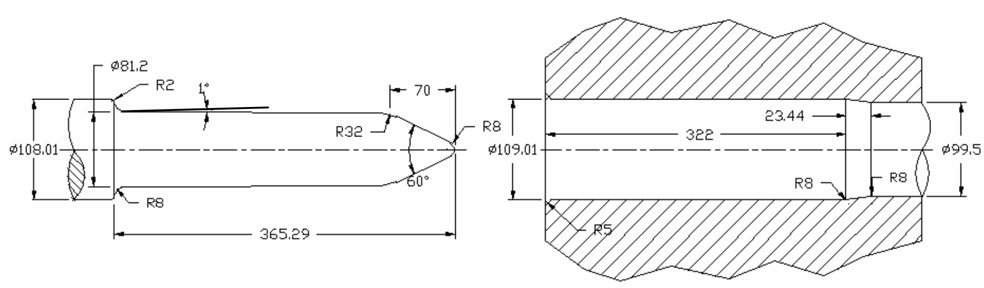


Figure 4.13. *Header tool and gripper die of 1st stage [3]*

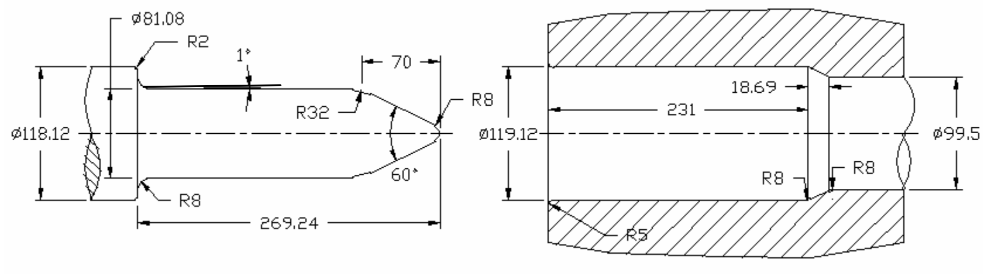


Figure 4.14. *Header tool and gripper die of 2nd stage [3]*

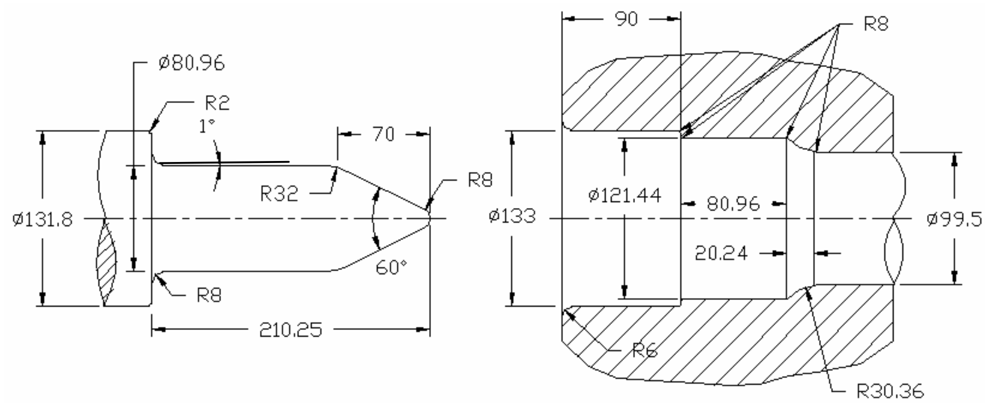


Figure 4.15. *Header tool and gripper die of 3rd stage [3]*

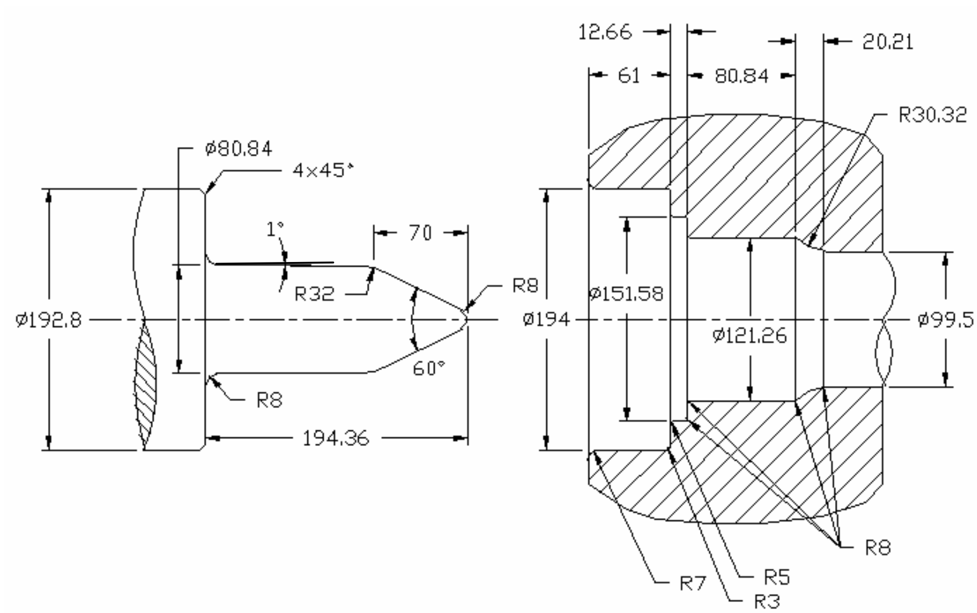


Figure 4.16. *Header tool and gripper die of 4th stage [3]*

4.2.2. Finite Element Analysis for Procedure I

The analysis is performed with axi-symmetric elements of type 10 of MSC.Superform as explained in Chapter 3. The geometries of four gripper dies and header tools, and the workpiece are modeled as shown in Figure 4.17. The workpiece is meshed with 3680 axi-symmetric quadrilateral elements. Element size is chosen as 1.25 mm which results in eight element layers through the tube wall thickness as shown in Figure 4.18. Header tools and gripper dies are modeled as rigid bodies and shown with lines only.

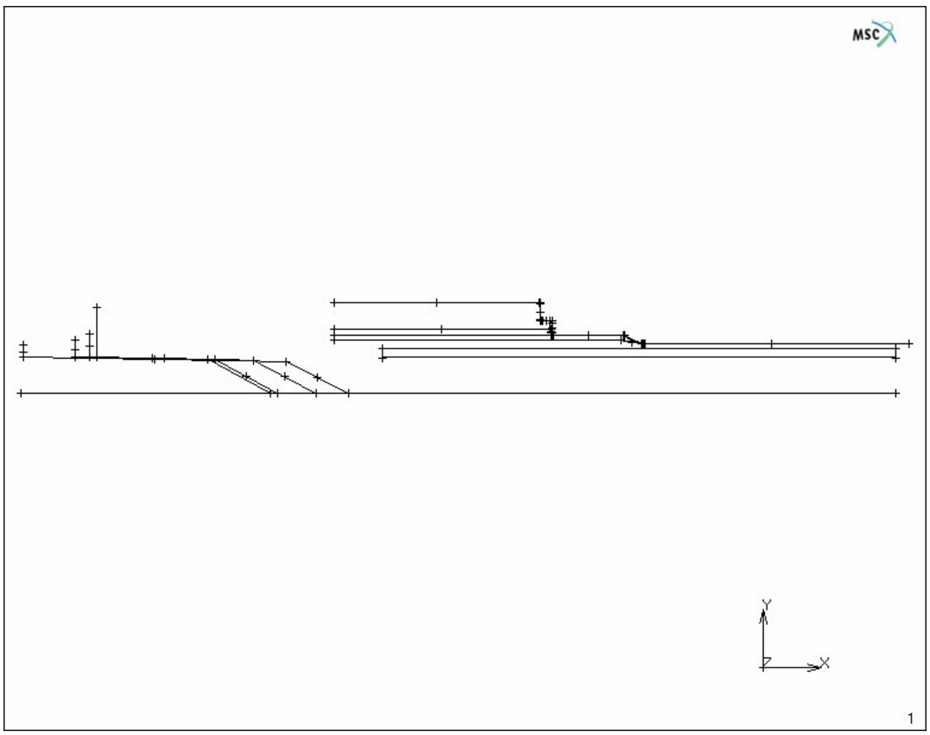


Figure 4.17. *Geometric model of the process for the finite element analysis*

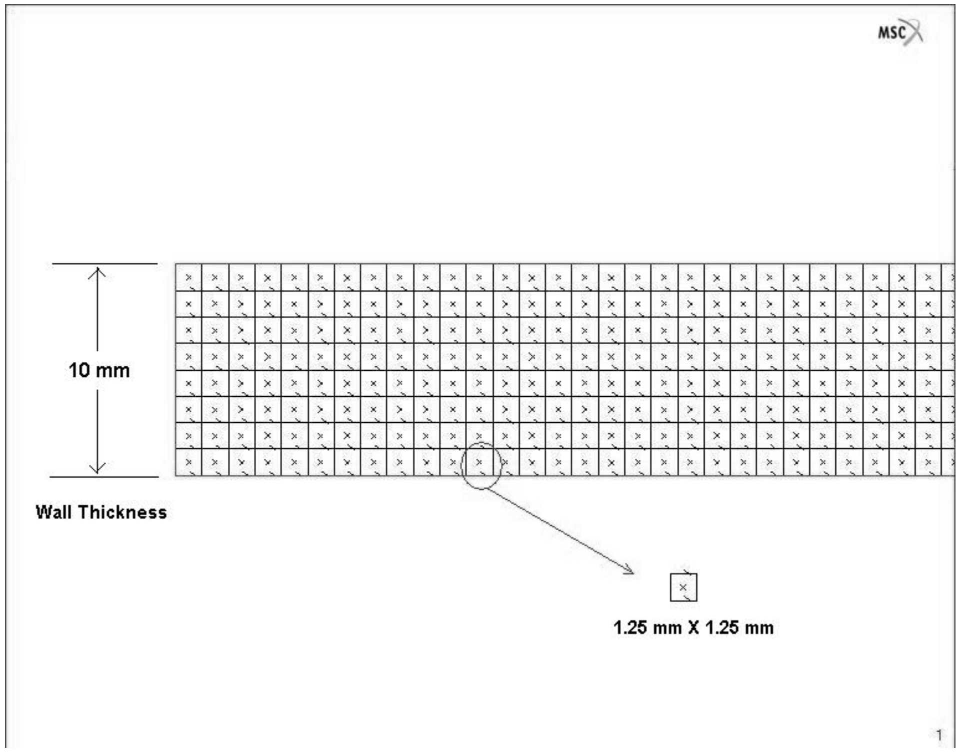


Figure 4.18. *Elements used in the finite element model*

The analysis of tube upsetting has mainly four distinctive analysis stages. These are heating, gripping, deformation and cooling of the tube.

4.2.2.1. Heating of the Tube

In order to simulate the heating of the tube by induction, heat flux boundary conditions are applied to the outer and inner surfaces of the workpiece at the deformation zone as shown in Figure 4.19, until a homogeneous temperature distribution is obtained. The surrounding temperature is taken as 25 °C. In the deformation zone, almost uniform temperature about 1200°C is obtained as shown in Figure 4.20. At the end of the deformation the workpiece is cooled to the room temperature.

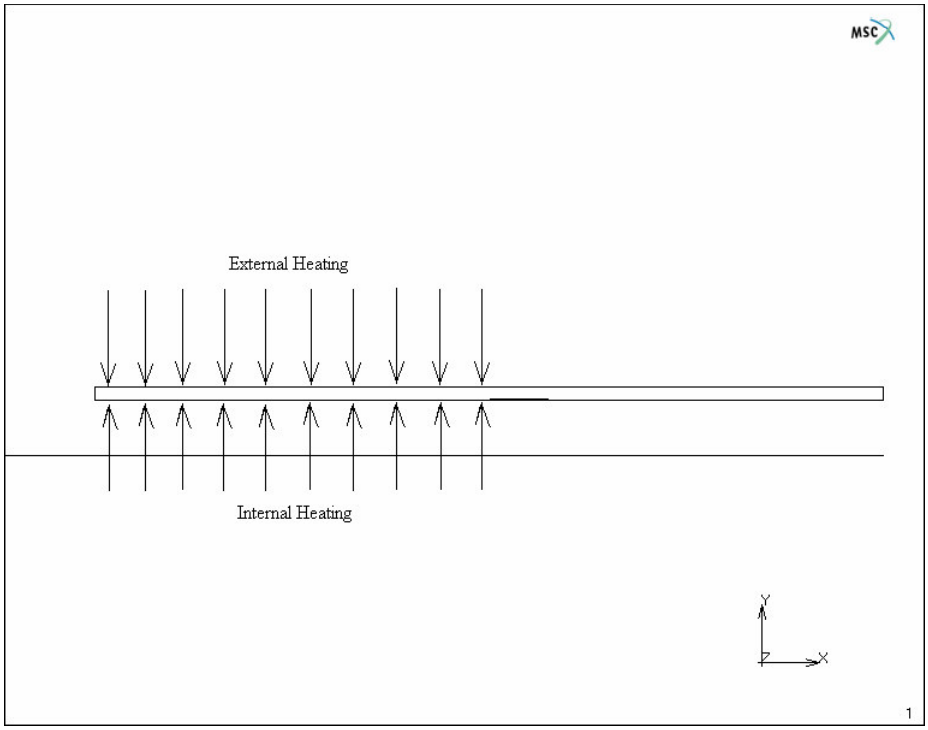


Figure 4.19. *Heat flux boundary condition in the finite element analysis*

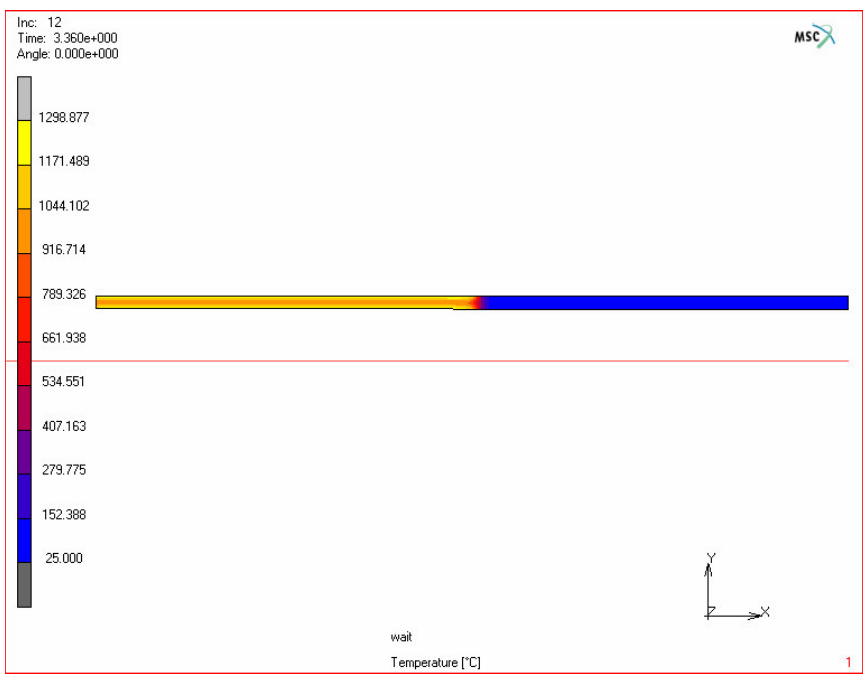


Figure 4.20. *Temperature distribution after heating (°C)*

4.2.2.2. Gripping of the Tube

In order to simulate gripping action for the mesh of axi-symmetric elements, the gripping die is moved toward the workpiece in radial direction. The diameter of the workpiece is reduced from 100 mm to 99.5 mm by sequezing. The stress distributions during the gripping of the first and the second stages are shown in Figure 4.21 and Figure 4.22. While gripping at the third stage, an unexpected workpiece and gripper die contact is observed at sub-region C as shown in Figure 4.23. The curved gripping die deforms the heated material radially towards the symmetry axis and causes plastic deformation which is not common to the tube upsetting process. It indicates that, in the previous stages, the outer region was deformed excessively at Sub-region C as shown in Figure 4.24. In a multi-stage tube upsetting process, deformed shape of the current stage must fit to the gripper dies of next stage. Otherwise, the design of the process should be modified in order to obtain the proposed forging.

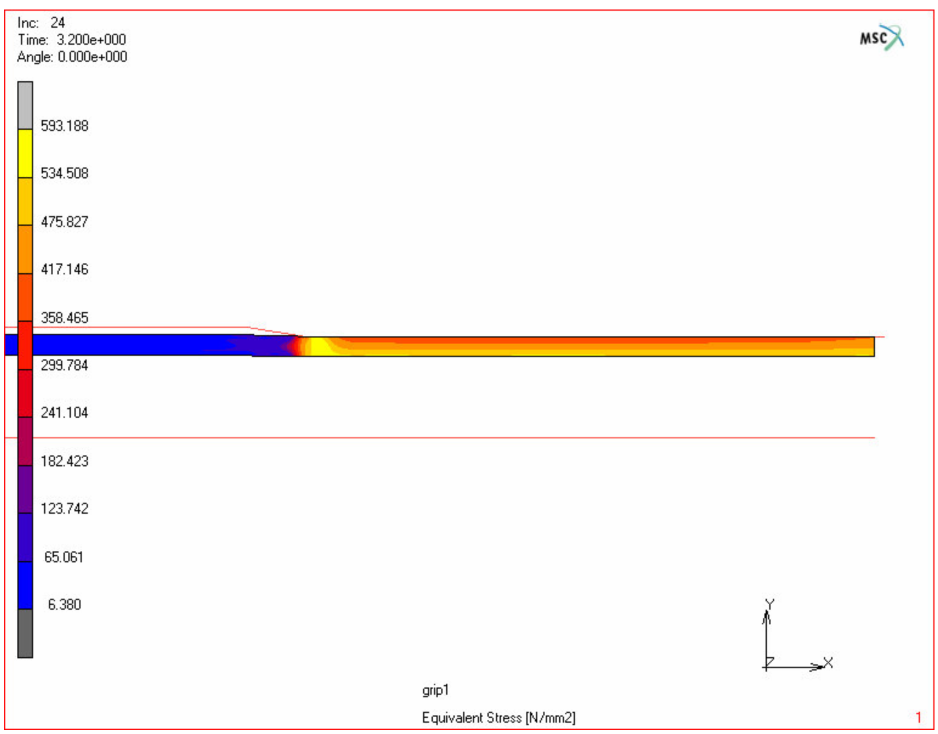


Figure 4.21. *Equivalent stress distribution during gripping at 1^{st} stage (MPa)*

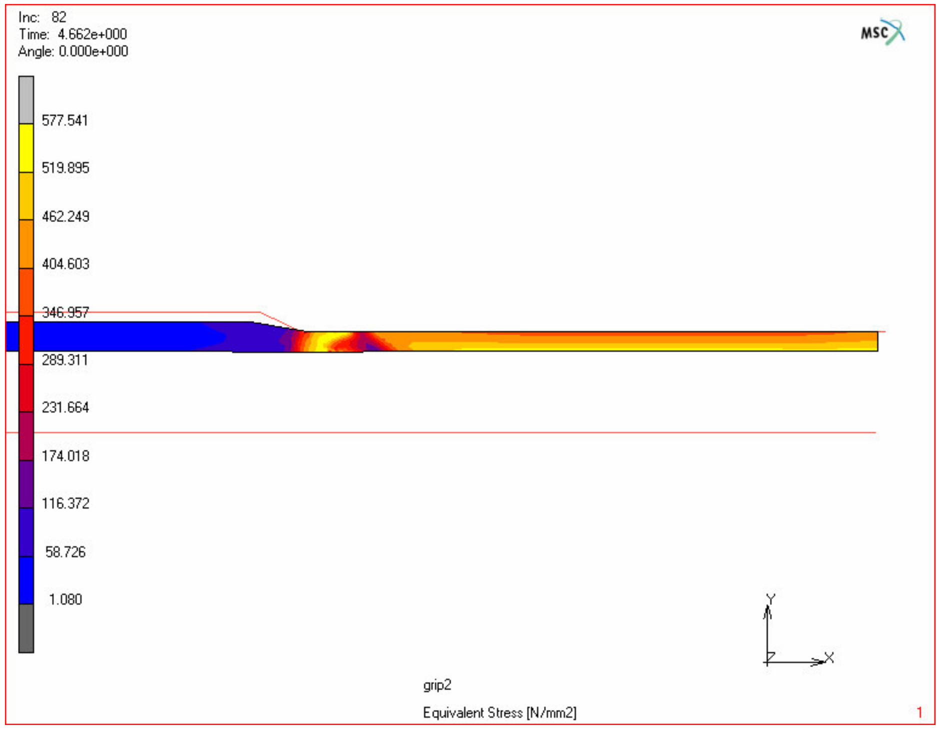


Figure 4.22. *Equivalent stress distribution during gripping at 2^{nd} stage (MPa)*

