Design and Analysis of an Industrial, Progressive Die for Cutting and Forming

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Design and analysis of an industrial, progressive die for cutting and forming

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Abstract

Nowadays, many components which were earlier cast or machined have now been replaced by steel metal stampings. Material economy and the resultant reduction in weight and cost, high productivity and a high degree of possible precision have made press-work essential for many mass-produced products such as electronic appliances, utensils and car parts. Although, laser-cut technology is widely developed and more flexible in terms of variety of produced components, it cannot reach the extremely high productivity rates of a progressive die. Progressive die can perform a sequence of operations, in different stations at a single stroke of press. In this work, an innovative progressive die consists of two stations was designed, in order to produce a complex metal part with three different manufacturing processes. The components of the die have been calculated by mathematical formulas and empirical data, designed with Computer Aided Design software and analyzed by Finite Element Analysis tool.

Keywords: Progressive Die; Piercing; Notching; Bending; Blanking; Finite Element Analysis

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1. Introduction

A progressive die performs a series of fundamental sheet-metal operations at two or more stations during each press stroke in order to develop a workpiece as the strip stock moves through the die. Each working station performs one or more distinct die operations, but the strip must move from the first station through each succeeding station to produce a complete part.

The workpiece in the investigation case is a part of the trigger mechanism for a speargun and it is build in 316L stainless steel, which has high corrosion resistance in very corrosive enviroments like sea .

This progressive die consists of two stations. To the first station are performed the operations of piercing and notching while to the second the operations of bending and blanking.

Many other works have involved in the study of progressive dies. References [1-7] and [8] developed the design of a die, while [8-10] developed the finite element analysis of a die. In this work, as in [11], we managed to develop both design and analysis.

For the design of the die and the simulation of the manufacturing process, the commercial Computer Aided Design software Solidworks was used and for the F.E analysis, the commercial code Ansys Workbench.

2. Research Objectives

The aim of this work is to design a progressive die in order to produce a complex metal part with four different manufacturing processes, piercing, notching, blanking and bending, with as few as possible stations. So, a two-stations die was designed with manual feeding in which a stripper plate is also helping the operator with the guidance and alignment of the metal sheet.

Fig. 1, present the flow chart of the manufacturing processes of the part. In Station 1, the piercing and notching process takes place and in Station 2 the bending and the final cut of the part.

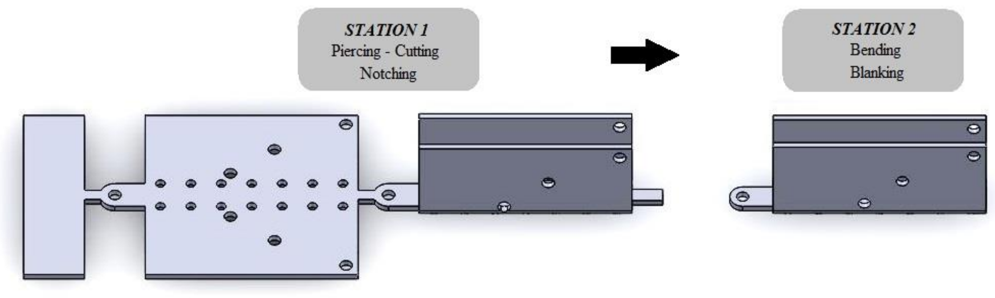
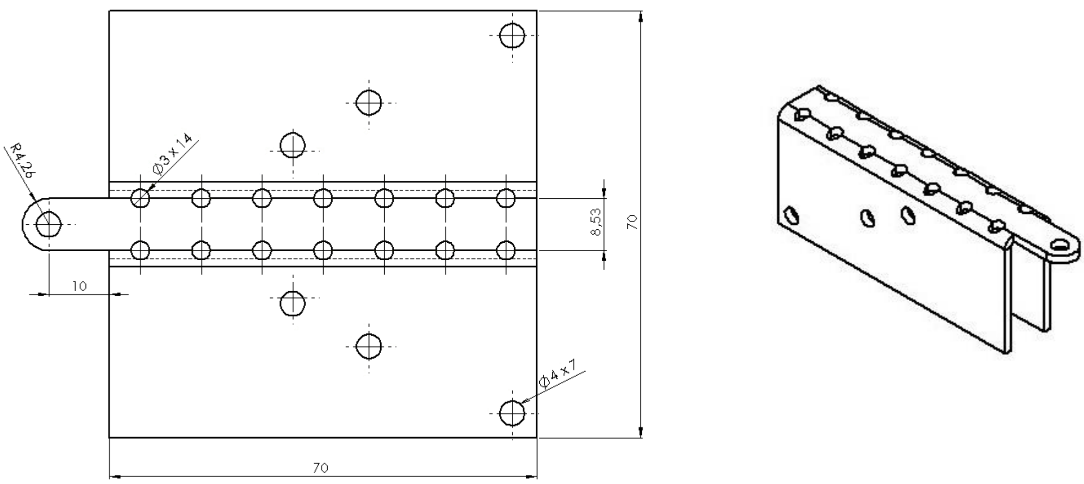


Fig. 1 *Stations of metal sheet forming*

In Fig. 2a,b, show the component's dimensions and the final part. It has 14 holes with 3mm diameter and 7 holes with 4mm diameter. The all part has 80mm length and 70mm width. The thickness of the material is 2mm.



(a) *(b)*

Fig. 2 *Component's (a) dimensions and (b) isometric view*

3. Calculations

For the workpiece a 316L stainless steel, was used as shown in Table 1.

Table 1 *Material Information*

Material	No.	SAE

	1.4404	316L
Thickness, t	2 mm	
Shear strength, f_s	418 MPa	
Yield strength, f_y	290 MPa	
Tensile strength, f_t	558 MPa	
Young modulus, E	193 GPa	

The components of the die have been calculated by mathematical formulas and empirical data, as presented in the next sections.

3.1 Total force

A. Cutting Force

During punching operations (Fig.3) such as piercing and blanking, the cutting force applied in the punch can be calculated using formula (1)[12,13].

$$\mathbf{F_c = \ f_s \times C \times t} \qquad \textbf{(1)}$$

where,

- f_s = shear strength of material (N/mm^2)
- C = cut length (mm)
- t = sheet thickness (mm)

So, in our case we have:

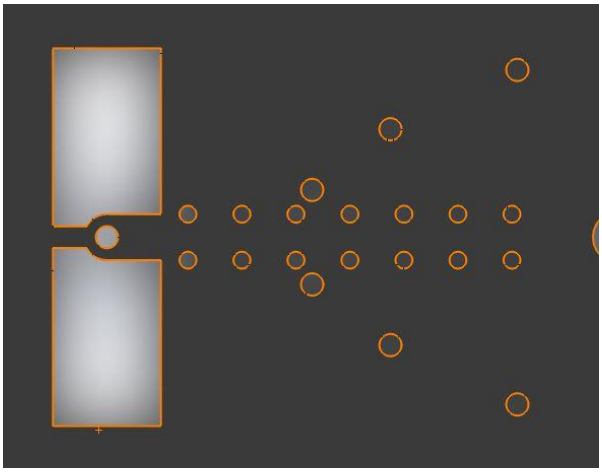


Fig.3 *Part cut outline*

Cut length calculation:

$$C_1 = 4 \times \pi \times 7 = 87.99 \text{ mm}$$
$$C_2 = 3 \times \pi \times 14 = 131.88 \text{ mm}$$
$$C_3 = 169.18 + 4.16 + 4.00 = 177.34 \text{ mm}$$
$$C_t = C_1 + C_2 + C_3 = 397.21\ mm$$

Total cut force:

$$F_c = 418\ {}^{N}/_{mm^2} \times 397.21 \text{ mm} \times 2 \text{ mm} = 332{,}068 \text{ N} = 33.86 \text{ tn}$$

B. Bending Force

A U-bend operation can be calculated using formula (2).

$$\mathbf{F_b} = \frac{\mathbf{2.66 \times f_t \times L \times t^2}}{\boldsymbol{W}} \qquad \mathbf{(2)}$$

where,

- f_t = tensile strength of material (N/mm^2)
- L = transverse length of bend (mm)
- t = sheet thickness (mm)
- W = width of channel (mm)

So, in our case:

$$F_b = \frac{2.66 \times 558\ {}^{N}/_{mm^2} \times 70 \text{ mm} \times 4 \text{ mm}^2}{14\ mm} = 29{,}686\ N = 3.03\ tn$$

C. Total Force

Due to friction between various components of the die, the cutting force must be increased by 20% [14].

$$F = 1.2 \times F_c + F_b = 428{,}168 \text{ N} = 43.66 \text{ tn} \approx 44 \text{ tn}$$

3.2 Strip economy factor

$$\boldsymbol{\eta} = \frac{\mathbf{A \times R}}{\mathbf{B \times V}} \times \mathbf{100\%} \qquad \textbf{[3]}$$

where,

- B = strip width (mm)
- V = progression (mm)
- A = part area without holes (mm^2)
- R = number of part rows

So, in our case:

$$\eta = \frac{5{,}013.77 \ \text{mm}^2 \times 1}{70.0 \text{ mm} \times 90.0 \text{ mm}} \times 100\% = 79.6\%$$

3.3 Definition of pressure center point

During the press working process of the shearing-cut and bending progressive die, the position of the die's pressure center has a direct impact on whether the die can work accurately in balance.

In Fig. 4, are presented the distances from the zero point (left corner).

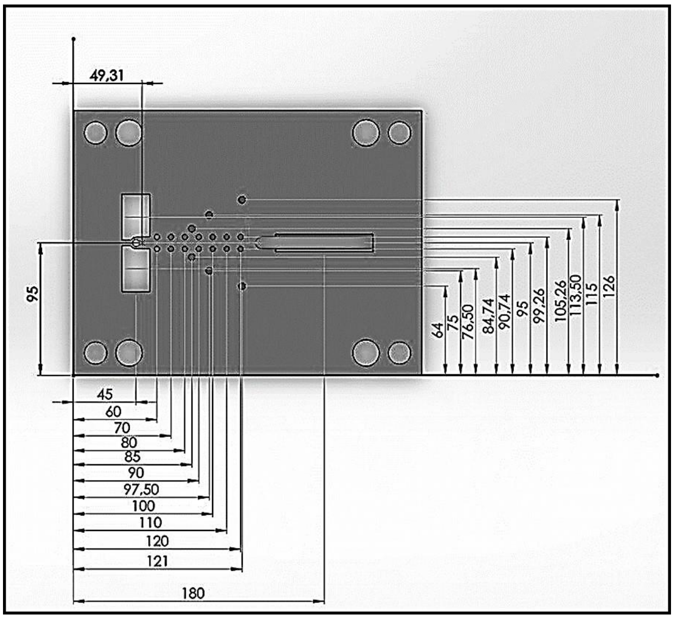


Fig. 4 *Distances from (0,0)*

For X and Y axis:

$$\mathbf{X} = \frac{(\sum_{i=1}^{n} F_m i) \times X_i}{\sum_{i=1}^{n} F_m i} \qquad \textbf{(4)}$$

$$\mathbf{Y} = \frac{(\sum_{i=1}^{n} F_m i) \times Y_i}{\sum_{i=1}^{n} F_m i} \qquad \textbf{(5)}$$

So, in our case:

Pressure center point = (**49.31** , **95.00**)

3.4 Springback

Springback occurs when a metal is bent and then tries to return to its original shape. After a bending operation, residual stresses will cause the sheet metal to spring back slightly. Due to this, it is necessary to over-bend the sheet an amount to achieve the desired bend radius and bend angle.

The springback radius can be calculated by formula (6)[15].

$$\frac{\mathbf{R_i}}{\mathbf{R_f}} = \mathbf{4} \times \left(\frac{\mathbf{f_y \times R_i}}{\mathbf{E \times t}}\right)^{\mathbf{3}} - \mathbf{3} \times \left(\frac{\mathbf{f_y \times R_i}}{\mathbf{E \times t}}\right) + \mathbf{1} \qquad \textbf{(6)}$$

where,

- Ri = initial radius (mm)
- Rf = final radius (mm)
- f_y = material yield strength (MPa)
- t = sheet thickness (mm)
- E = Young's modulus (MPa)

So, in our case:

$$\frac{1.74}{R_f} = 4 \times \left(\frac{290 \times 1.74}{193{,}000 \times 2}\right)^3 - 3 \times \left(\frac{290 \times 1.74}{193{,}000 \times 2}\right) + 1 => \frac{1.74}{R_f} = 0.9961 =>$$

$$=> R_f = 1.747 \text{ mm}$$

The springback angle can be calculated by formula (7).

$$\boldsymbol{\alpha_f} = \frac{\mathbf{R_i}+\frac{\mathbf{t}}{\mathbf{2}}}{\mathbf{R_f}+\frac{\mathbf{t}}{\mathbf{2}}} \times \mathbf{a_i} \qquad \textbf{(7)}$$

where,

- Ri = initial radius (mm)
- Rf = final radius (mm)
- a_i = initial angle (degrees)
- t = sheet thickness (mm)

So, in our case:

$$\alpha_f = \frac{1.74 + \frac{2}{2}}{1.747 + \frac{2}{2}} \times 90° \Rightarrow \alpha_f = 89.77°$$

The springback factor, commonly denoted by Ks, is the relation between the initial and final angles. A springback factor of Ks = 1 means there is no springback, where a value of 0 means total springback.

The springback factor can be calculated by formula (8).

$$\mathbf{K_s} = \frac{\mathbf{a_f}}{\mathbf{a_i}} \qquad \textbf{(8)}$$

where,

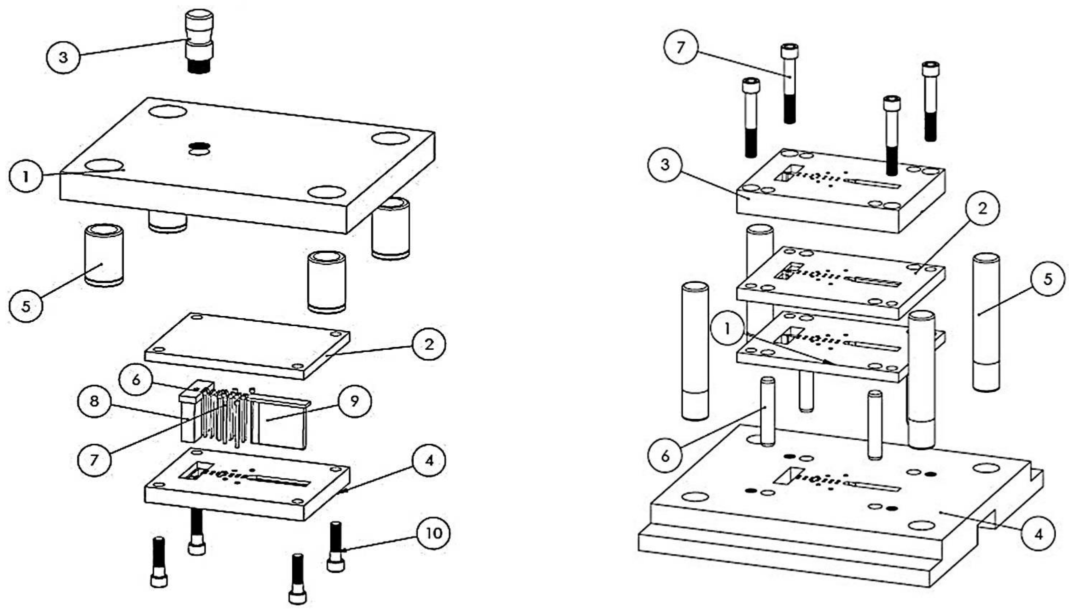
- a_f = final angle (degrees)
- a_i = initial angle (degrees)

So, in our case:

$$K_s = \frac{89.77°}{90°} \Rightarrow K_s = 0.997$$

4. Die Design

The die design was made with the help of commercial software SolidWorks, in which was also made the assembly of the die and the motion study (Fig.5a,b). Also, in Table 2, die components and materials are presented.



(a) (b)

Fig. 5 *Assembly of the die*

Table 2 *Die components and materials*

No.	Die part	Material No.
Upper die assembly		
1.	Punch plate	1.0050
2.	Punch back plate	1.0050
3.	Top plate	1.0037
4.	Guide bushes	1.6757
5.	Punches	1.3343
6.	Clamping pivot	1.0503
Lower die assembly		
7.	Stripper plate	1.0050
8.	Die block	1.2436
9.	Die block back plate	1.0050
10.	Bottom plate	1.0037
11.	Guide pillars	1.3505

4.1 Die block

The die block is the most important part of a progressive die and it defines the design of all the other components.