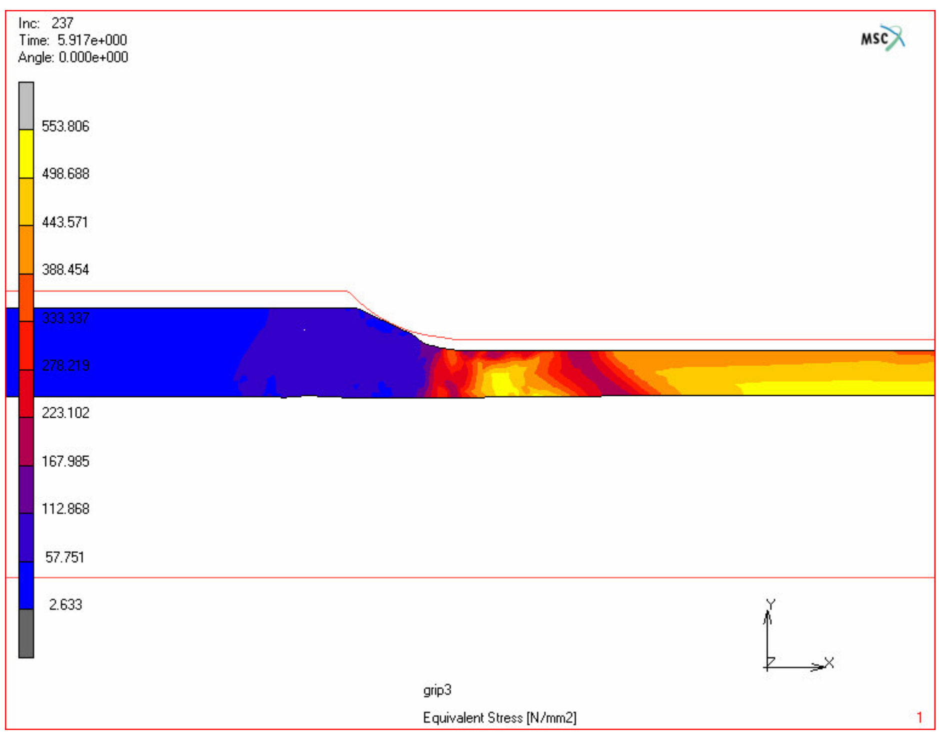


Figure 4.23. *Equivalent stress distribution during gripping at 3^{rd} stage (MPa)*

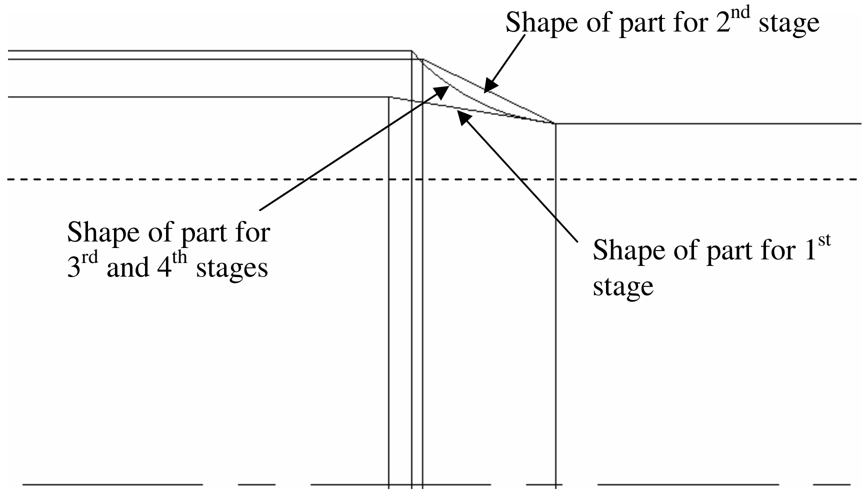


Figure 4.24. *Shape of the part at different stages*

Shapes of the sub-region C at the first and second stages must be re-determined, and for this purpose a CAD software is used in order to obtain the shape limitations of the forging as shown in Figures 4.25 - 4.27. With the modifications made, the volumes of sub-region C at the first and second stages were decreased. The changes in volume are reflected to the volume of sub-region A to satisfy the volume constancy through the process.

In order to obtain the modified shapes after the first and the second stages, the gripper dies should also be modified by considering the contraction allowance. The modified gripper die shapes are shown in Figures 4.28 and 4.29.

4.2.2.3. Deformation of the Tube

After the workpiece is held by gripper dies, the header tool is moved toward the workpiece. The velocity of the header tool while deforming the workpiece is defined as 100 mm/s [14]. The length of the deformation zone of the workpiece is reduced by 32.4% in the first stages. The length reduction ratios for the second, third and fourth stages are 29.5%, 11.2% and 6.6% respectively.

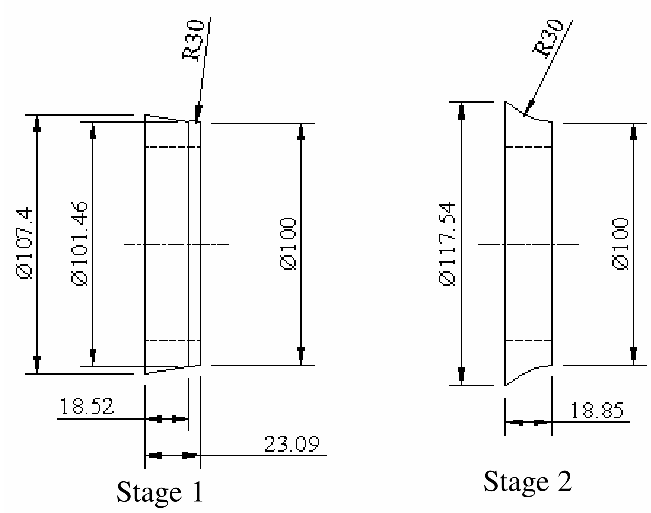


Figure 4.25. *Shape of Sub-region C for Stages 1 and 2*

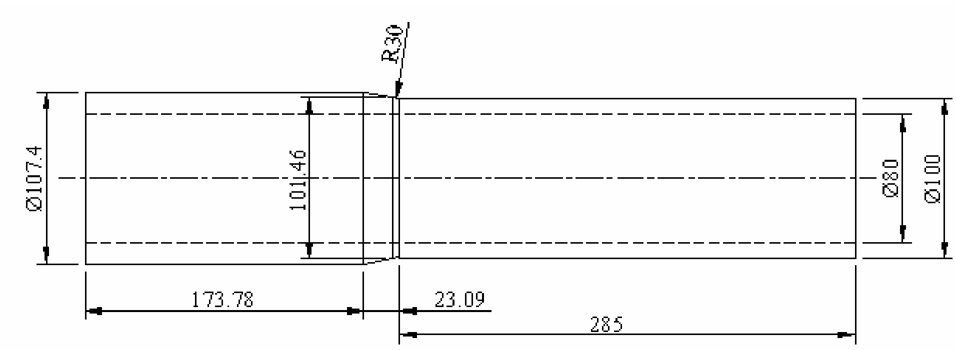


Figure 4.26. *Modified shape of part at stage 1*

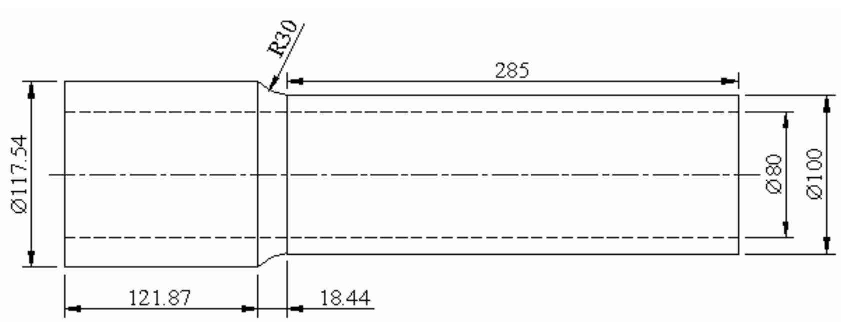


Figure 4.27. *Modified shape of part at stage 2*

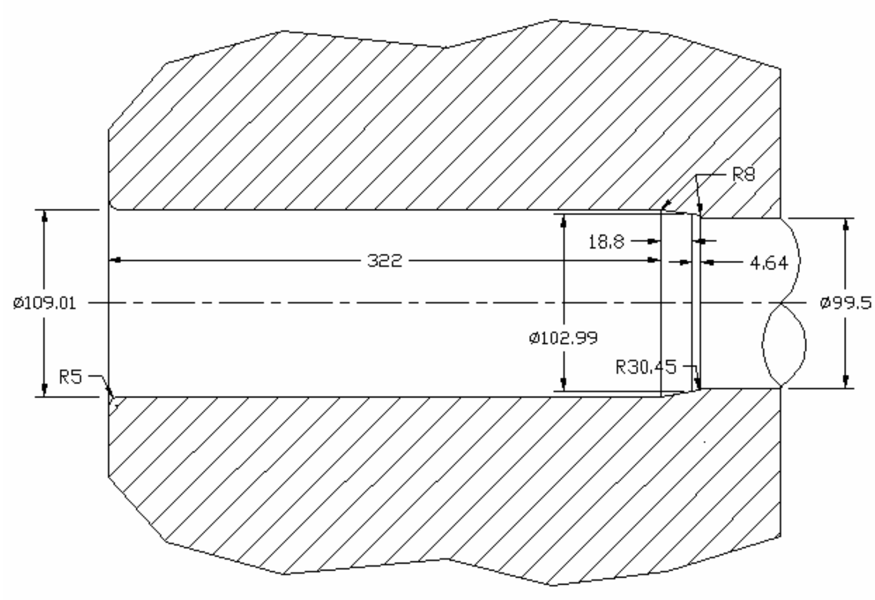


Figure 4.28. *Modified gripper die of 1st stage*

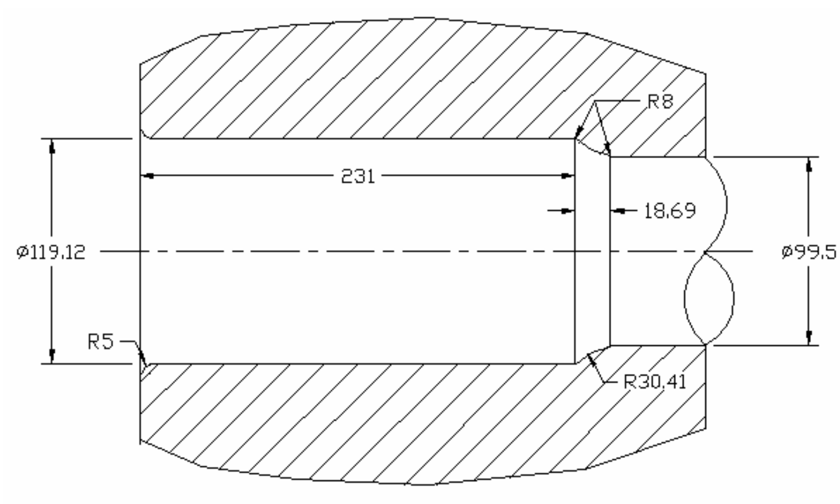


Figure 4.29. *Modified gripper die of 2nd stage*

Solution of the analysis is completed in 532 increments. In the first 8 increments, heating of the tube is completed. Then, 2 increments are progressed for first gripping action. Movement of first header tool (first stage) is solved in 102 increments. Plastic strain and equivalent stress distribution at the end of the first stage are shown in Figures 4.30 and 4.31. The cavity in the first gripper die is completely filled with the heated material. The plastic strain values at the shank part of the tube are almost zero as expected.

The second gripping action is solved in two increments. Then the movement of second header tool (second stage) is completed in 102 increments. The plastic strain and the equivalent stress distributions at the end of the second stage is shown in Figures 4.32 and 4.33. The third and the fourth gripping actions are solved in 2 increments similarly. Solutions of the third and the fourth stages take 152 increments. The strain and the stress distributions after the third and the fourth stages are shown in Figures 4.34-4.37, respectively.