A. Active surface

Our die has two stations and constant width, so:

B = active width = 70 mm

A = active length = 2 x V = 180 mm

B. Thickness

The thickness of the die block can be calculated by formula (9).

$$\mathbf{T_r} = \sqrt{\frac{3\times F}{f_t} \times \left[\frac{\left(\frac{B}{A}\right)^2}{1+\left(\frac{B}{A}\right)^2}\right]} + 3\ mm \qquad \textbf{(9)}$$

where,

- F = total force (N)
- f_t = tensile strength of die block (N/mm^2)
- A = active length (mm)
- B = active width (mm)

So, in our case:

$$T_r = \sqrt{\frac{3 \times 428{,}168\ \mathrm{N}}{756\ \mathrm{N}/\mathrm{mm}^2} \times \left[\frac{\left(\frac{70}{180}\right)^2}{1 + \left(\frac{70}{180}\right)^2}\right]} + 3\ \mathrm{mm} \cong 18\ \mathrm{mm}$$

* 3 mm resharpening allowance

C. Margin

Margin is the solid cross-section around the die cutting edge. The fixing screws and dowels should be placed outside the margin to prevent weakening of the die.

$$\mathrm{M} = 2 \times \mathrm{T_r} = 2 \times 18 = 36\ \mathrm{mm} \qquad \textbf{(10)}$$

D. Die Clearance

The intentional gap between the punch and the cutting edges, depends upon the physical properties of the sheared material. Our material is stainless steel and the clearance is 20% of the sheet thickness. So:

$$u = 20\% \times t = 0.2 \times 2 = 0.4 \text{ mm} \qquad \textbf{(11)}$$

E. Width and length

The total width of the die block can be calculated by formula (12).

$$\mathbf{W_d = B + 2 \times M + 3 \times d_k} \qquad \textbf{(12)}$$

where,

- B = active width (mm)
- M = margin (mm)
- d_k = screw head diameter (mm)

So, in our case:

$$W_d = 70 + 2 \times 36 + 3 \times 16 = 190 \text{ mm (min)}$$

The total length of the die block can be calculated by formula (13).

$$\mathbf{L_d = A + 2 \times M} \qquad \textbf{(13)}$$

where,

- A = active length (mm)
- M = margin (mm)

So, in our case:

$$L_d = 180 + 2 \times 36 = 252 \text{ mm (min)}$$

4.2 Stripper plate

The stripper plates guide the punches through the sheet and also helps the operator with the manual feed of the strip.

W = 190 mm, L = 250 mm

$$\mathbf{t_s = \frac{1}{3} \times B \times +2 \times t + h_{in}} \qquad \textbf{(14)}$$

where,

- B = sheet width (mm)

- t = sheet thickness (mm)
- h_{in} = sheet opening height (mm)

So, in our case:

$$t_s = \frac{1}{3} \times 70 \text{ mm} \times +2 \times 2 \text{ mm} + 5 \text{ mm} = 32.33 \cong 33 \text{ mm}$$

4.3 Die block back plate - punch back plate

These components are made by softer steel in order to the die block and the punches do not break or bend. Also, they are interchangeable because they are simpler and cheaper parts.

W = 190 mm, L = 250 mm

t_{bp} = 10 to 15 mm = 15 mm

4.4 Top plate

The top plate is mounted on the press and it is standardized. Its dimensions depend on the width and length on the die block.

- Width-Length: A x B = 450 x 365 mm
- Height: C = 45 mm
- Guide bushes insert diameter: F = 55 mm

4.5 Bottom plate

The bottom plate is mounted on the bed of the press and it is also standardized. Its dimensions depend on the width and length of the die block.

- Width-Length: A x B = 450 x 365 mm
- Height: C = 55 mm
- Guide pillars insert diameter: E = 38 mm

4.6 Punch plate

On the punch plate are mounted the cutting and bending punches. The punch-head inserts are slightly bigger in case they deform so they do not stick in the plate.

$$W = 190 \text{ mm}, \; L = 250 \text{ mm}$$

$$t_{pp} = 12 \text{ to } 25 \text{ mm} = 25\text{mm}$$

4.7 Guide bushes

The guide bushes guide the pillars so the whole assembly is perfectly straight and also lubricate the pillars. They are standardized.

- Outside diameter: D_{out} = 55 mm
- Inside diameter: D_{in} = 38 mm
- Height: H = 85 mm

4.8 Guide pillars

The guide pillars guide with the help of the bushes the whole die. They are press fitted on the bottom plate. Their height depends on the height of the die. They are also standardized.

- Diameter: D = 38 mm
- Bottom diameter: D_{bottom} = 38.013 mm
- Length: L = 200 mm

4.9 Punches

In this die assembly there are four kinds of punches. There two standardized circular punches, a custom-made cutting punch and a custom-made bending punch.

First, we should calculate the critical length of the punches. The lengths of the punches are calculated from Euler's formula (15).

$$\mathbf{L_{cr}} = \sqrt{\mathbf{n} \times \frac{\boldsymbol{\pi^2 \times E \times I}}{\mathbf{P}}} \qquad \textbf{(15)}$$

where,

- n = factor accounting for the end conditions
- E = Young's modulus (N/mm^2)
- P = load (N)
- I = Moment of inertia (mm^4)

So, in our case:

A. D3 piercing punch

$$L_{cr} = \sqrt{2 \times \frac{\pi^2 \times 200{,}000 \, \frac{N}{mm^2} \times 3.98 \, mm^4}{7{,}875.12 \, N}} = 44.7 \, mm$$

B. D4 piercing punch

$$L_{cr} = \sqrt{2 \times \frac{\pi^2 \times 200{,}000 \, \frac{N}{mm^2} \times 12.57 \, mm^4}{10{,}508.52 \, N}} = 68.7 \, mm$$

C. Notching punch

$$L_{cr} = \sqrt{2 \times \frac{\pi^2 \times 200{,}000 \, \frac{N}{mm^2} \times 42{,}420.31 \, mm^4}{141{,}434.48 \, N}} = 1{,}088.1 \, mm$$

D. Bending-blanking punch

$$L_{cr} = \sqrt{2 \times \frac{\pi^2 \times 200{,}000 \, \frac{N}{mm^2} \times 1{,}755.02 \, mm^4}{36{,}507.76 \, N}} = 435.6 \, mm$$

During the production, all the punches must have the same, safe length. So, for our case we choose 40 mm.

5. Finite Element Analysis

The analysis of the parts was made with the commercial code Ansys Workbench. The type of the analysis we chose is Static Analysis and every part had a fixture at one end and the other end was free. The right load for each part was applied at the free end.

In Fig. 6-15, are presented the results of the F.E analysis for the most important components of the die.

All the parts can withstand the load that is applied to them without failure according to Von-Mises criterion of failure.