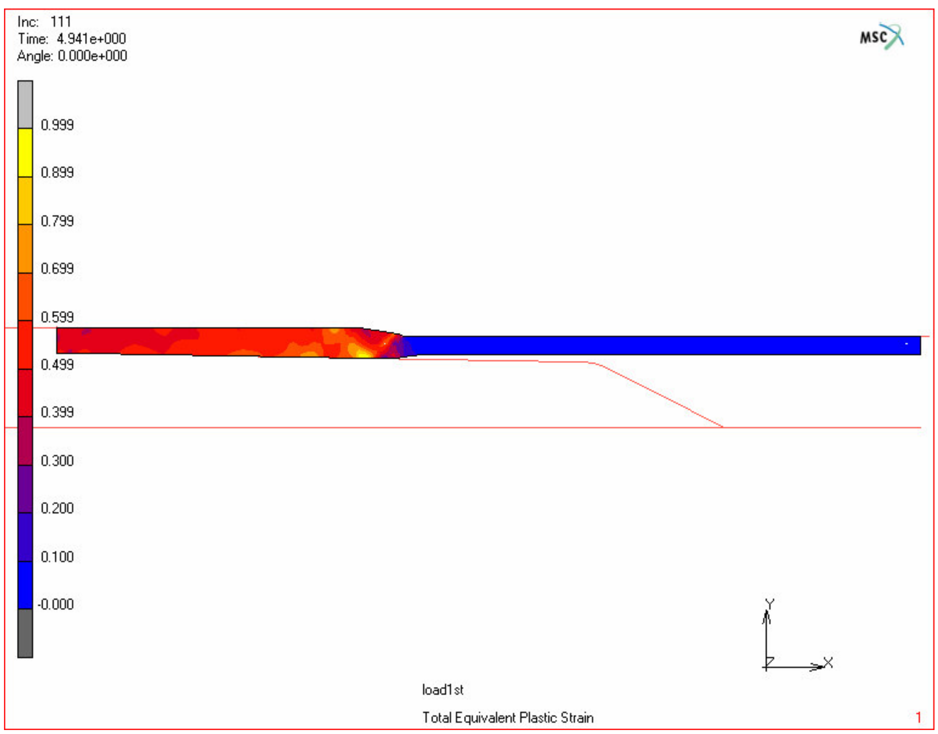


Figure 4.30. *Total equivalent plastic strain distribution after 1st stage*

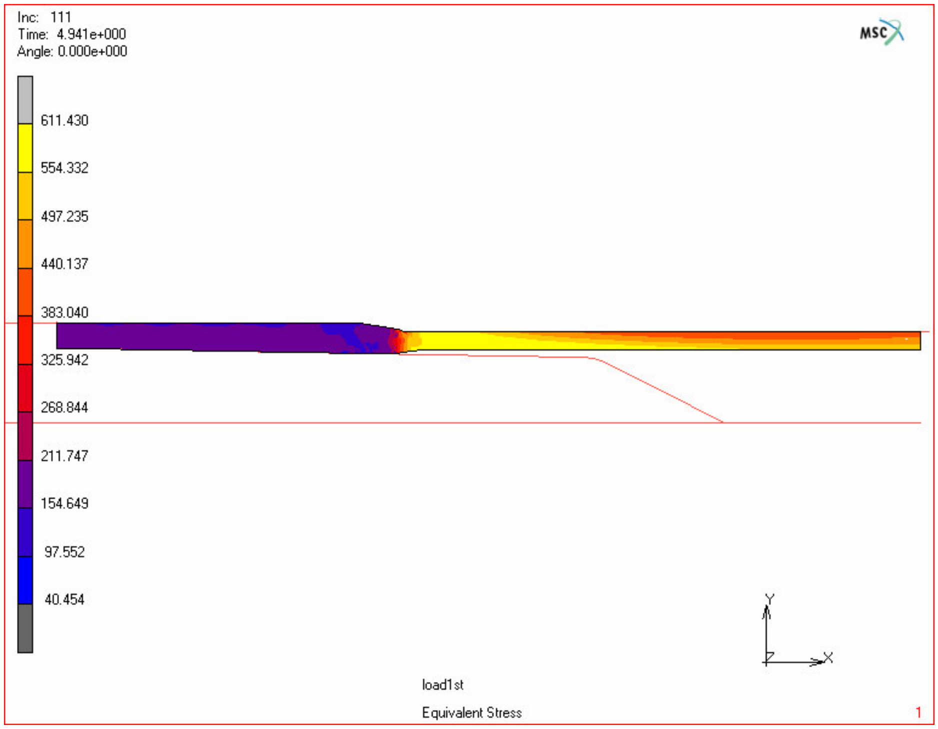


Figure 4.31. *Equivalent stress distribution after 1st stage (MPa)*

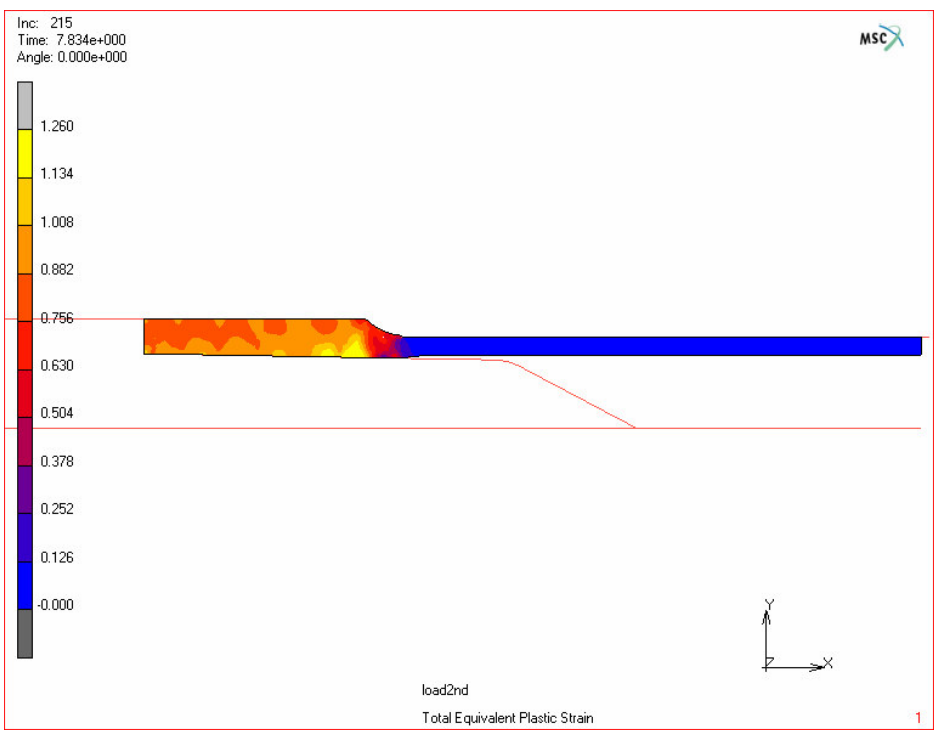


Figure 4.32. *Total equivalent plastic strain distribution after 2nd stage*

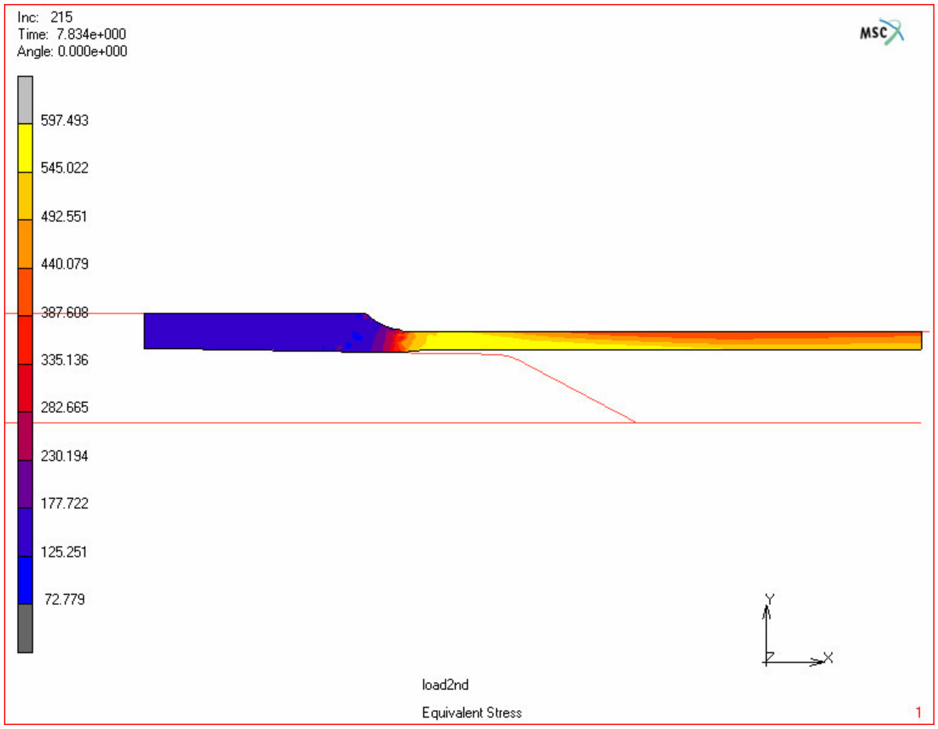


Figure 4.33. *Equivalent stress distribution after 2nd stage (MPa)*

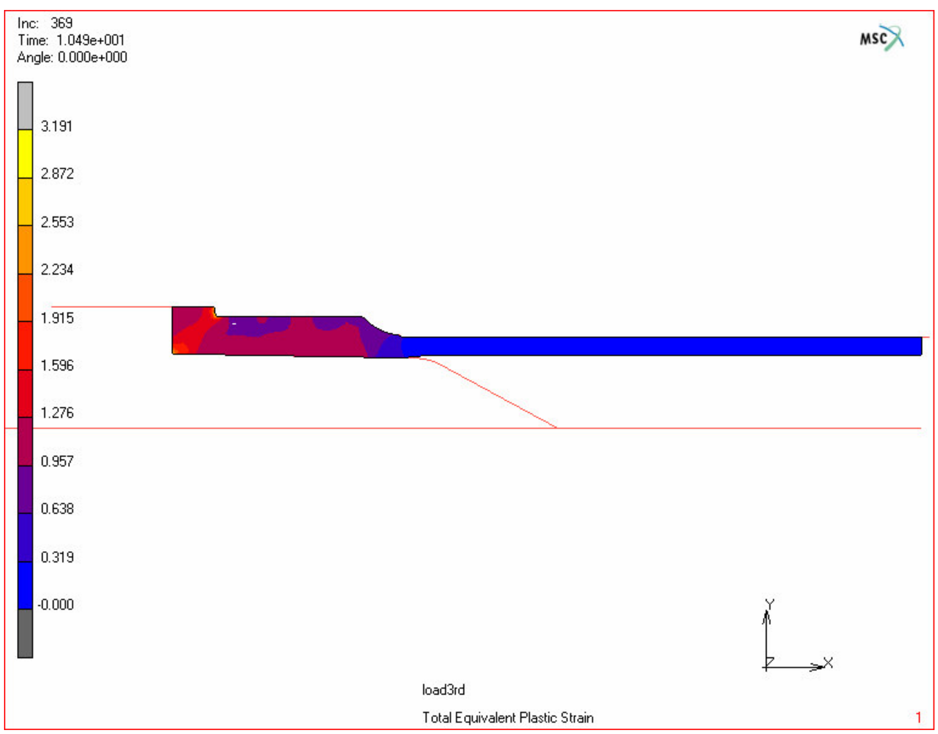


Figure 4.34. *Total equivalent plastic strain distribution after 3rd stage*

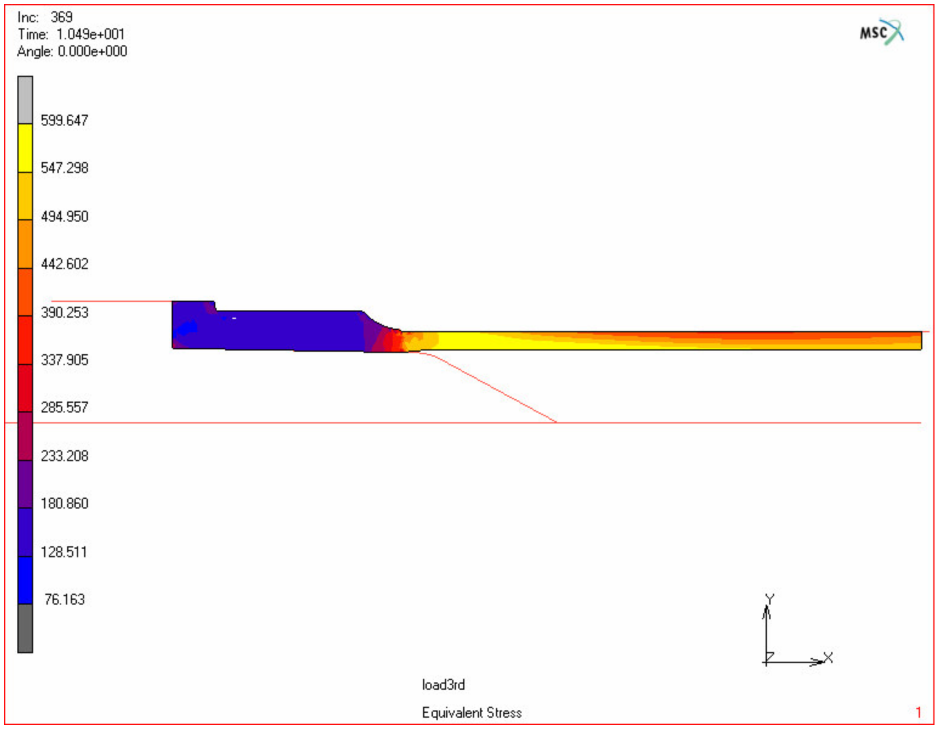


Figure 4.35. *Equivalent stress distribution after 3rd stage (MPa)*

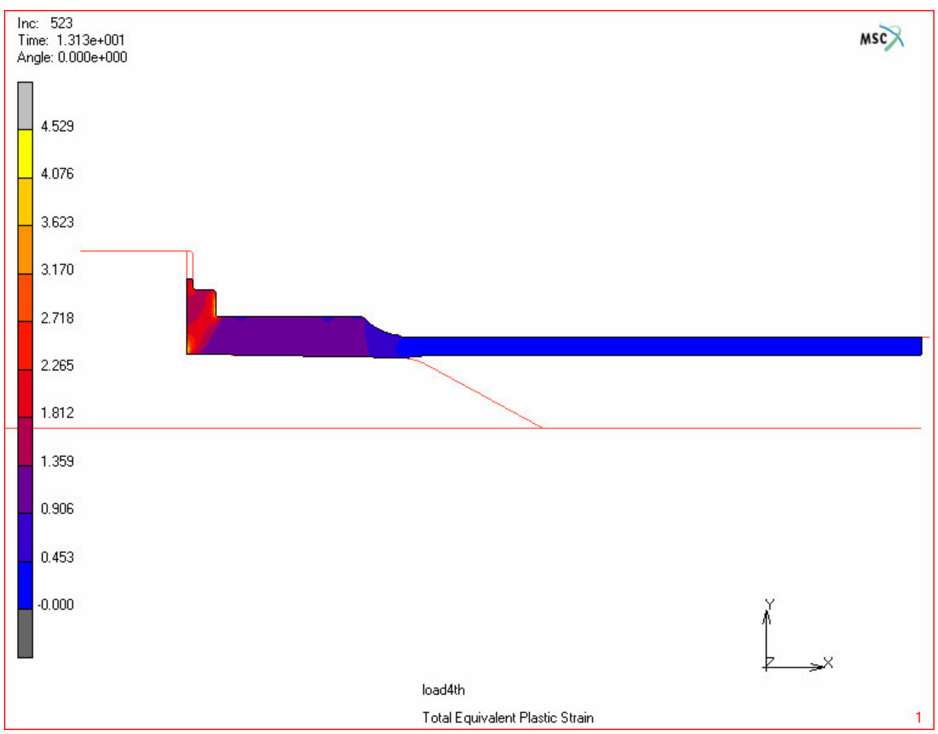


Figure 4.36. *Total equivalent plastic strain distribution after 4th stage*

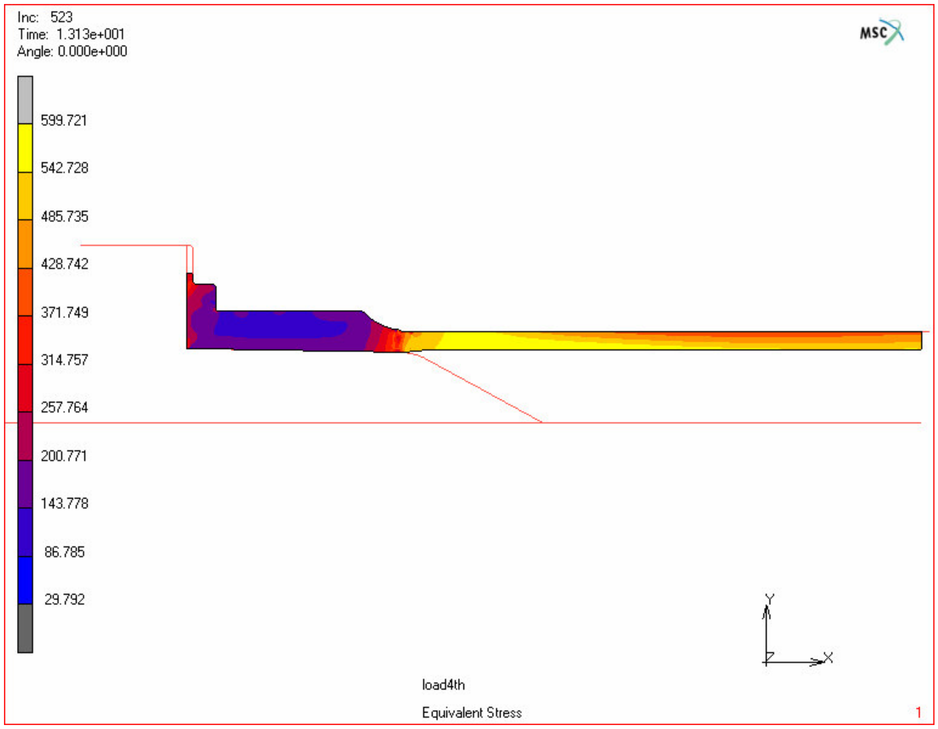


Figure 4.37. *Equivalent stress distribution after* 4^{th} *stage (MPa)*

4.2.2.4. Cooling of the Tube

After the forging operation has been completed, the tube is cooled to the room temperature. In the cooling analysis, tube is kept at 25°C surrounding temperature until it cools down to the room temperature. Solution is completed in 8 increments. Temperature distributions before and after the cooling stage are shown in Figures 4.38 and 4.39. As can be seen from the figures, almost uniform temperature distribution about 25°C is obtained at the end of the simulation.

By cooling stage, the analysis of the process is completed. Obtained total equivalent plastic strain and equivalent stress distributions at the end of the analysis are shown in Figures 4.40 and 4.41 respectively.

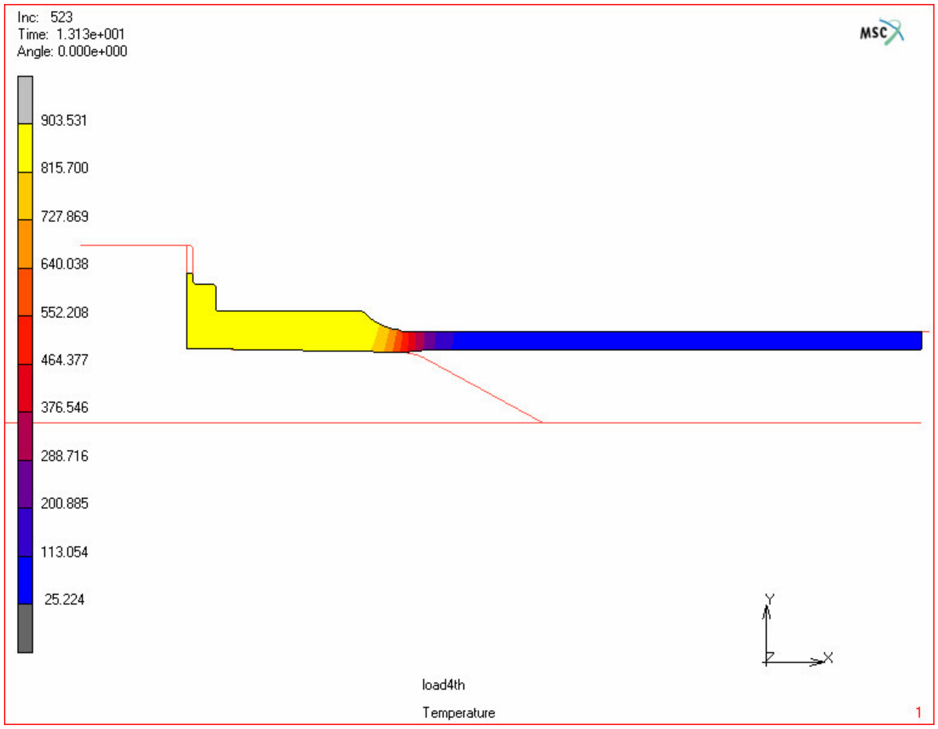


Figure 4.38. *Temperature distribution after 4th stage (°C)*

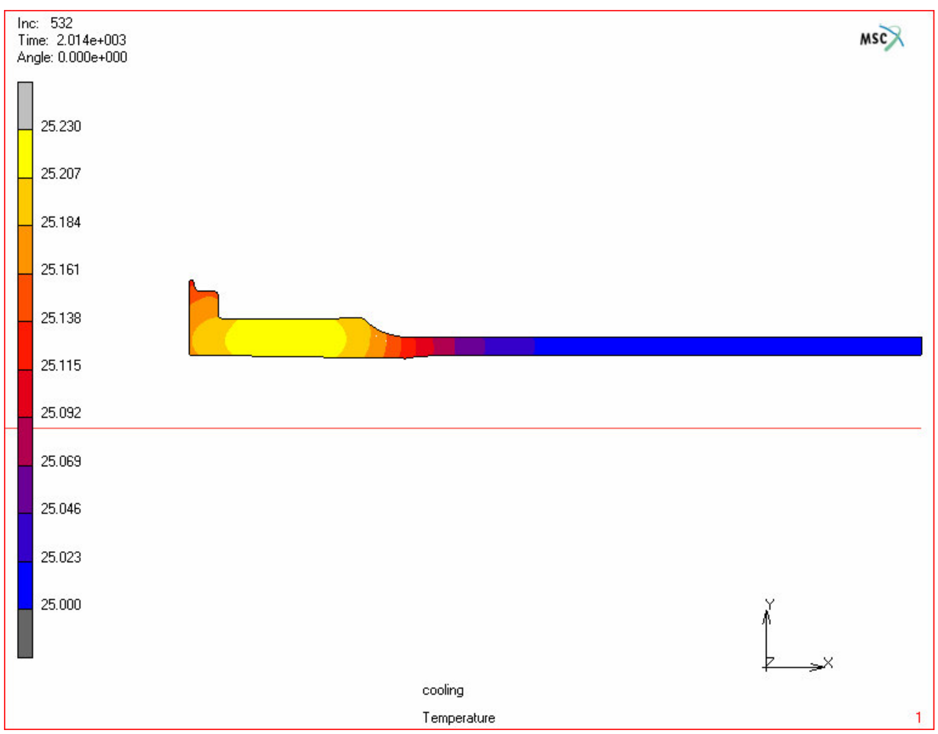


Figure 4.39. *Temperature distribution after cooling stage (°C)*

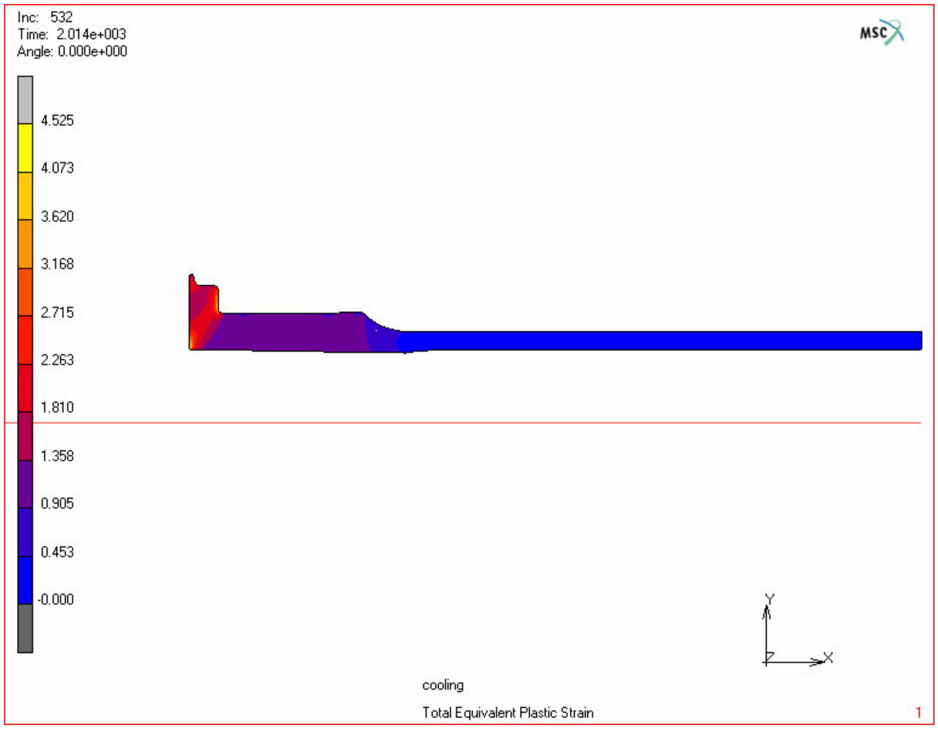


Figure 4.40. *Total equivalent plastic strain distribution at the end of the analysis*

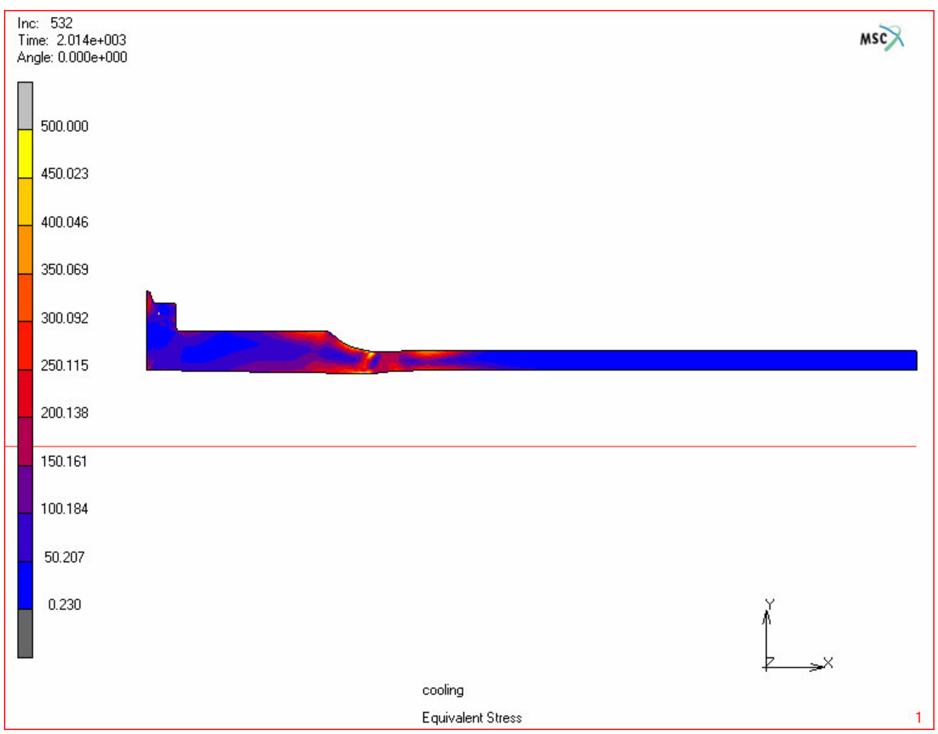


Figure 4.41. *Equivalent stress distribution at the end of the analysis (MPa)*

4.2.3. Sequence and Die Design for Procedure II

As discussed in Chapter 2, Procedure II, which is suggested by Russian Forging Handbook [19] and modified by Karavelioğlu [3], is employed for the finite element analysis. Initial tube length is determined as in Procedure I. However, number of stages to complete the process is reduced from four to three. The wall thickness ratios for the stages are calculated as 1.42, 1.51 and 1.64 [3]. Shapes of the tube at the intermediate stages are shown in Figure 4.42.