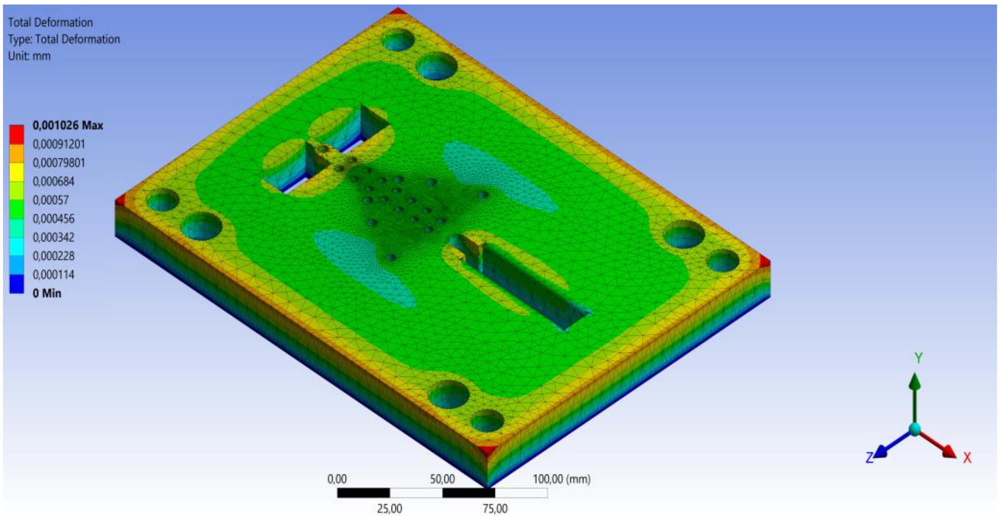


Fig. 6 *Deformation of Die block*

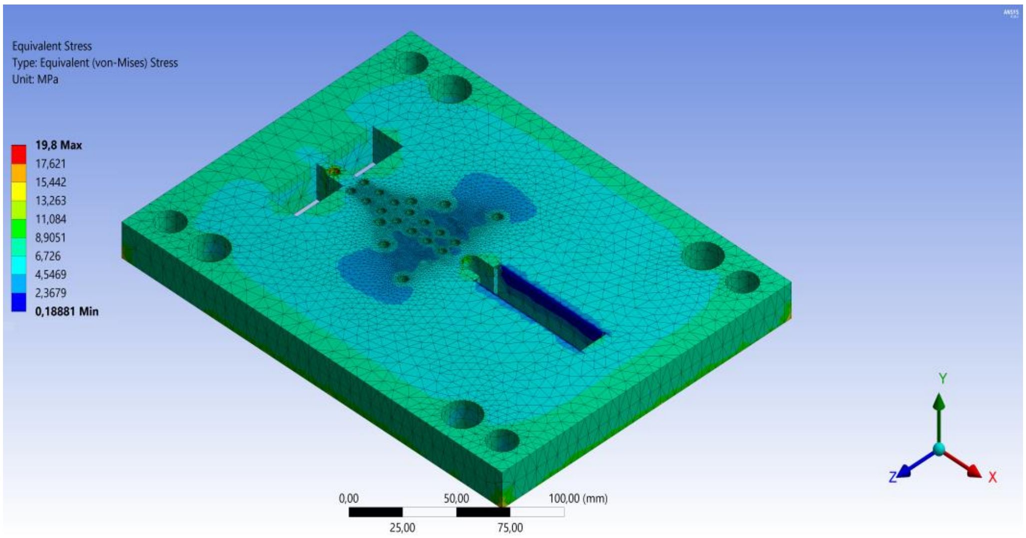


Fig. 7 *Von-Mises stress of Die block*

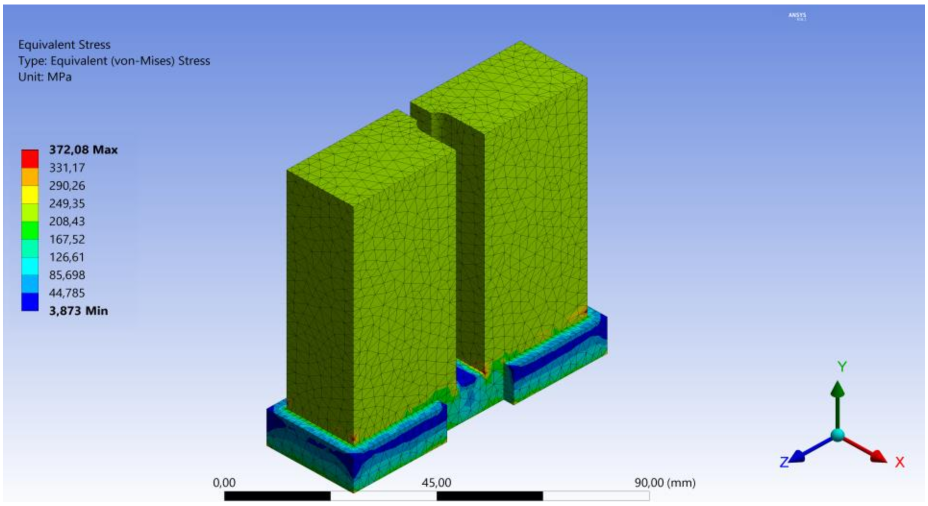


Fig. 8 *Von-Mises stress of Notching punch*

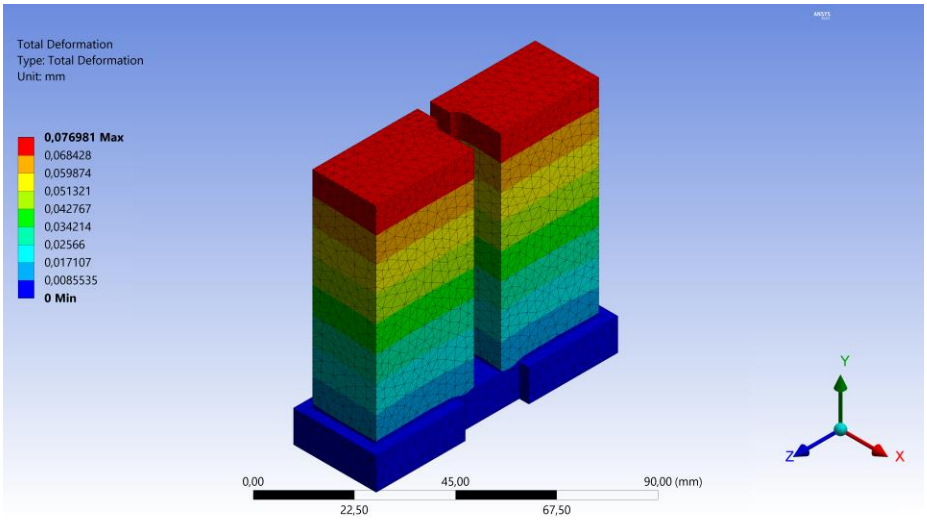


Fig. 9 *Deformation of Notching punch*

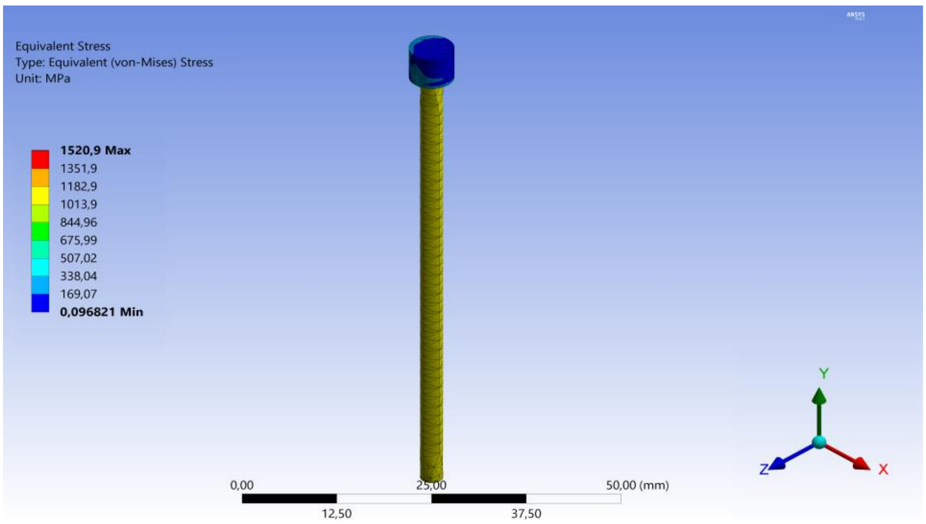


Fig. 10 *Von-Mises stress of D3 piercing punch*

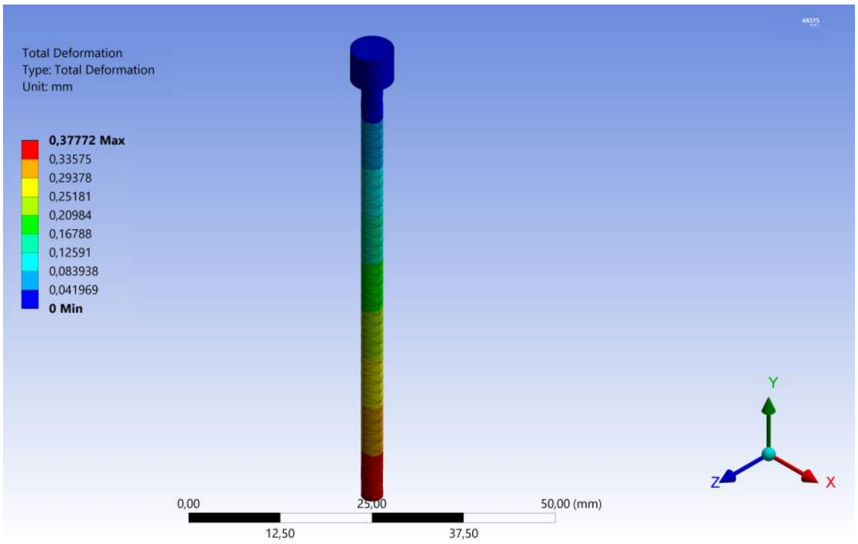


Fig. 11 *Deformation of D3 piercing punch*

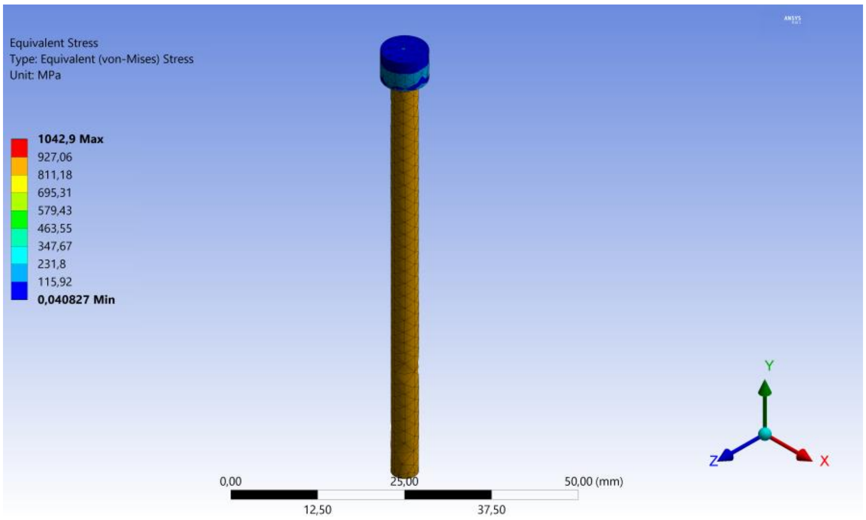


Fig. 12 *Von-Mises stress of D4 piercing punch*

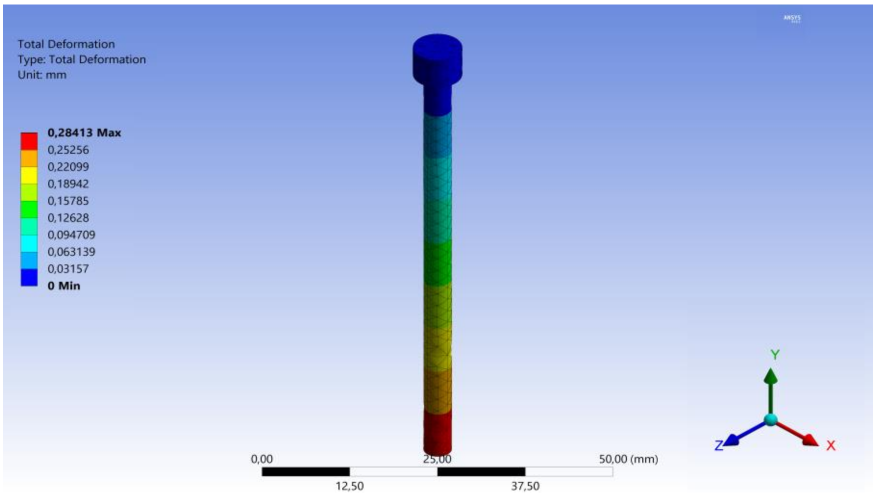


Fig. 13 *Deformation of D4 piercing punch*

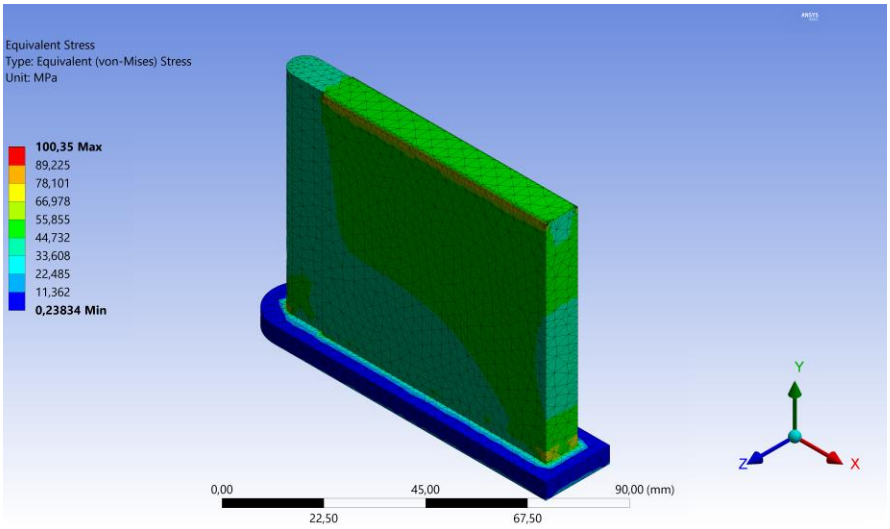


Fig. 14 *Von-Mises stress of Bending-blanking punch*

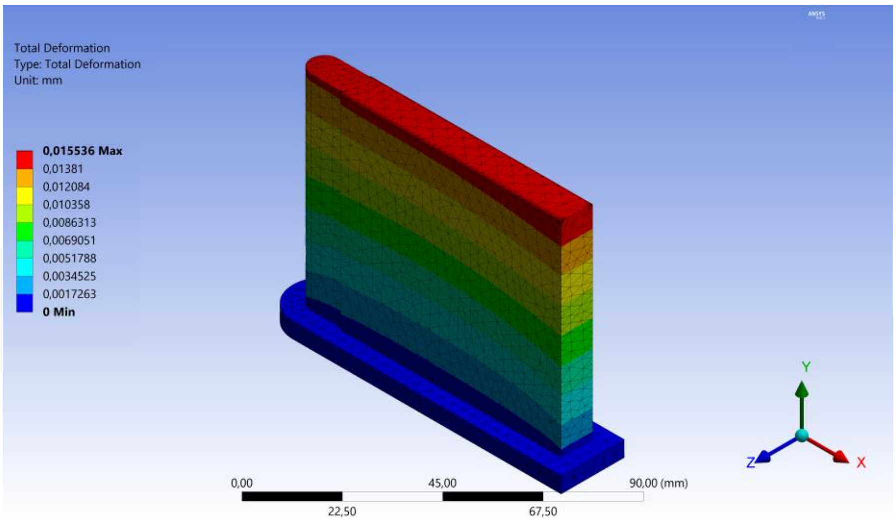


Fig. 15 *Deformation of Bending-notching punch*

The results of the FE analysis are given in Table 3.

Table 3 *FEA results*

No.	**Die component**	**Deformation [mm]**	**Von-Mises Stress [MPa]**	**Part yield strength [MPa]**
1.	Punch plate	0.00225	46.00	250
2.	Punch back plate	0.00077	15.67	250
3.	Top plate	0.11013	179.63	225
4.	Stripper plate	0.00520	27.08	250
5.	D3 punch	0.37772	1,520.90	3,250
6.	D4 punch	0.28413	1,042.90	3,250
7.	Cutting punch	0.07698	372.08	3,250
8.	Bending punch	0.01554	100.35	3,250

9.	Guide pillars	0.07244	718.18	1,390
10.	Die block	0.00103	19.80	860
11.	Die block back plate	0.00083	19.32	250
12.	Bottom plate	0.00462	30.94	225

In conclusion according to the Fig. 6-15 and Table 3, the results of Von-Mises stress and deformation of the most important parts of the die specifically the punches and the die, can withstand the load of the procedure.

6. Conclusions