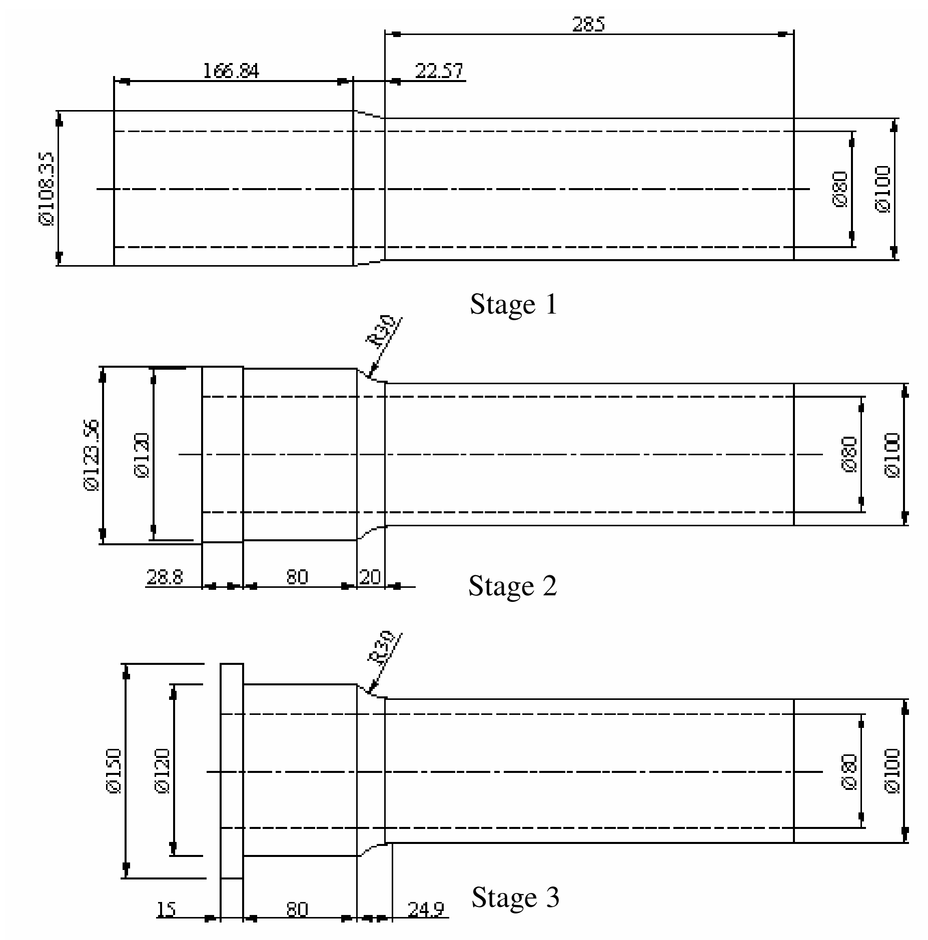


Figure 4.42. *Shape of the tube at intermediate stages [3]*

Design of Karavelioğlu [3] for header tools and gripper dies are shown in Figures 4.43-4.45. In the die design of stages, 1.5%, 1.35% and 1.2% contraction allowances are used for the die dimensions.

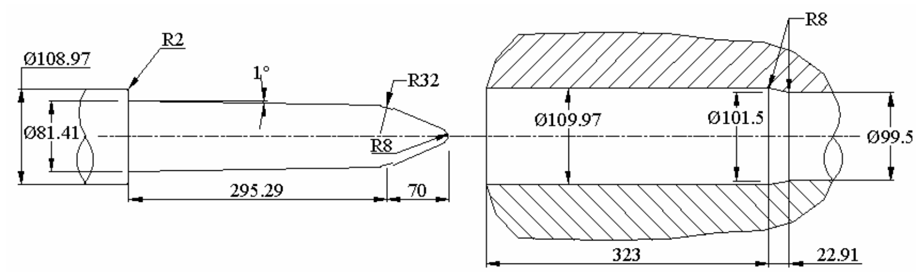


Figure 4.43. *Header and gripper dies for 1st stage [3]*

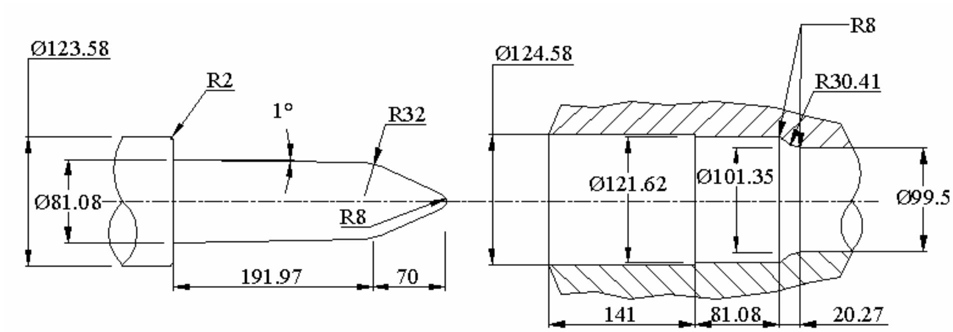


Figure 4.44. *Header and gripper dies for 2nd stage [3]*

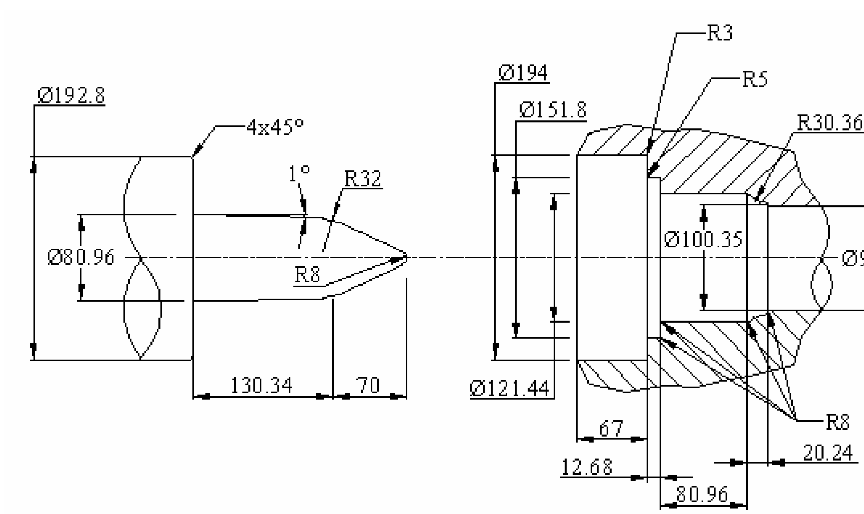


Figure 4.45. *Header and gripper dies for 3rd stage [3]*

4.2.4. Finite Element Analysis for Procedure II

In the finite element analysis, the same element density is used as in the procedure I. The finite element model of the workpiece and, header and gripper dies is shown in Figure 4.46. Dies are modelled as rigid bodies.

The length of the deformation zone is decreased by 34.9%, 32.0% and 10.7% in the first, second and third stages. Obtained total equivalent strain distributions at the end of the upsetting stages are shown in Figures 4.47 – 4.49. Equivalent stress and temperature distributions after cooling stage are shown in Figures 4.50 and 4.51.

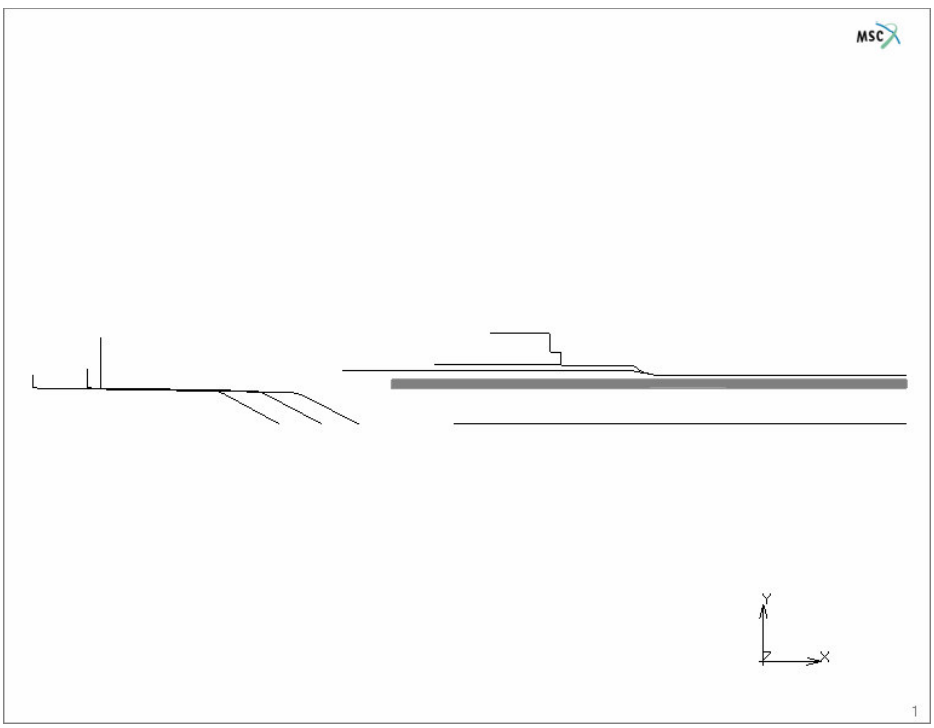


Figure 4.46. *Finite element model for procedure II*

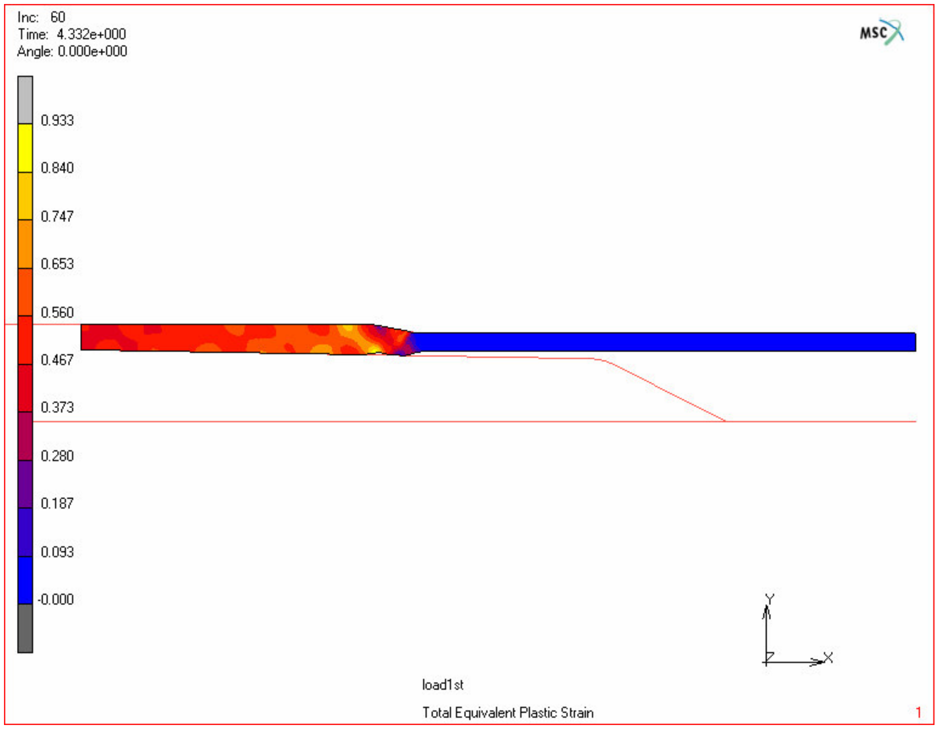


Figure 4.47. *Total equivalent plastic strain distribution after 1st stage*

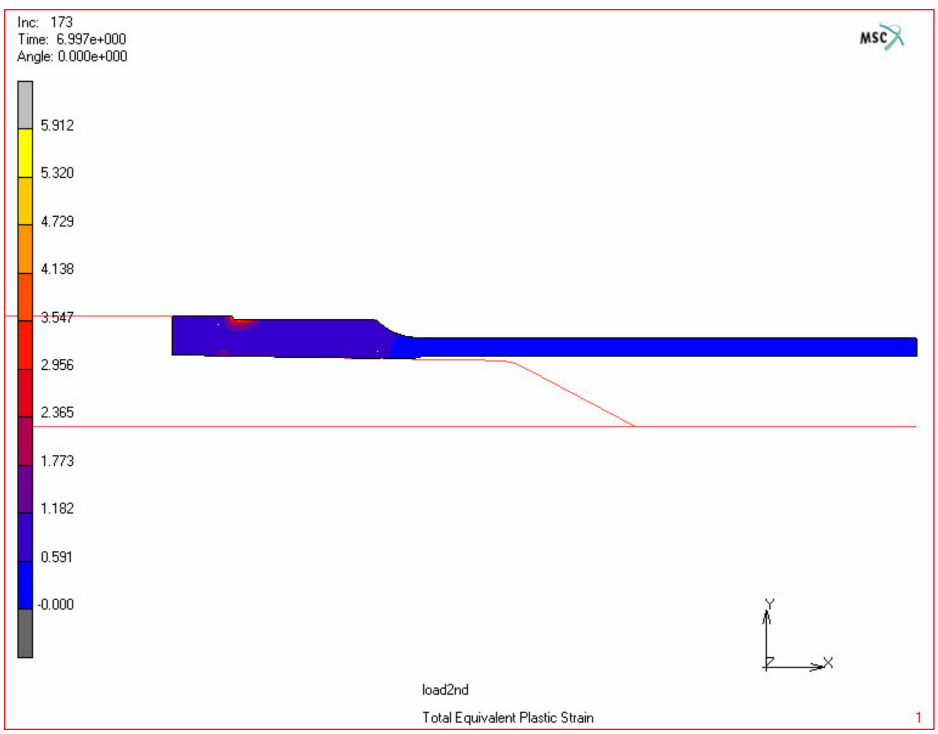


Figure 4.48. *Total equivalent plastic strain distribution after 2nd stage*

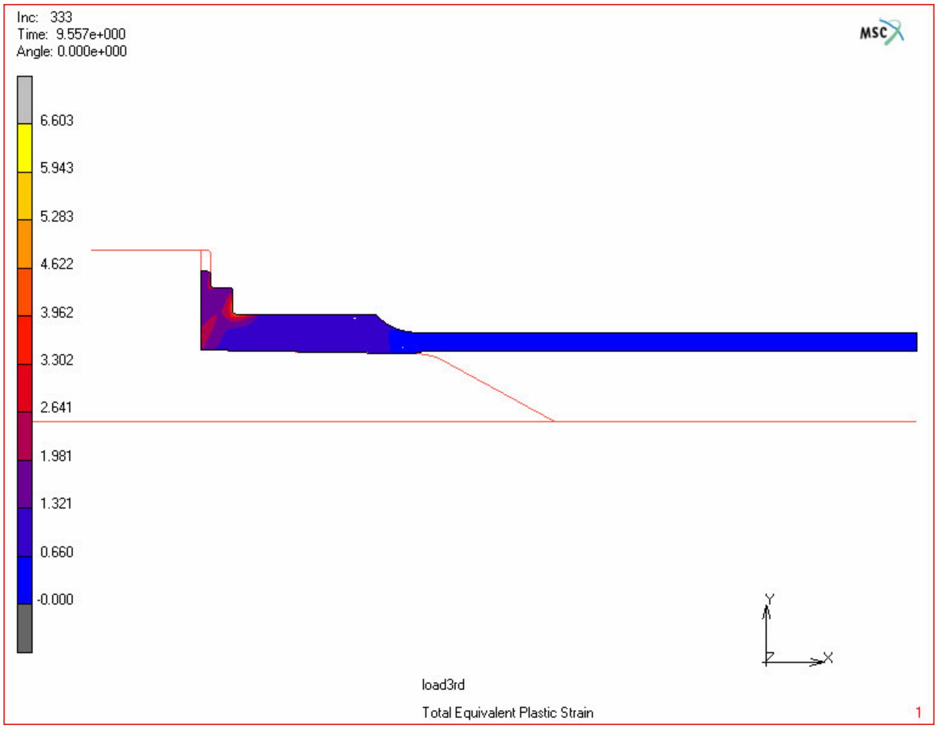


Figure 4.49. *Total equivalent plastic strain distribution after 3rd stage*

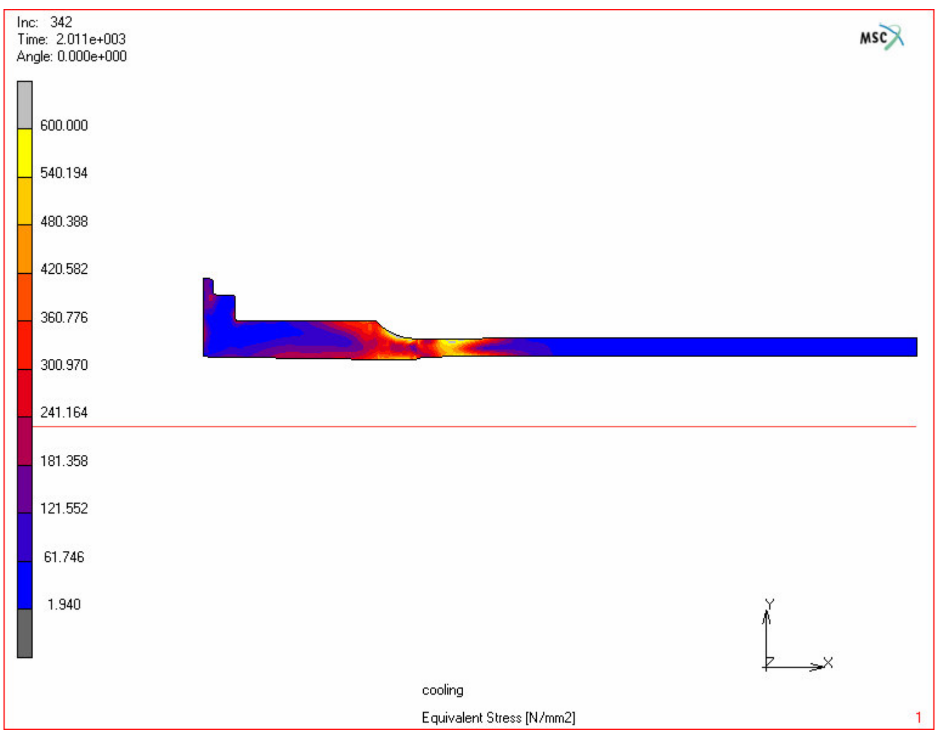


Figure 4.50. *Equivalent stress distribution after cooling (MPa)*

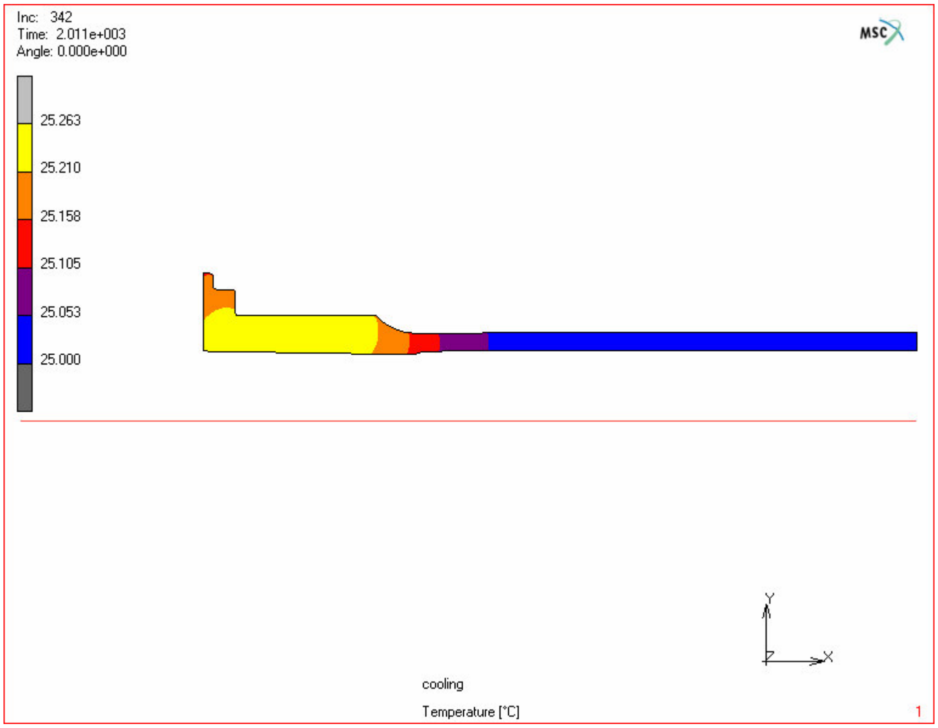


Figure 4.51. *Temperature distribution after cooling (°C)*

When the results of the analyses for procedure I and II are compared, it is observed that, the stresses are concentrated on the transition between the heated zone and the shank part of the final product. However, the Procedure II is advantegous due to reduction in the required die number to complete the process. Additionally, the residual stress values in the procedure I are smaller than the values in the procedure II as shown in Figures 4.41 and 4.50.

CHAPTER 5

THE ANALYSIS OF EXTERNAL AND INTERNAL TUBE UPSETTING

In Case Study II, as shown in Figure 5.1, finite element analysis of a part which requires internal upsetting at the right hand side and external upsetting at the left hand side is done. The sequence and die design of the part have been performed by Karavelioğlu [3] by using the procedure II which has been described in Chapter 2.