In this work a progressive die was developed, in order to produce a complex metal part with four different manufacturing processes, piercing, notching blanking and bending, with as few as possible stations.

The components of the die have been calculated by mathematical formulas and Finite Element Analysis tools.

The proposed approach is based on real manufacturing data, in order to be easily produced.

Ethical Approval

For this type of study formal consent is not required.

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent to Publish

The participants have consented to the submission of the case report to the journal.

Author contribution

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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Competing Interests

There are no relevant financial or non-financial competing interests to report.

Availability of data and materials

All the data (numerical, figures, diagrams, tables, etc.) used to support the findings of our study are included within the article. Thus, data sharing regarding the aforementioned paper is totally allowed and any reader can access the data supporting the conclusions of the study.

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References

[1] Pawar S.,Dalu R. (2014), Compound Die Design: A Case Study, International Journal of Science and Research (IJSR) 3(5):389-392

[2] Choi J. C., Kim B. M., Kim Chul (1999), An Automated Progressive Process Planning and Die Design and Working System for Blanking or Piercing and Bending of a Sheet Metal Product, Int J Adv Manuf Technol 15:485–497

[3].Bhajantri V., Kapashi G., Bajantri S. (2014), Analysis of Progressive Dies, International Journal of Engineering and Innovative Technology (IJEIT) 3(7):223-231.