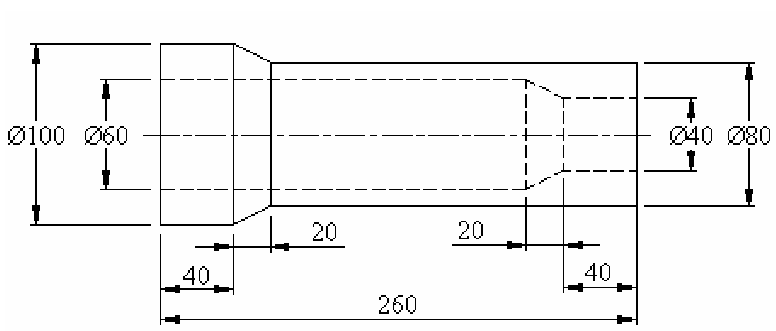


Figure 5.1. *A part requiring upsetting at both ends [3]*

5.1. Sequence and Die Design

Length of the required initial workpiece is determined as 368.07 mm by volume constancy as shown in Figure 5.2. Flash width, f_w, and flash thickness, f_t, are taken as 12 mm and 2.5 mm respectively according to Table 2.5. By applying the sequence design rules for the procedure II, the number of stages to produce the proposed forging is determined as 3. In the first stage, internal upsetting for the right side of the forging is performed. At the remaining two stages, the left side of the forging is completed by external upsetting. The overall wall thickness ratios are determined as 2 for both internal and external upsetting cases by using Equation 2.4. Shapes of the part at the stages one and two are shown in Figures 5.3 and 5.4 whereas the shape of the part at the last stage is the same as the proposed forging, which is shown in Figure 5.1.

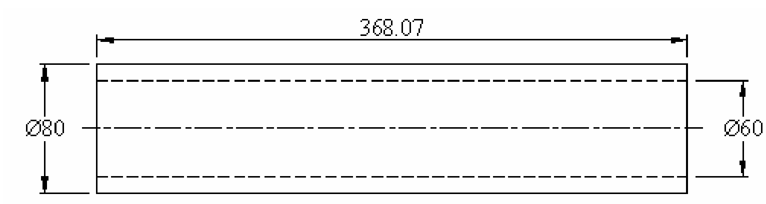


Figure 5.2. *Required initial tube for upsetting [3]*

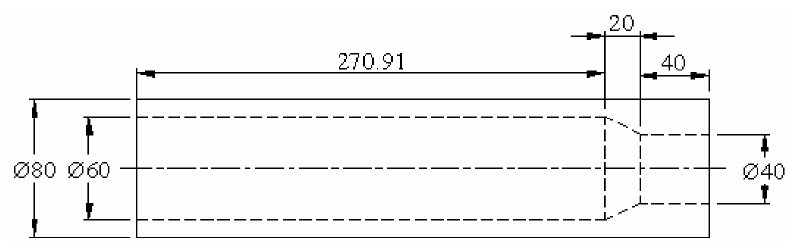


Figure 5.3. *Shape of part for stage 1 [3]*

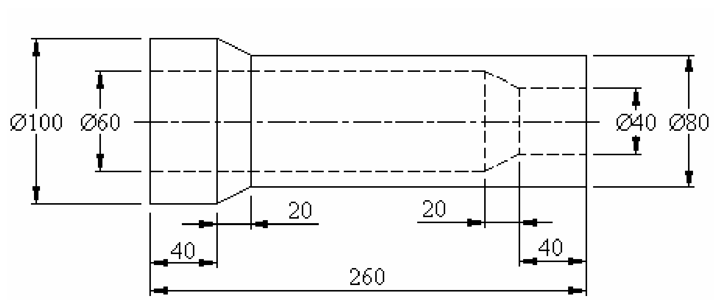


Figure 5.4. *Shape of part for stage 2 [3]*

In the design of header tools, 1° draft angle is used [3]. The workpiece is heated before the first and second stages. Therefore, 1.5% contraction allowance is used in the design of dies for both stages. However, in the third stage 1.35% contraction allowance is applied to allow progressive cooling. The designed dies are shown in Figures 5.5, 5.6 and 5.7.

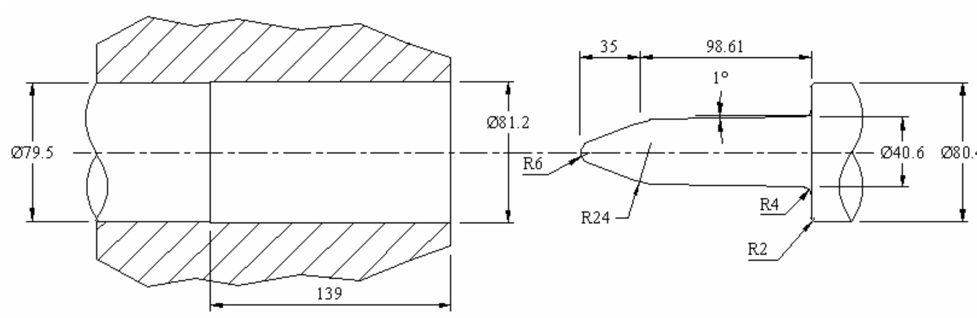


Figure 5.5. *Header tool and gripper die of 1st stage [3]*

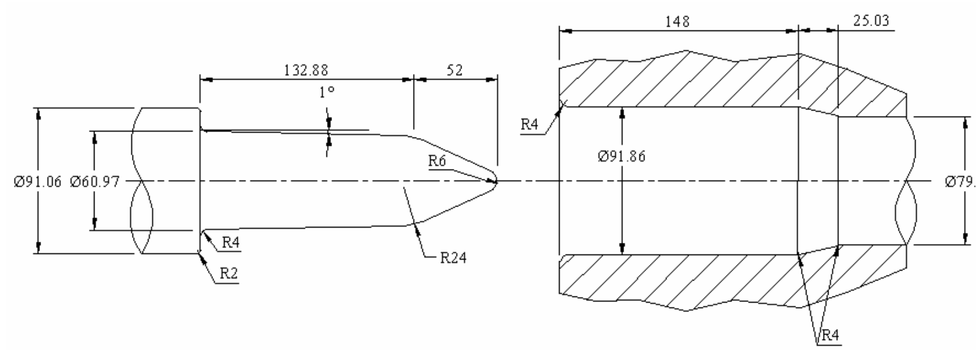


Figure 5.6. *Header tool and gripper die of 2nd stage [3]*

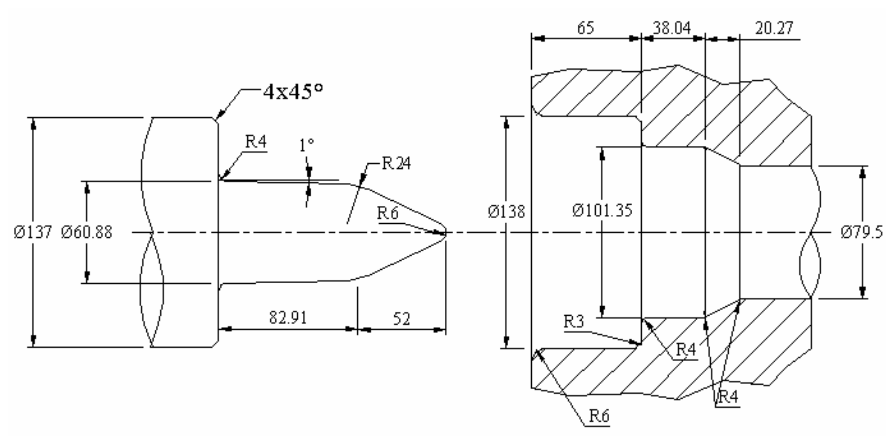


Figure 5.7. *Header tool and gripper die of 3rd stage [3]*

5.2. Finite Element Analysis

The analysis is performed with axi-symmetric elements of type 10 of MSC.Superform. The geometry used in the analysis is shown in Figure 5.8. The workpiece is meshed with 2352 axi-symmetric quadrilateral elements. Element size is chosen as 1.25 mm which results in eight element layers through the tube wall thickness. Header tools and gripper dies are modeled as rigid bodies and shown with lines only.

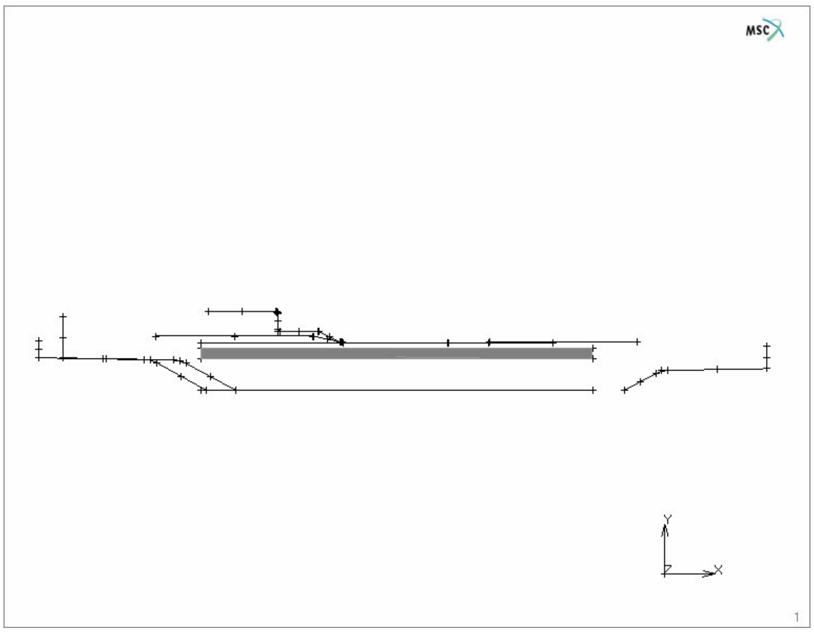


Figure 5.8. *Geometric model of the process*

In the analysis, firstly the workpiece is heated up to 1200 °C by applying boundary conditions as explained in Chapter 4. Then, the workpiece is held by the movement of the first gripper die in –y direction. Diameter of the workpiece is reduced from 80 mm to 79.5 mm by sequezing.

5.2.1. Deformation of the Tube

After the workpiece is held by gripper dies, the header tool is moved toward the workpiece. The length of the first deformation zone, which is for internal upsetting of the workpiece, is reduced by 38.2% in the first stages. The length reduction ratios for the second deformation zone, which is for external upsetting, at the second and third stages are 37.5% and 26.7%. Total equivalent plastic strain distributions after the stages have been completed are shown in Figures 5.9, 5.10 and 5.11.

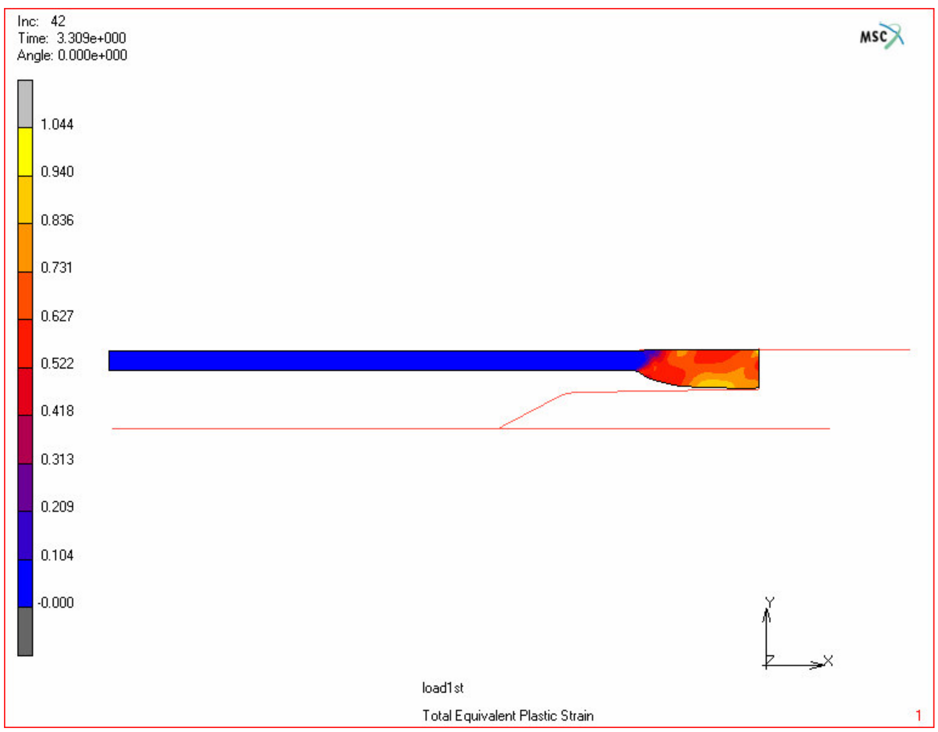


Figure 5.9. *Total equivalent plastic strain distribution after 1st stage*

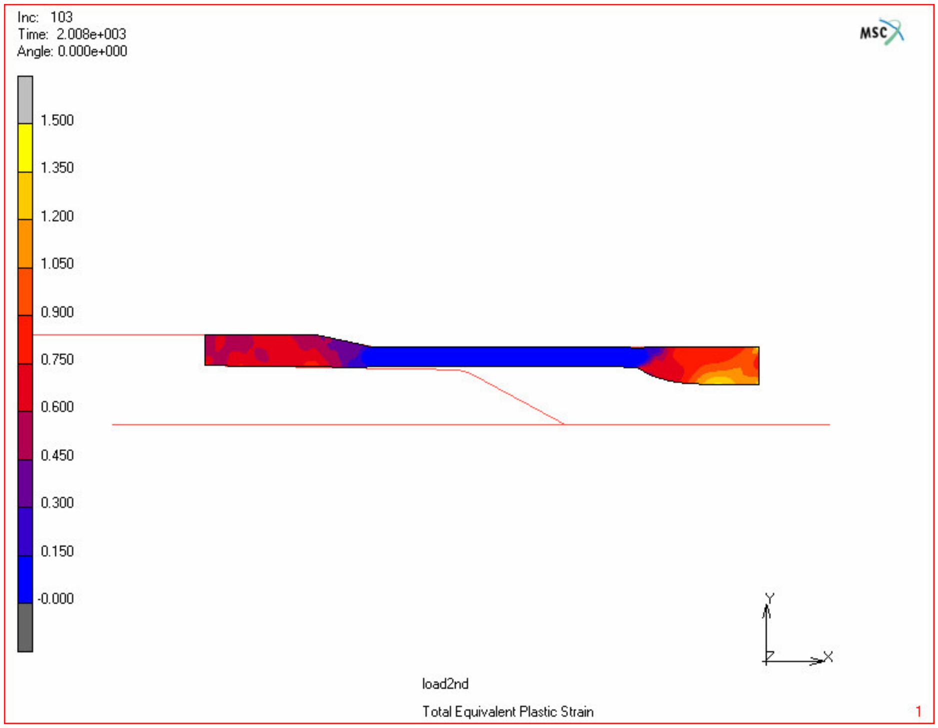


Figure 5.10. *Total equivalent plastic strain distribution after 2nd stage*

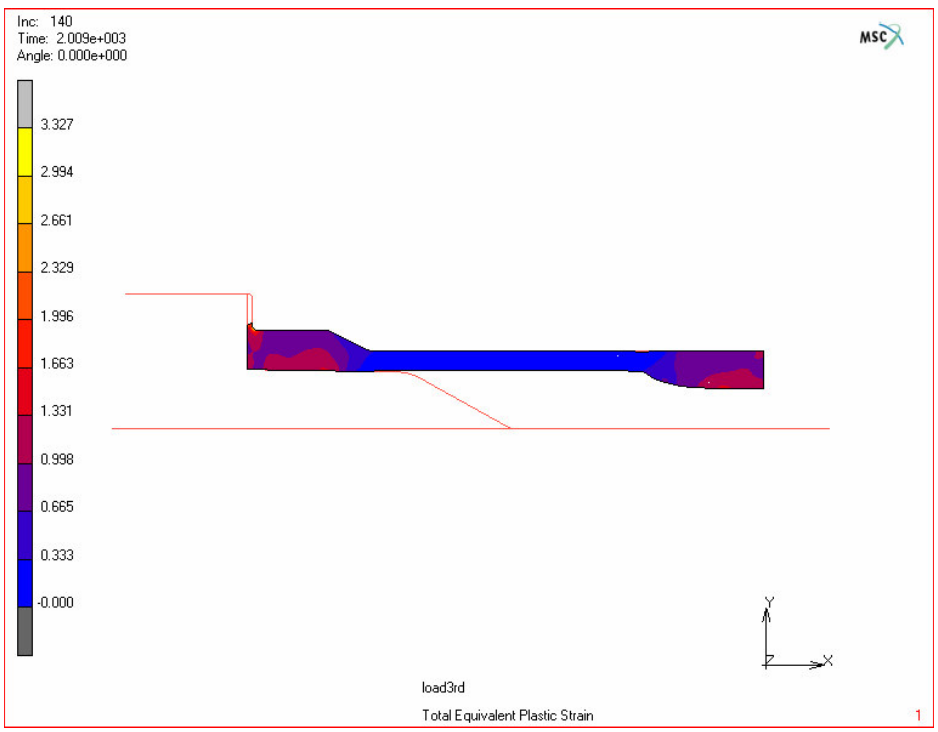


Figure 5.11. *Total equivalent plastic strain distribution after 3rd stage*

5.2.2. Cooling of the Tube

After the forging operation has been completed, the tube is cooled to the room temperature. In the cooling analysis, the tube is kept at 25°C surrounding temperature until it cools down to the room temperature. Temperature distribution after the cooling analysis is shown in Figure 5.12. Total equivalent plastic strain and equivalent stress distributions after the process are shown in Figures 5.13 and 5.14.

The workpiece completely filled the die cavities during the analysis as shown in Figures 5.9 – 5.11. The maximum stresses are concentrated at the transition region, where the one side is deformed and the other side is undeformed, as shown in Figure 5.14.