[4] Zhi-Xin Jia, Hong-Lin Li, Xue-Chang Zhang, Hong-Bing Wu, Ming-Cai Fang (2010), Study on the correlated design method of plate holes for progressive dies based on functional feature, Int J Adv Manuf Technol 49:1–12

[5] Zhi-Xin Jia, Hong-Lin Li, Xue-Chang Zhang, Ji-Qiang Li, Bo-Jie Chen (2011), Computer-aided structural design of punches and dies for progressive die based on functional component, Int J Adv Manuf Technol 54:837–852

[6] Zone-Ching Lin, Chun-Yao Hsu (1996), An Investigation of an Expert System for Shearing Cut Progressive Die Design, Int J Adv Manuf Technol 11:1-11

[7].Zone-Ching Lin, Ching-Hua Deng (2001), Analysis of a torque equilibrium model and the optimal strip working sequence for a shearing-cut and bending progressive die, Journal of Materials Processing Technology 115(3):302-312

[8]. Mastanamma Ch., Prasada Rao K., Venkateshwara Rao M. (2012), Design and Analysis of Progressive Tool, International Journal of Engineering Research & Technology (IJERT) 1(6):1-10

[9]. Ramegowda D., Madhusudhana M. (2015), Design of Blanking Punch and Die for Cam Head Washer Component using Finite Element Analysis, Journal of Engineering Research & Technology (IJERT) 4(7):410-414,

[10] Effect of two-stage press blanking on edge stretchability with third-generation advanced high-strength steels

[11]. Kumaresh A.K., Balaji B., Raj Kumar M. (2016), Design and Analysis of Punching Die, Journal of Engineering Research & Technology (IJERT) 5(4):249-255

[12]. Prakash H. Joshi (1999), Press Tools: Design and Construction, Wheeler Publishing, New Delhi

[13]. Paquin J.R. (1987), Die Design Fundamentals, Industrial Press Inc., New York

[14]. Smith D. (1990), Die Design Handbook, Society of Manufacturing Engineers, Michigan
[15].Suchy I. (1988), Handbook of Die Design, McGraw-Hill Handbooks, New York