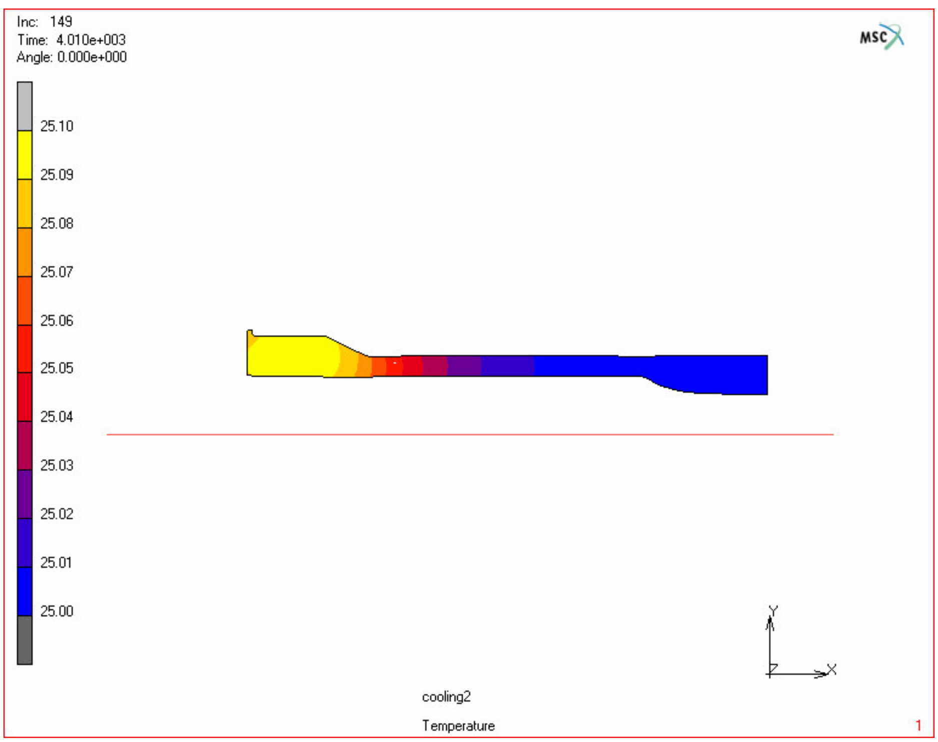


Figure 5.12. *Temperature distribution after cooling stage (°C)*

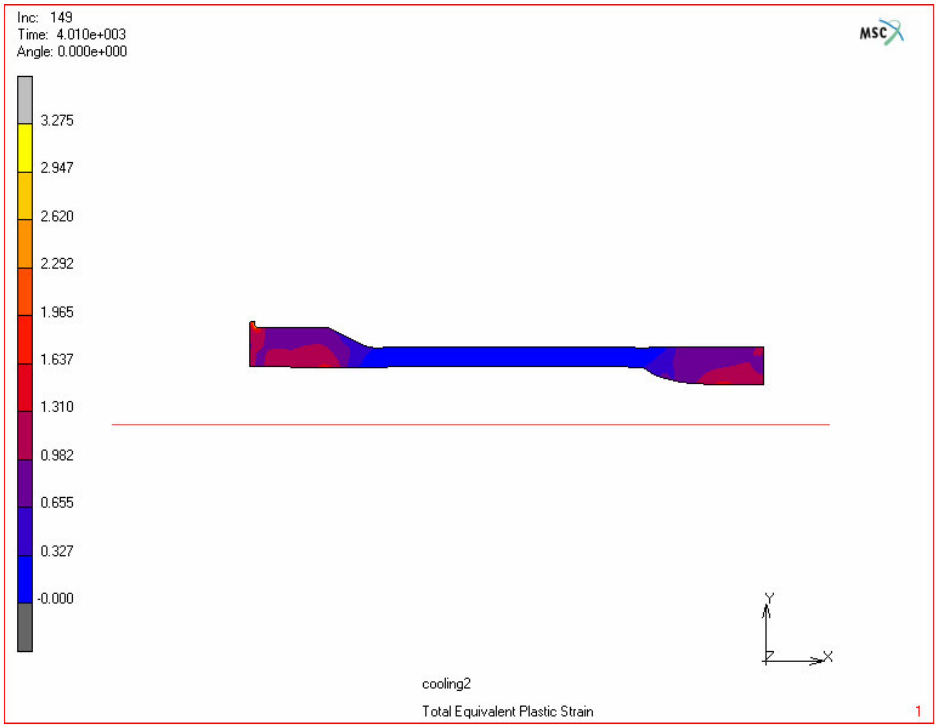


Figure 5.13. *Total equivalent plastic strain distribution after cooling*

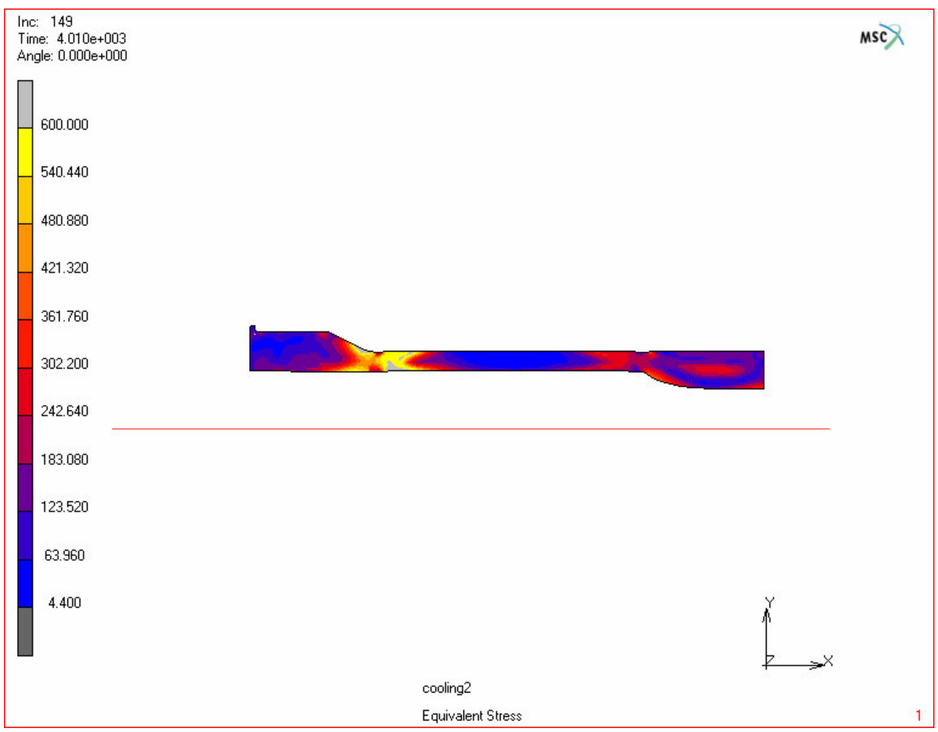


Figure 5.14. *Equivalent stress distribution after cooling (MPa)*

CHAPTER 6

THE ANALYSIS OF SIMULTANEOUS INTERNAL AND EXTERNAL TUBE UPSETTING

In case III, as shown in Figure 6.1, finite element analysis of the part, which requires simultaneous internal and external upsetting at the left hand side, is done. The sequence and die design of the part have been performed by Karavelioğlu [3] by using the procedure I, which is described in Chapter 2.

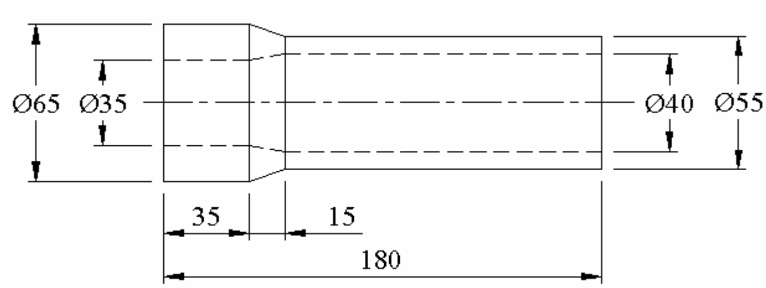


Figure 6.1. *A part requiring upsetting at both ends [3]*

6.1. Sequence and Die Design

Length of the required initial workpiece is determined as 228.86 mm by volume constancy as shown in Figure 6.2. By applying the sequence design rules for the procedure I, the number of stages to produce the proposed forging is determined as 2. The equalized wall thickness ratio is calculated as 1.42 and applied to both stages. Shape of the part at the first stage is shown in Figures 6.3

whereas shape of the part at the last stage is the same as proposed forging, which is shown in Figure 6.1.

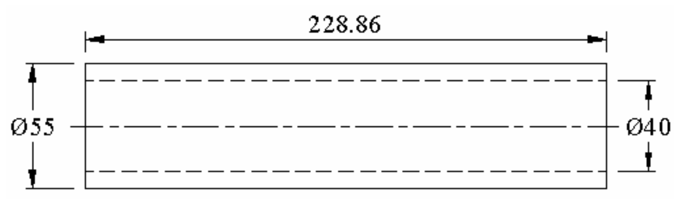


Figure 6.2. *Required initial tube for upsetting [3]*

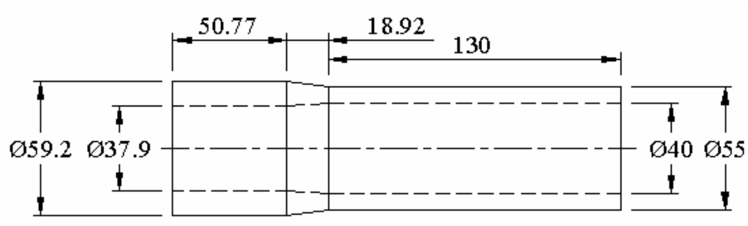


Figure 6.3. *Shape of part for stage 1 [3]*

In the design of header tool, 1° draft angle is used [3]. The workpiece is heated before the first stage. Therefore, 1.5% contraction allowance is used in the design of dies. However, in the second stage 1.35% contraction allowance is applied to allow progressive cooling. The designed dies are shown in Figures 6.4 and 6.5.

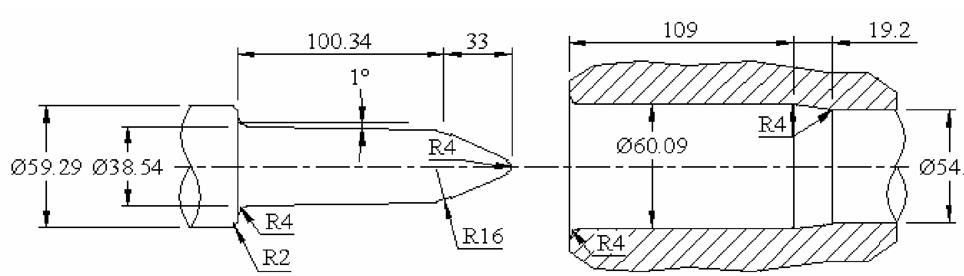


Figure 6.4. *Header tool and gripper die of 1st stage [3]*

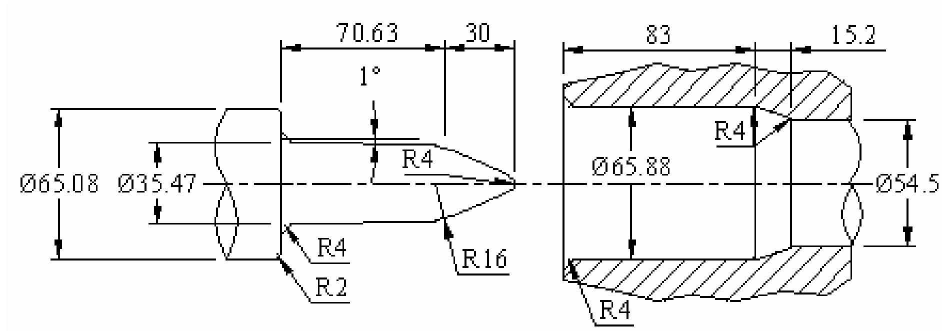


Figure 6.5. *Header tool and gripper die of 2nd stage [3]*

6.2. Finite Element Analysis

The analysis is performed with axi-symmetric elements of type 10 of MSC.Superform. The geometry used in the analysis is shown in Figure 6.6. The workpiece is meshed with 1098 axi-symmetric quadrilateral elements. Element size is chosen as 1.25 mm which results in six element layers through the tube wall thickness. The header tools and gripper dies are modeled as rigid bodies and shown with lines only.

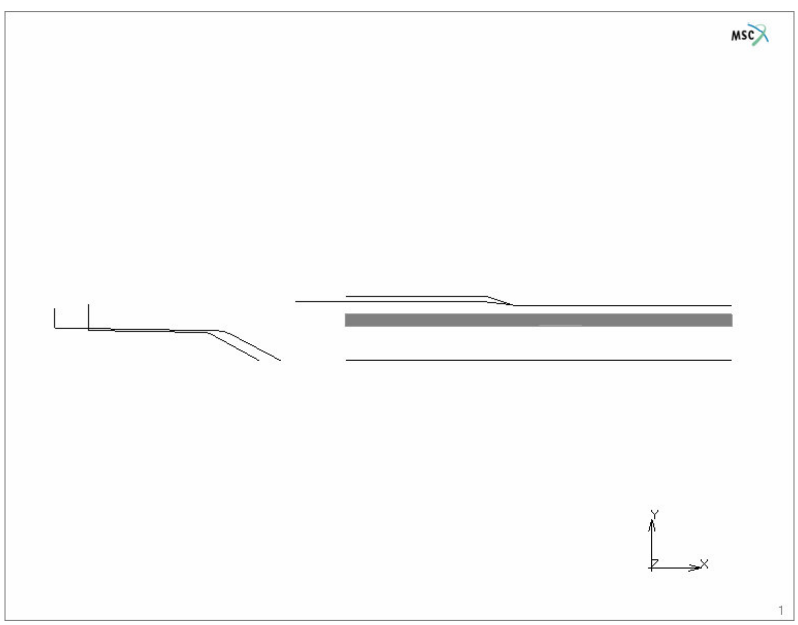


Figure 6.6. *Geometric model of the process*

In the analysis, firstly the workpiece is heated up to 1200 °C by applying boundary conditions as explained in Chapter 4. Then, the workpiece is held by the movement of the first gripper die in –y direction. Diameter of the workpiece is reduced from 55 mm to 54.5 mm by sequezing.

6.2.1. Deformation of the Tube

After the workpiece is held by gripper dies, the header tool is moved toward the workpiece. The length of the first deformation zone is reduced by 29.5% in the first stage. The length reduction ratio for the second stage is 28.3%. Total equivalent plastic strain distributions after the stages completed are shown in Figures 6.7 and 6.8.

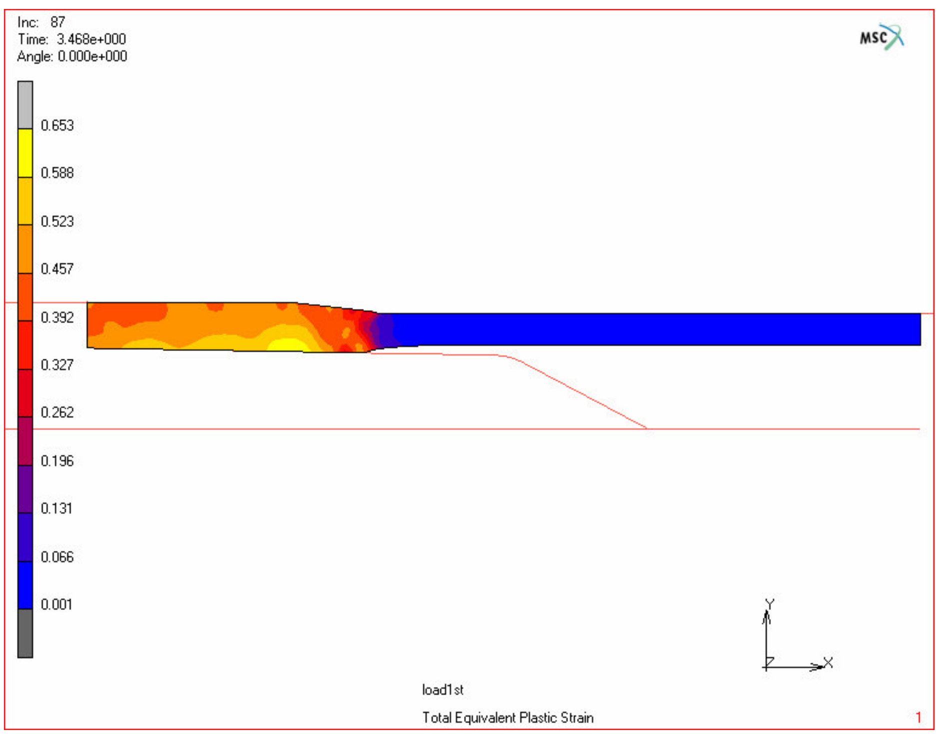


Figure 6.7. *Total equivalent plastic strain distribution after 1st stage*

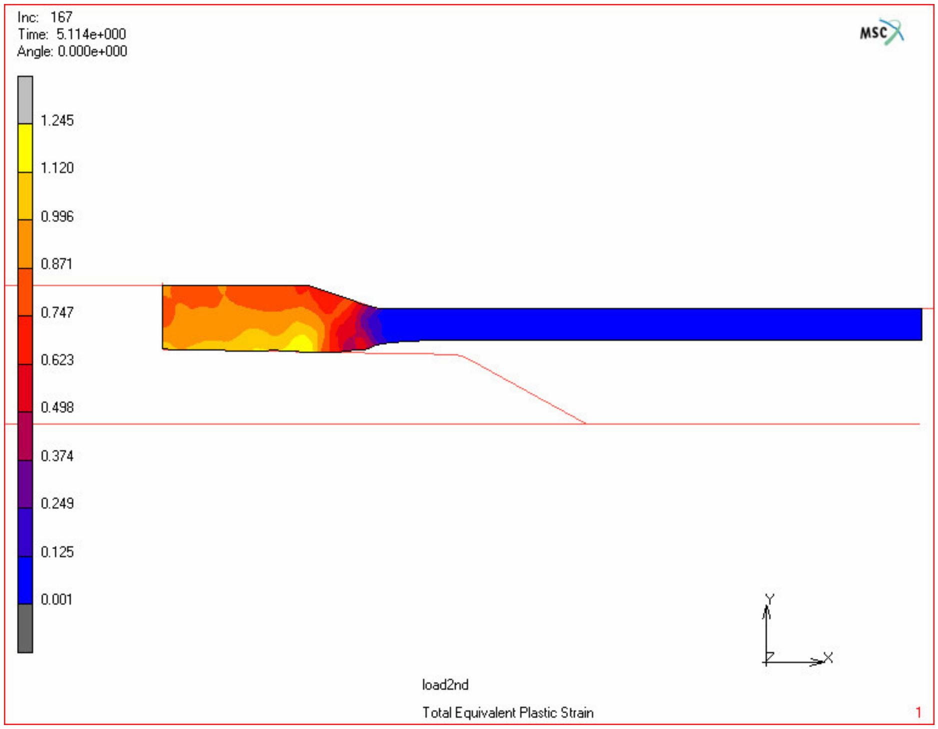


Figure 6.8. *Total equivalent plastic strain distribution after 2nd stage*

6.2.2. Cooling of the Tube

After the forging operation has been completed, the tube is cooled to the room temperature. In the cooling analysis, the tube is kept at 25°C surrounding temperature until it cools down to the room temperature. Temperature distribution after the cooling analysis is shown in Figure 6.9. Total equivalent plastic strain and equivalent stress distributions after the process are shown in Figures 6.10 and 6.11.

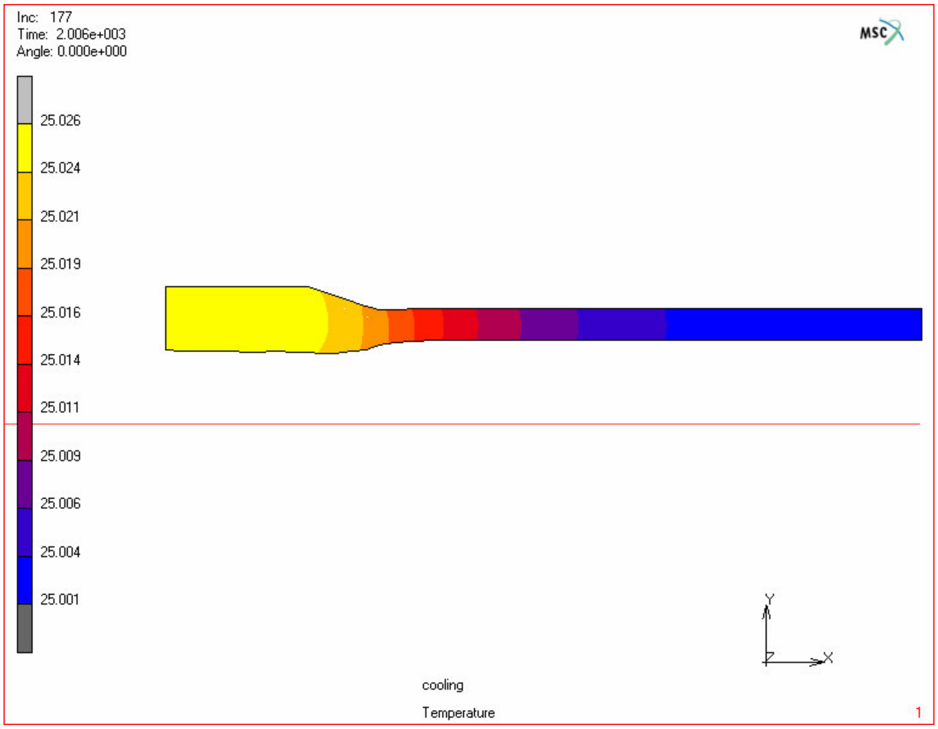


Figure 6.9. *Temperature distribution after cooling stage (°C)*

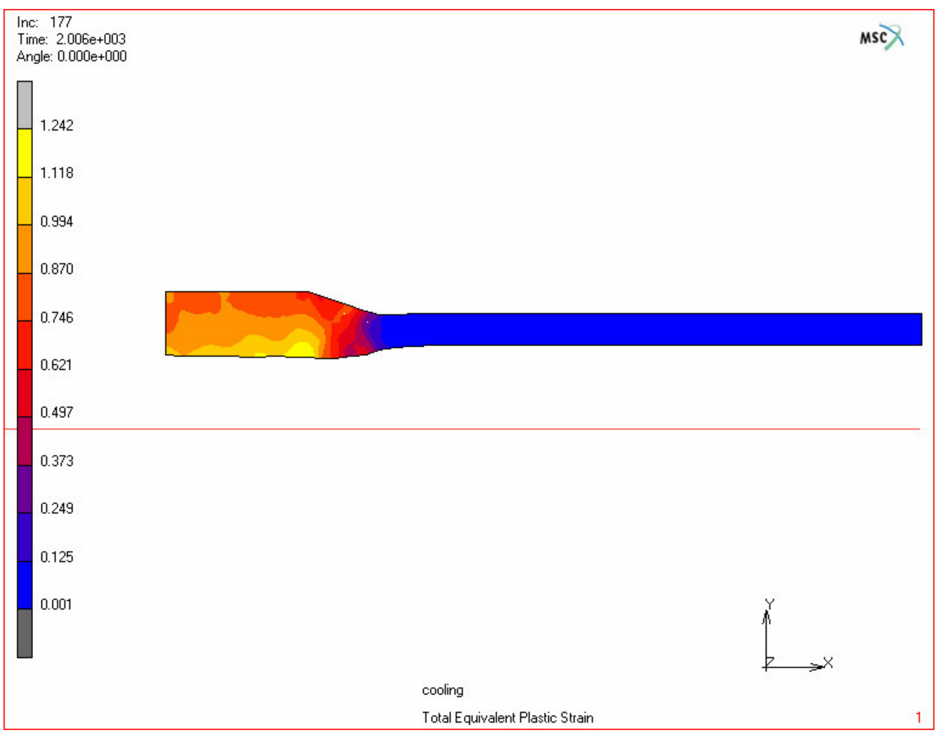


Figure 6.10. *Total equivalent plastic strain distribution after cooling*

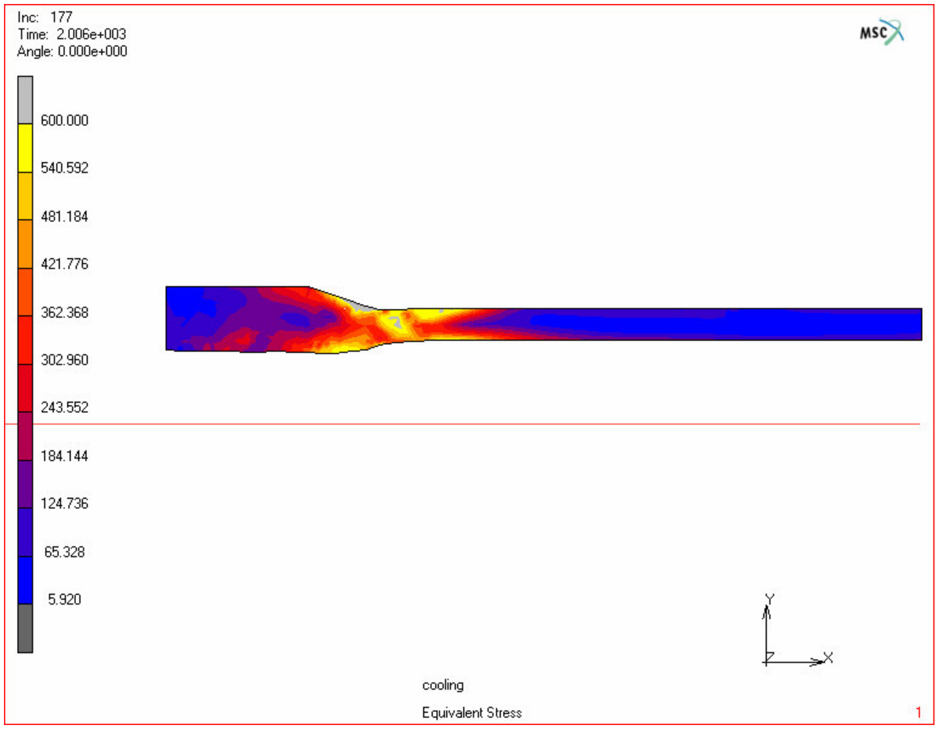


Figure 6.11. *Equivalent stress distribution after cooling (MPa)*

The workpiece completely filled the die cavities during the analysis as shown in Figures 6.7 and 6.8. The maximum stresses are concentrated at the transition region, where the one side is deformed and the other side is undeformed, as shown in Figure 6.11. As shown in Figure 6.11, the internal profile of the obtained forging is different from the proposed forging shape due to the draft angle in the header tools.

CHAPTER 7

THE ANALYSIS OF TUBE EXPANDING

In case study IV, as shown in Figure 7.1, the part requires tube expanding at the left hand side. The sequence and die design of the part have been performed by Karavelioğlu [3] by using the procedure II, which is described in Chapter 2.

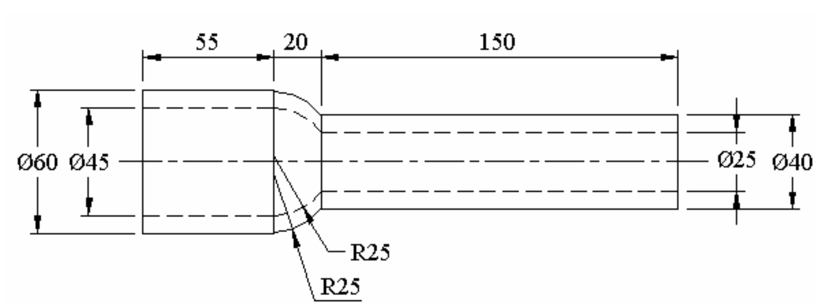


Figure 7.1. *A part requiring upsetting at both ends [3]*

7.1. Sequence and Die Design

Length of the required initial workpiece is determined as 228.86 mm by volume constancy as shown in Figure 7.2. By applying the sequence design rules for the procedure II, the number of stages to produce the proposed forging is determined as 2. Shape of the part at the first stage is shown in Figures 7.3

whereas the shape of the part at the last stage is the same as the proposed forging, which is shown in Figure 7.1.

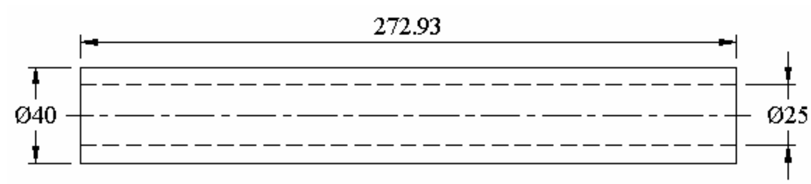


Figure 7.2. *Required initial tube for upsetting [3]*

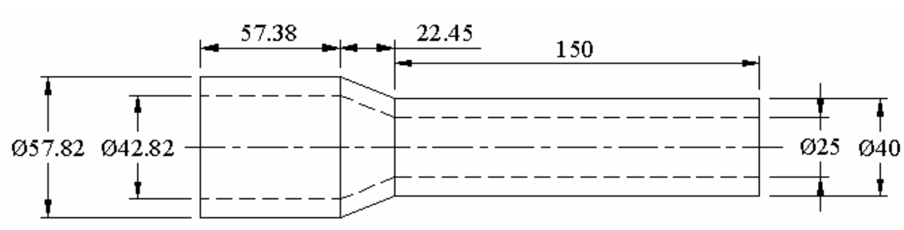


Figure 7.3. *Shape of part for stage 1 [3]*

In the design of header tool, 1° draft angle is used [3]. The workpiece is heated before the first stage. Therefore, 1.5% contraction allowance is applied in the design of dies. However, in the second stage 1.35% contraction allowance is used to allow progressive cooling. The designed dies are shown in Figures 7.4 and 7.5.

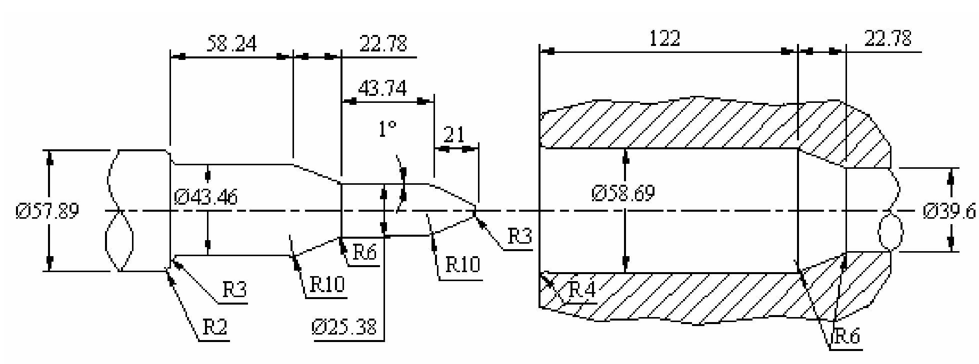


Figure 7.4. *Header tool and gripper die of 1st stage [3]*

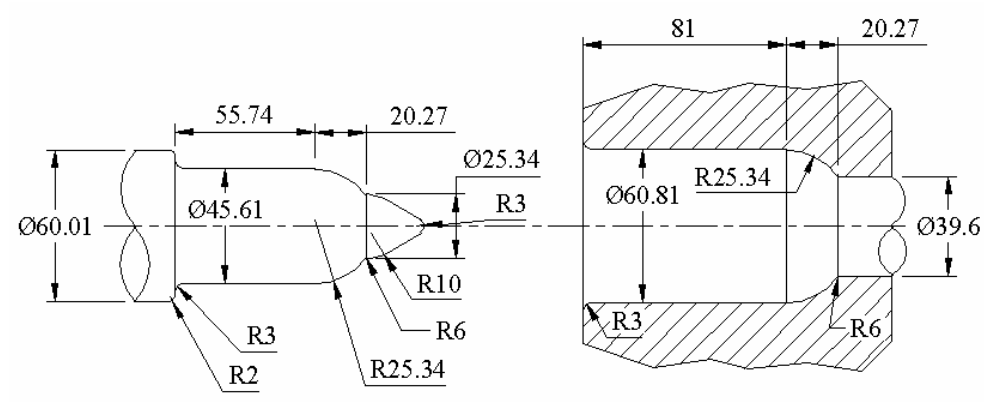


Figure 7.5. *Header tool and gripper die of 2nd stage [3]*

7.2. Finite Element Analysis

The analysis is performed with axi-symmetric elements of type 10 of MSC.Superform. The geometry used in the analysis is shown in Figure 7.6. The workpiece is meshed with 1308 axi-symmetric quadrilateral elements. Element size is chosen as 1.25 mm which results in six element layers through the tube wall thickness. The header tools and gripper dies are modeled as rigid bodies and shown with lines only.

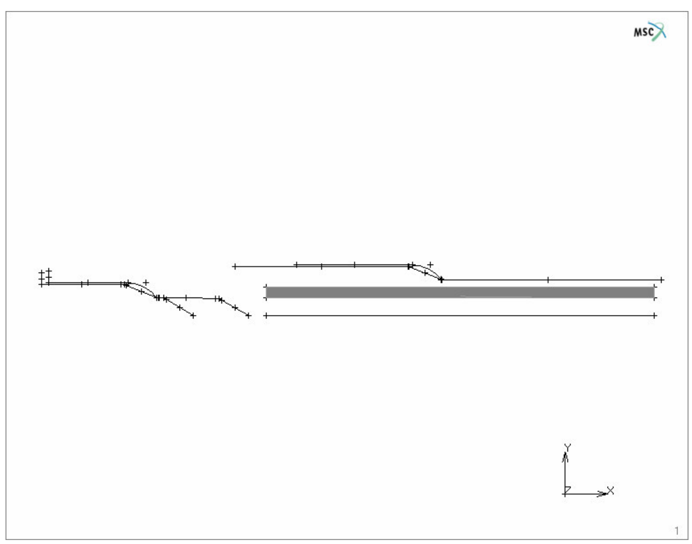


Figure 7.6. *Geometric model of the process*

In the analysis, firstly the workpiece is heated up to 1200 °C by applying boundary conditions as explained in Chapter 4. Then, the workpiece is held by the movement of the first gripper die in –y direction. Diameter of the workpiece is reduced from 40 mm to 39.6 mm by sequezing.

7.2.1. Deformation of the Tube

After the workpiece is held by gripper dies, the header tool is moved toward the workpiece. The length of the first deformation zone is reduced by 35.1% in the first stages. The length reduction ratio for the second stage is 6.1%. Total equivalent plastic strain distributions after the stages completed are shown in Figures 7.7 and 7.8.

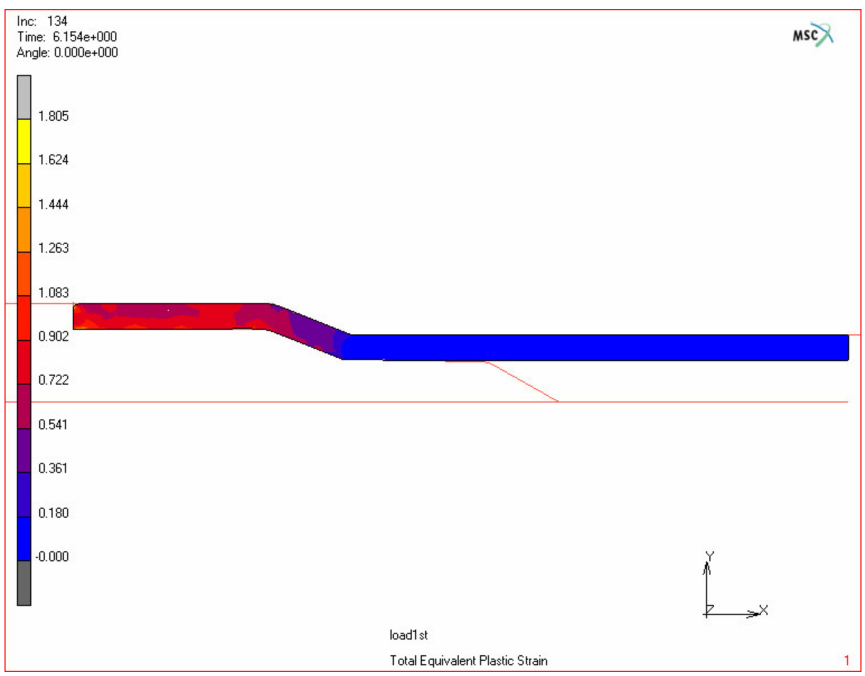


Figure 7.7. *Total equivalent plastic strain distribution after 1st stage*

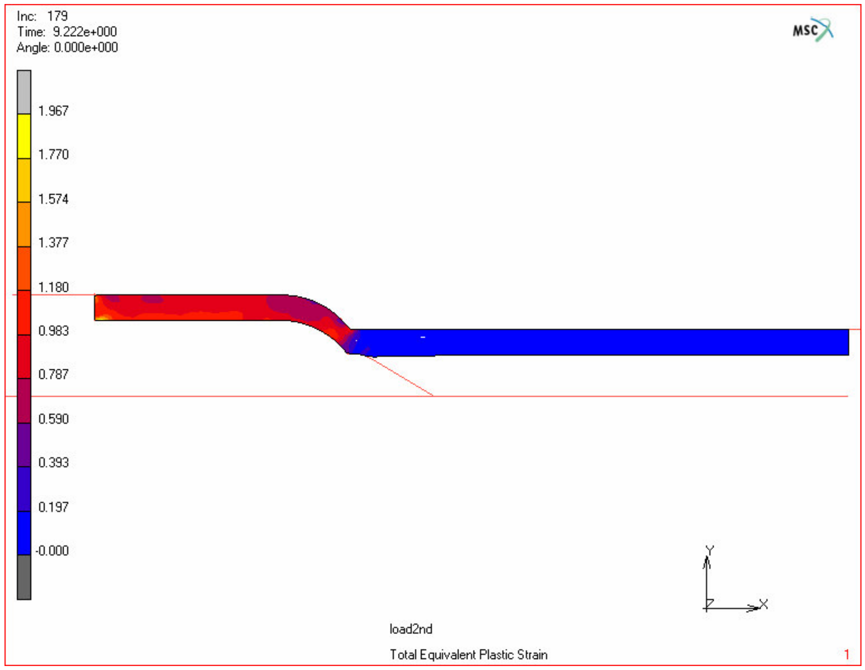


Figure 7.8. *Total equivalent plastic strain distribution after 2nd stage*

7.2.2. Cooling of the Tube

After the forging operation has been completed, the tube is cooled to the room temperature. In the cooling analysis, tube is kept at 25°C surrounding temperature until it cools down to the room temperature. Temperature distribution after the cooling analysis is shown in Figure 7.9. Total equivalent plastic strain and equivalent stress distributions after the process is shown in Figures 7.10 and 7.11.

Figure 7.9. *Temperature distribution after cooling stage (°C)*

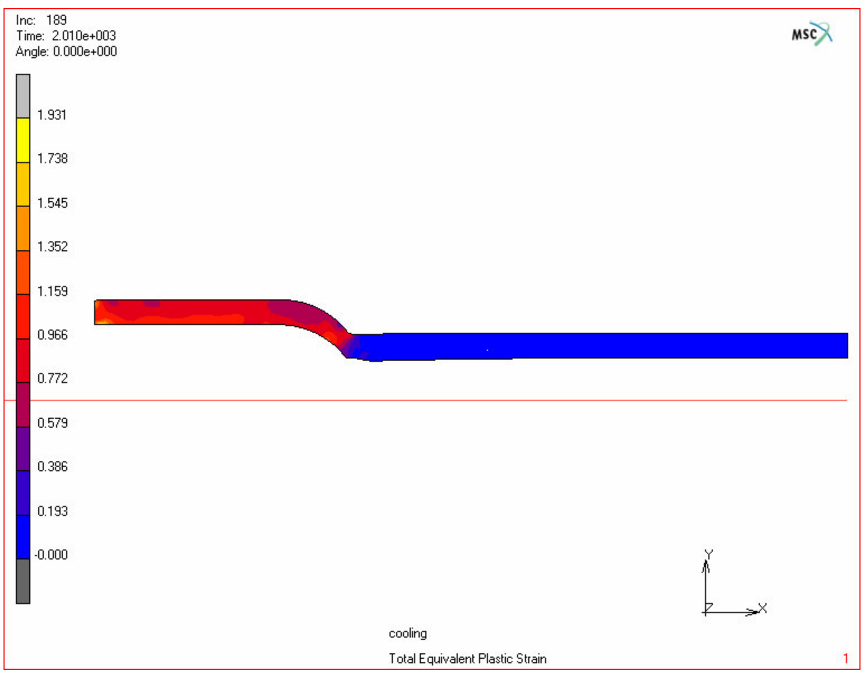


Figure 7.10. *Total equivalent plastic strain distribution after cooling*

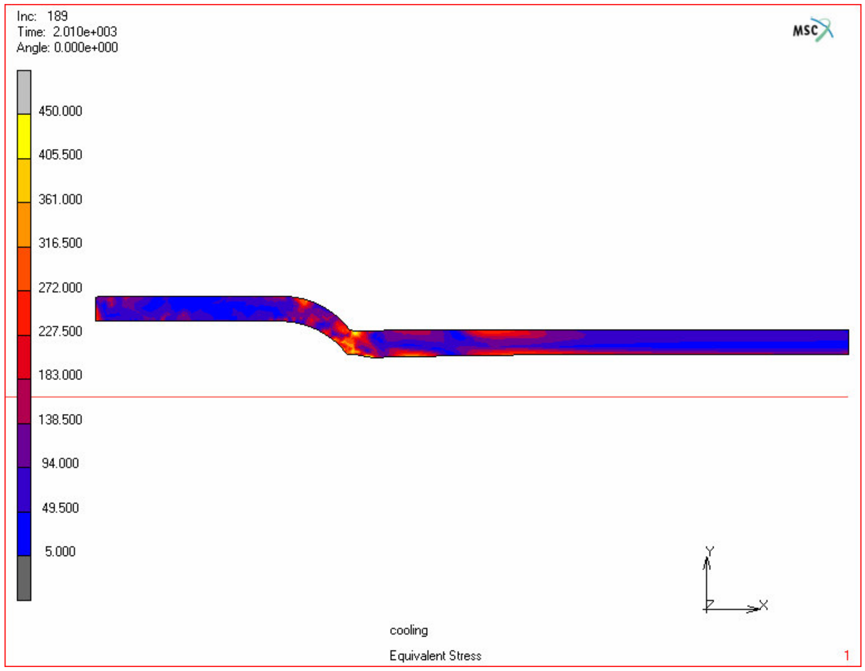


Figure 7.11. *Equivalent stress distribution after cooling (MPa)*

The workpiece completely filled the die cavities during the analysis as shown in Figures 7.7 and 7.8. The maximum stresses are concentrated at the transition region, where the one side is deformed and the other side is undeformed, as shown in Figure 7.11.

CHAPTER 8

DISCUSSION AND CONCLUSION

8.1. General Discussion and Conclusion

The aim of this study is to verify the procedures suggested in the tube upsetting by using finite element analysis. In the thesis, finite element analyses of tube upsetting processes for four different tube upsetting techniques have been completed. These are external, internal, simultaneous internal and ezternal tube upsetting and tube expanding techniques. Several finite element simulations have been completed with different geometries and process parameters; however, some of the analyses are presented in the thesis.

There are two different sequence design procedures proposed [3] as discussed in Chapter 2. The first procedure is based on the maximum allowable increase in wall thickness in each stage. The second procedure is mainly based on the recommendations of Russian Forging Handbook [19]. However, some modifications on the procedure have been done by Karavelioğlu [3].

The sequence and die design based on two procedures for the same forging, which requires external tube upsetting at one end, have been simulated by the finite element software in Chapter 4. The obtained results show that the workpiece completely fills the die cavities in both cases. However, the required numbers of stages are different for the procedures I and II. The first procedure results in four stages and the second procedure results in three stages. In industry, it is always important to minimize the cost of the production. Therefore, the second procedure can be preferred in the production of the part by considering the number of stages. The residual stresses obtained in the analyses of the first procedure are smaller than those obtained in the second procedure. Therefore, the selection of the appropriate procedure should be made carefully by taking also the stress values and other parameters into account.

It has been observed that the success of the tube upsetting process is highly sensitive to the initial volume. A small amount of lack in the volume of the initial tube may cause unfilled regions in the die cavities. In order to observe the volume sensitivity of the process, the volume due to the draft angle was neglected in the initial volume calculations and the finite element analysis, which is not given in the thesis, was performed. 1.72% decrease in the volume of the initial tube have resulted unfilled regions in the die cavities. On the other hand, the excessive volume of the initial tube may cause the forging machine to be overloaded and failed. During the preparation of the initial tube, the dimensions and volumes should be carefully controlled.

In the simulation of external tube upsetting based on procedure I, an unexpected workpiece deformation has been observed during the gripping at the third stage as shown in Figure 4.23. The gripper die deformed the workpiece radially towards the symmetry axis. In order to prevent this, some modifications have been made on the gripper dies of the first and the second stages as explained in Chapter 4. In the sequence design, the external geometries of the part at the intermediate stages should be determined according to the final forging geometry. It is especially important for the forgings, which have concave curved portions on the external surface. In a multi-stage tube upsetting process, deformed shape of the current stage must fit to the gripper dies of the next stage.