Figures

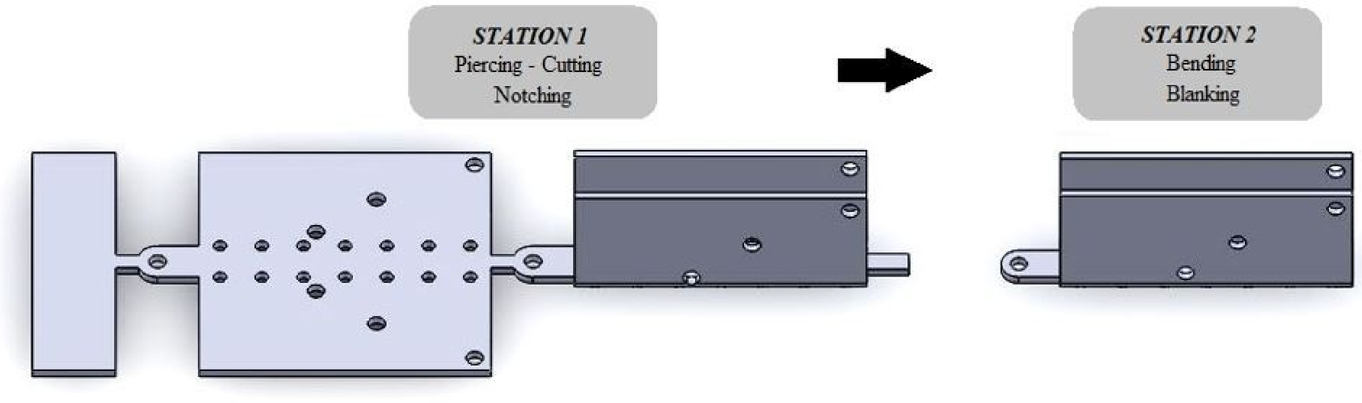

Figure 1

Stations of metal sheet forming

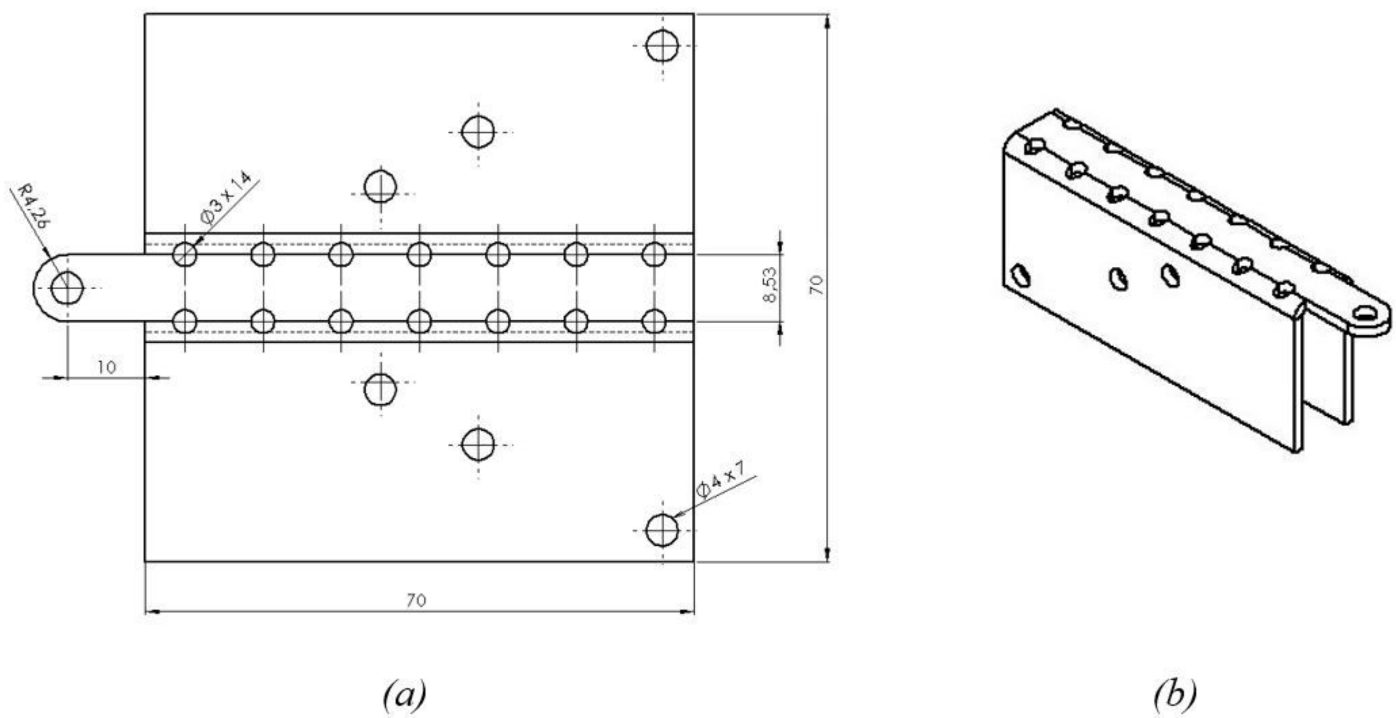

Figure 2

Component's (a) dimensions and (b) isometric view

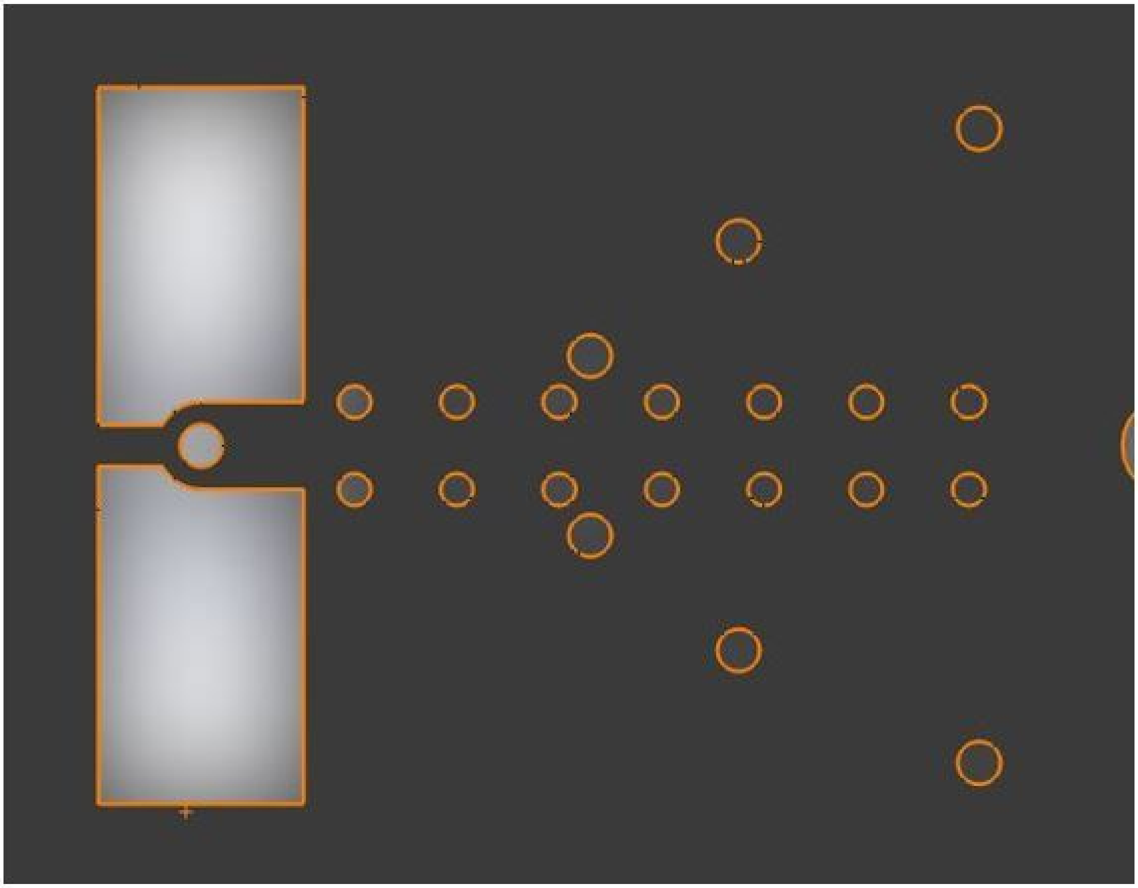

Figure 3

Part cut outline

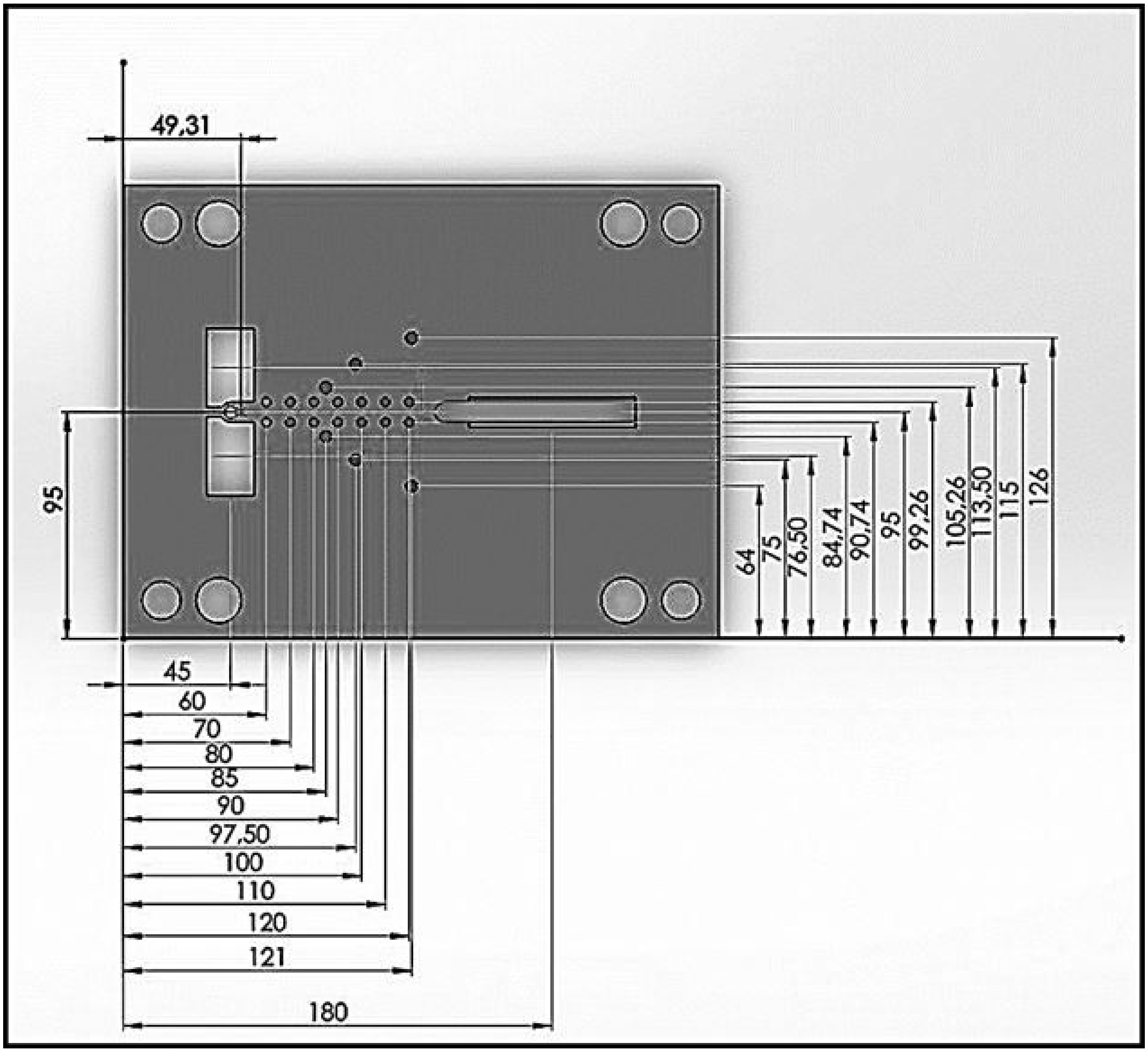

Figure 4

Distances from (0,0)