In Chapter 5, the finite element analysis of the part, which requires external and internal upsetting, has been performed. The second sequence design procedure had been employed for the part shown in Figure 5.1 by Karavelioğlu [3]. The workpiece completely filled the die cavity in the simulation. However, in the internal tube upsetting stage, the workpiece deformed freely due to the unrestricted heated material inside the tube as seen in Figure 5.9. Due to unrestricted workpiece deformation internally, it is difficult to predict the internal geometry of the forging at the related region. If the shape of the transition region between the different internal diameters is not specifically required, the unrestricted deformation can easily be applied to the workpiece. Otherwise, internal mandrels, applied from the shank side, can be suggested to be employed depending on the forging machine capabilities in order to restrict the material flow internally, and obtain the predefined internal shapes.

The finite element analysis for the simultaneous internal and external tube upsetting has been performed in Chapter 6. The first procedure had been employed for the part shown in Figure 6.1 by Karavelioğlu [3]. The external geometry has been completely obtained while minor changes in the internal geometries due to the unrestricted forming in the internal part of the forging has been observed as seen in Chapter 5.

The analysis of tube expanding process, depending on the procedure I, has been presented in Chapter 7. It has been observed that the die cavities are completely filled at the intermediate stages as shown in Figures 7.7 and 7.8. The wall thickness of the tube decreases as the header tool moves against the workpiece until the instance, when the header tool touches to the end of the tube, and the wall thickness increases to the original value by upsetting. It has been shown by the finite element simulation that it is possible to decrease the wall thickness of a tube while increasing internal and external diameters by using proper header tools and gripper dies by using the volume constancy.

In all the finite element simulations performed, the draft angles on the header tools cause tapered holes on the final products. During the part design, this should be taken into account accordingly.

The stress distributions obtained in the analyses show that there exist high residual stresses in the transition region between the deformed portions and the shank of the forging. These high residual stresses are due to heat gradient and plastic deformation. For example, at the end of the deformation stages, the temperature of the deformed part is about 800°C and the temperature at the shank is about 25 °C for the external tube upsetting case study as given in Chapter 4. Stress relieving operations may be performed in order to get rid of the residual stress, if required.

The geometry of the parts, the punch loading, heating and cooling conditions are all appropriate for an axi-symmetric analysis except the gripping action. In order to verify the axi-symmetric loading assumption for simulating the gripping action, a three dimensional analysis is performed in Appendix A and the results obtained from the axi-symmetric and three dimensional approaches are compared. Since the results are found close to each other and the shank region has no significant effect on the deformation, axi-symmetrical analyses have been performed in the study.

In the finite element analyses of the tube upsetting processes, MSC.Superform software has been employed. It has been seen that the software is effective in simulating the forging processes. Especially, in tube upsetting process, it is recommended to apply computer based numerical analysis, such as, finite element and finite volume methods, to see the success of the process before producing the dies and applying in the industry to prevent waste of material, time, labor and decrease cost.

8.2. Recommendation for Future Studies

Recommendations for future studies related with this thesis can be summarized as follows;

1. In order to verify the results of numerical solution, experimental studies can be performed.

2. Process limitations of the tube upsetting, such as; maximum wall thickness increase in one stage, can be studied by finite element method.

3. Finite element analysis of dies used in tube upsetting can be performed.

4. Effect of forging parameters, such as; temperature, forging speed, friction, wear, etc., on the workpiece can be analyzed.

5. Finite element analysis of warm and cold tube upsetting can be studied.

6. For internal tube upsetting, the design of mandrels can be studied.

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APPENDIX A

FINITE ELEMENT ANALYSIS OF THE GRIPPING ACTION

During gripping action, shank of the tube is squeezed between two gripper dies and fixed against the header tool movement by friction. In this thesis, axi-symmetric elements have been preferred in the finite element analyses. However, the deformation during gripping is not axi-symmetric. Hence, the validity of applying axi-symmetric gripping force should be analyzed. For this purpose, two different approaches have been applied; the three dimensional and axi-symmetric modeling of the shank.

In the three dimensional analysis, initial tube is meshed with 13800 full integration hexahedron elements as shown in Figure A.1. There are 20880 nodes in the mesh. The outer diameter of the initial tube is 100 mm and the gripping diameter of the gripper dies is 99.5 mm as suggested in [3]. C35 steel is used for material. Elastic-plastic material approach is used. Shank part of the tube is not heated and remains almost cold. Therefore, the analysis is performed with constant temperature initial condition assumption and 25°C is assigned to 20880 nodes as initial condition.

One of the gripper dies is kept fixed and the other is moved against the workpiece in gripping direction with 100 mm/s velocity. For the contacting surfaces, the shear friction coefficient is set as 0.2 [19]. Figure A.1 shows the finite element mesh used in the analysis and the rigid gripping dies.

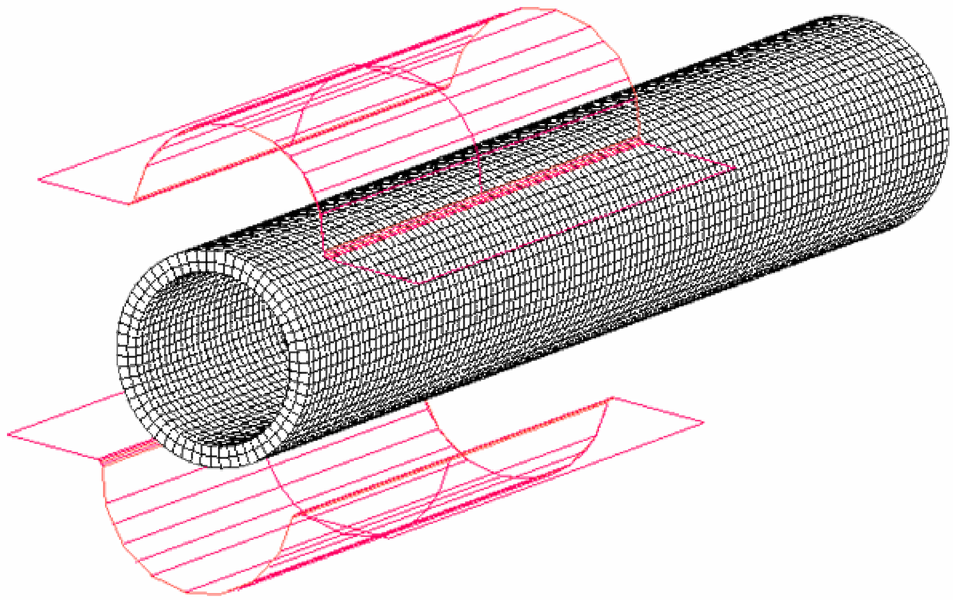

Figure A.1. *Finite element mesh of initial tube*

Figure A.2 and Figure A.3 shows total equivalent plastic strain distribution during gripping and after the tools are removed. As can be seen from the results there is negligible plastic deformation at the workpiece. Stress distribution during gripping and after the tools removal can be seen from the Figures A.4 and A.5 respectively.

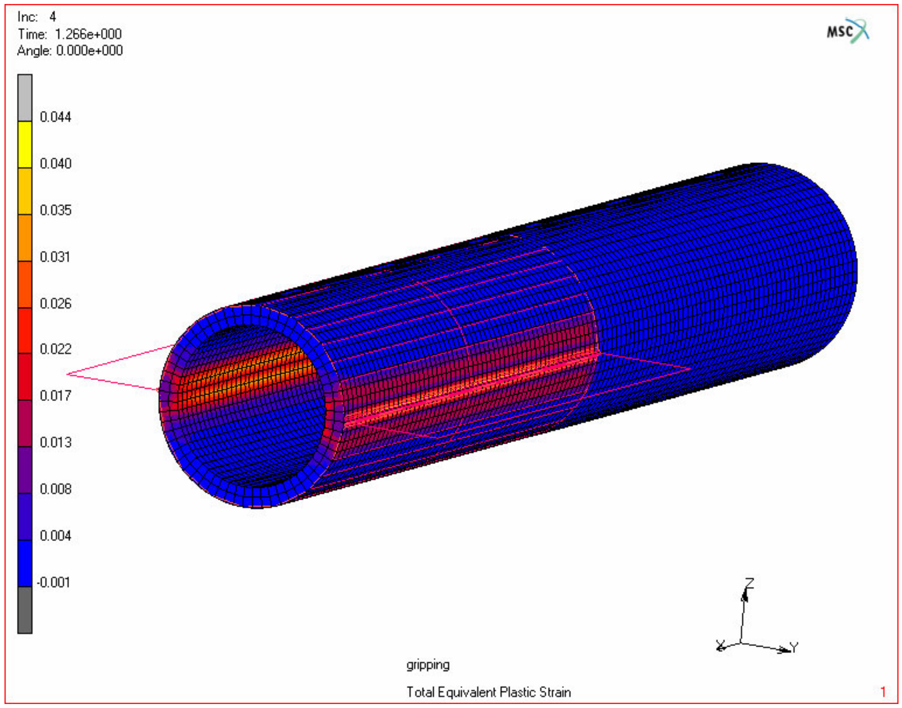

Figure A.2. *Total equivalent plastic strain distribution at the end of gripping*

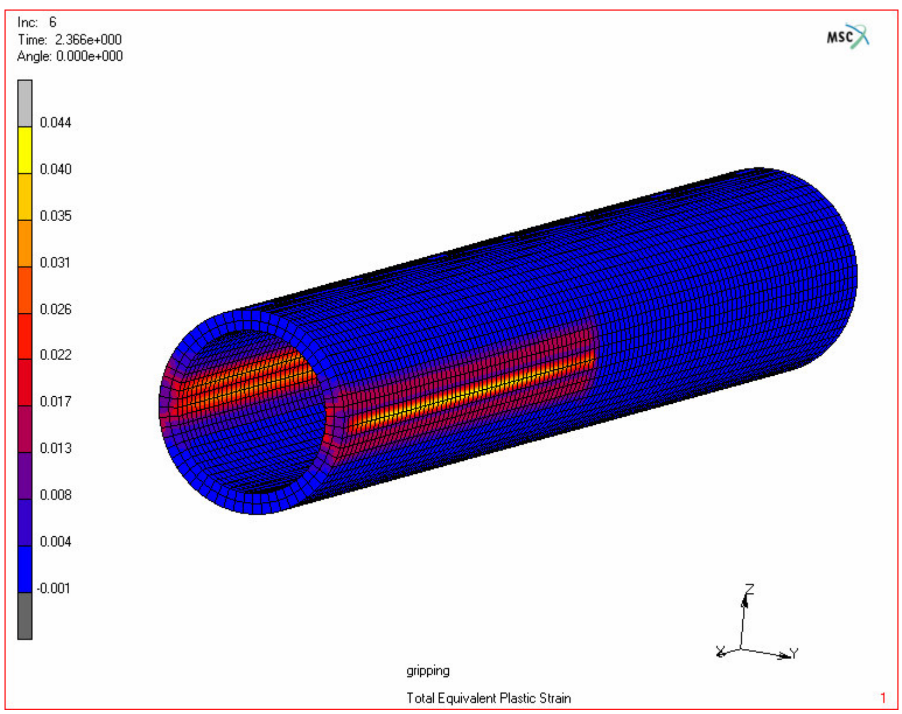

Figure A.3. *Total equivalent plastic strain distribution after tools are removed*

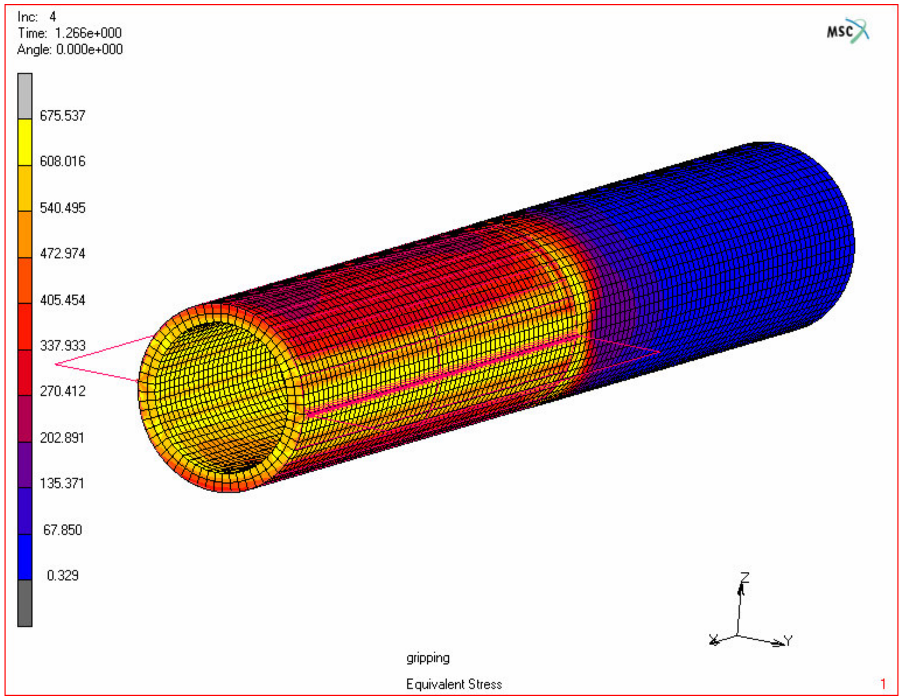

Figure A.4. *Equivalent stress distribution during gripping (MPa)*

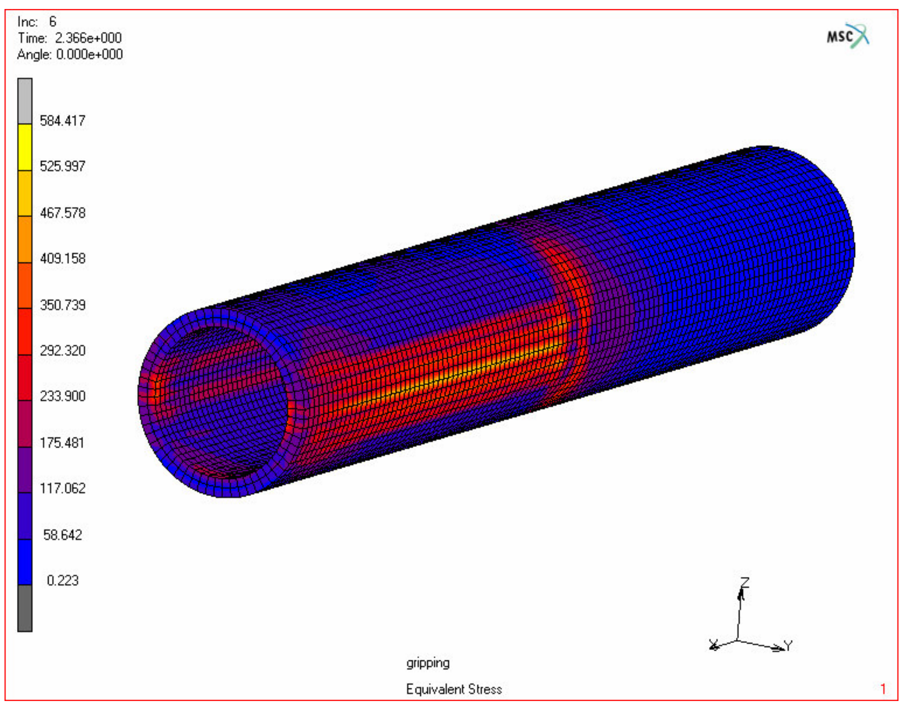

Figure A.5. *Equivalent stress distribution after tools are removed (MPa)*

In order to assure convergence by finite element method, analysis is repeated with finer mesh as shown in the Figure A.6. Number of elements is increased from 13800 to 110400 and number of nodes is increased from 20880 to 138600. The analysis is completed at 8 increments. Despite change in the number of increments, the obtained strain and stress values for the course and fine meshes are close to each others. Therefore, results of course mesh approximation can be said as reliable. In Figure A.7, the equivalent stress distribution just before the separation of gripper dies for the fine mesh approximation is shown. Similarity between the two approximations can be observed from the maximum stress values seen in Figures A.4 and A.7.

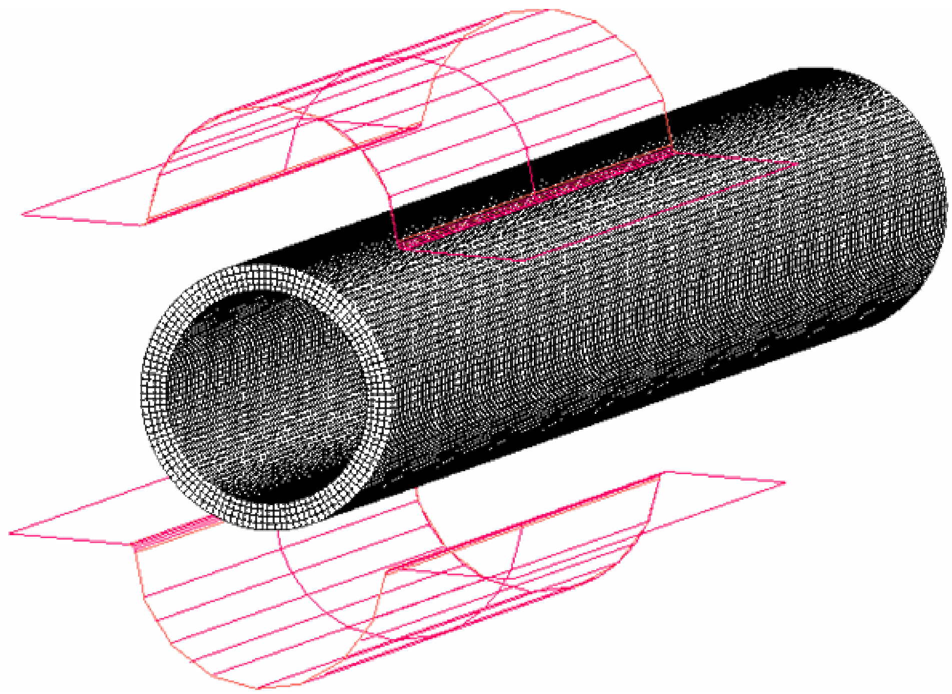

Figure A.6. *Fine mesh for convergence control*

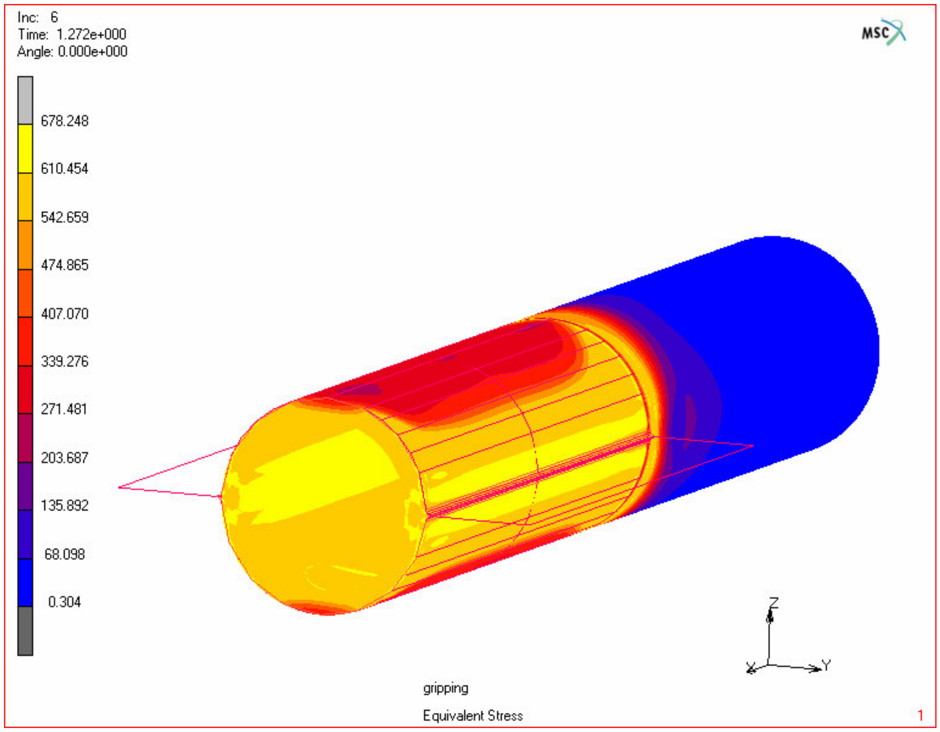

Figure A.7. *Equivalent stress distribution during gripping with fine mesh (MPa)*

The stress values at the shank are between 340 MPa and 610 MPa at the end of the three dimensional analysis. The obtained stress distribution is not axi-symetrical, however the stress values are close to the values obtained in axi-symmetric analysis as shown in Figure 4.21 and A.7. Additionally, the stresses and the strains due to gripping do not have significant effect on the deformation of the workpiece. Therefore, the tube upsetting analyses are performed with axi-symetric elements in Chapters 4, 5, 6 and 7.