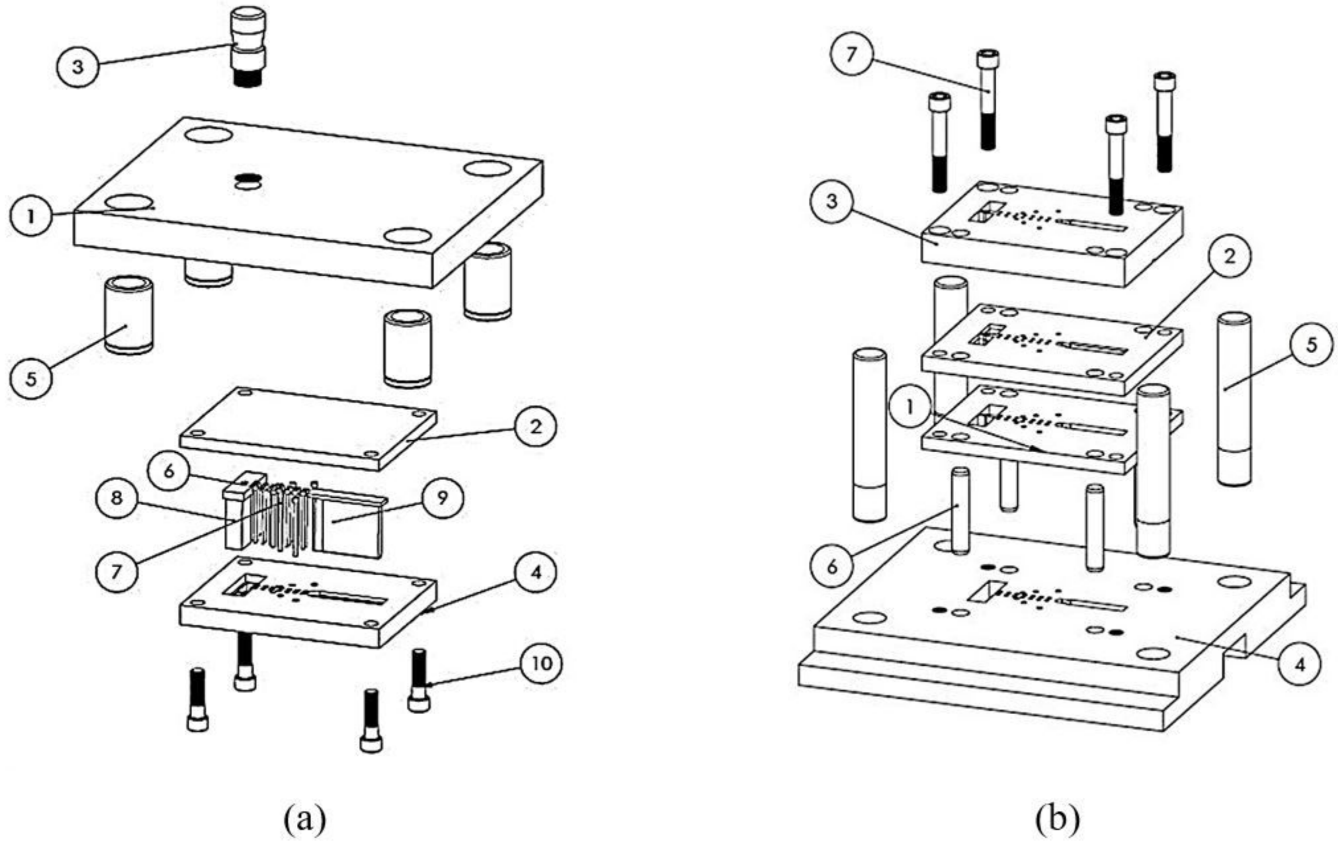

Figure 5

Assembly of the die

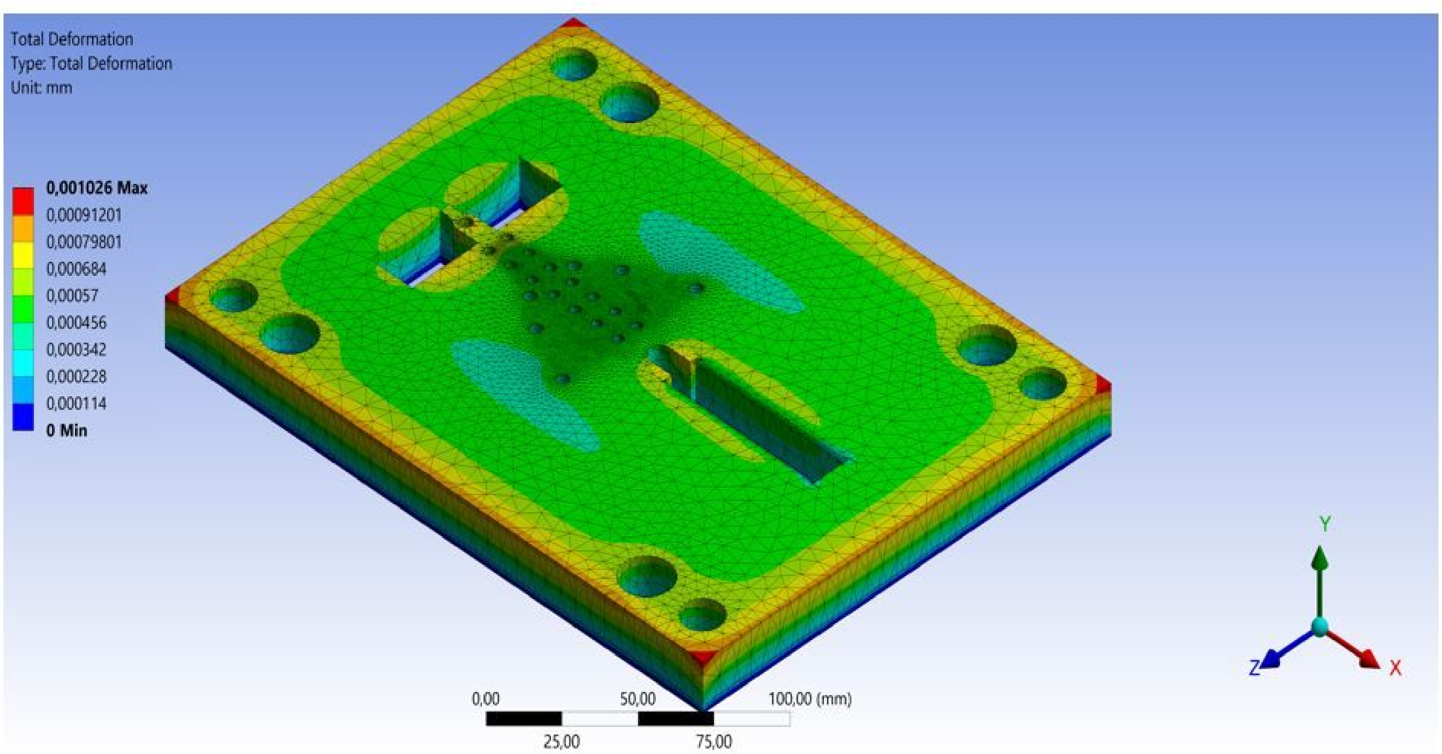

Figure 6

Deformation of Die block

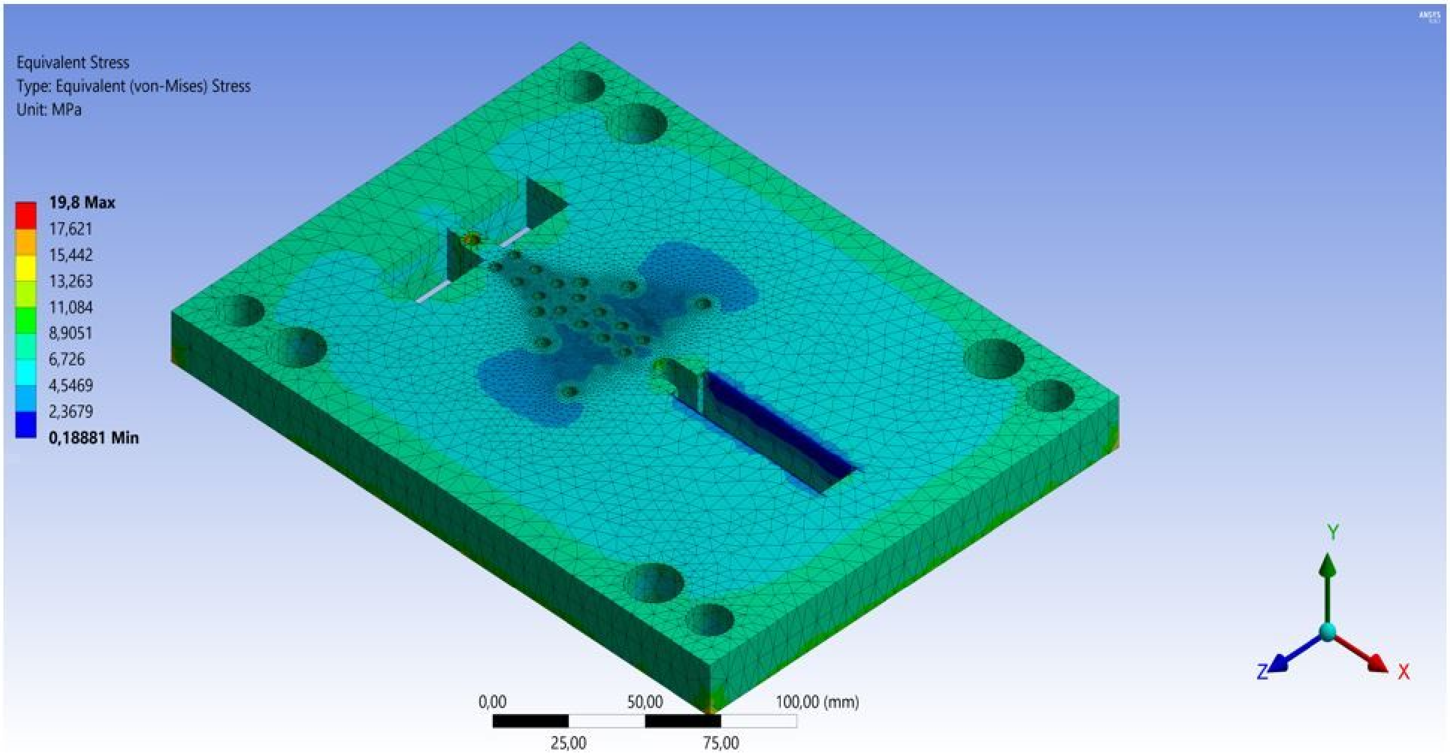

Figure 7

Von-Mises stress of Die block

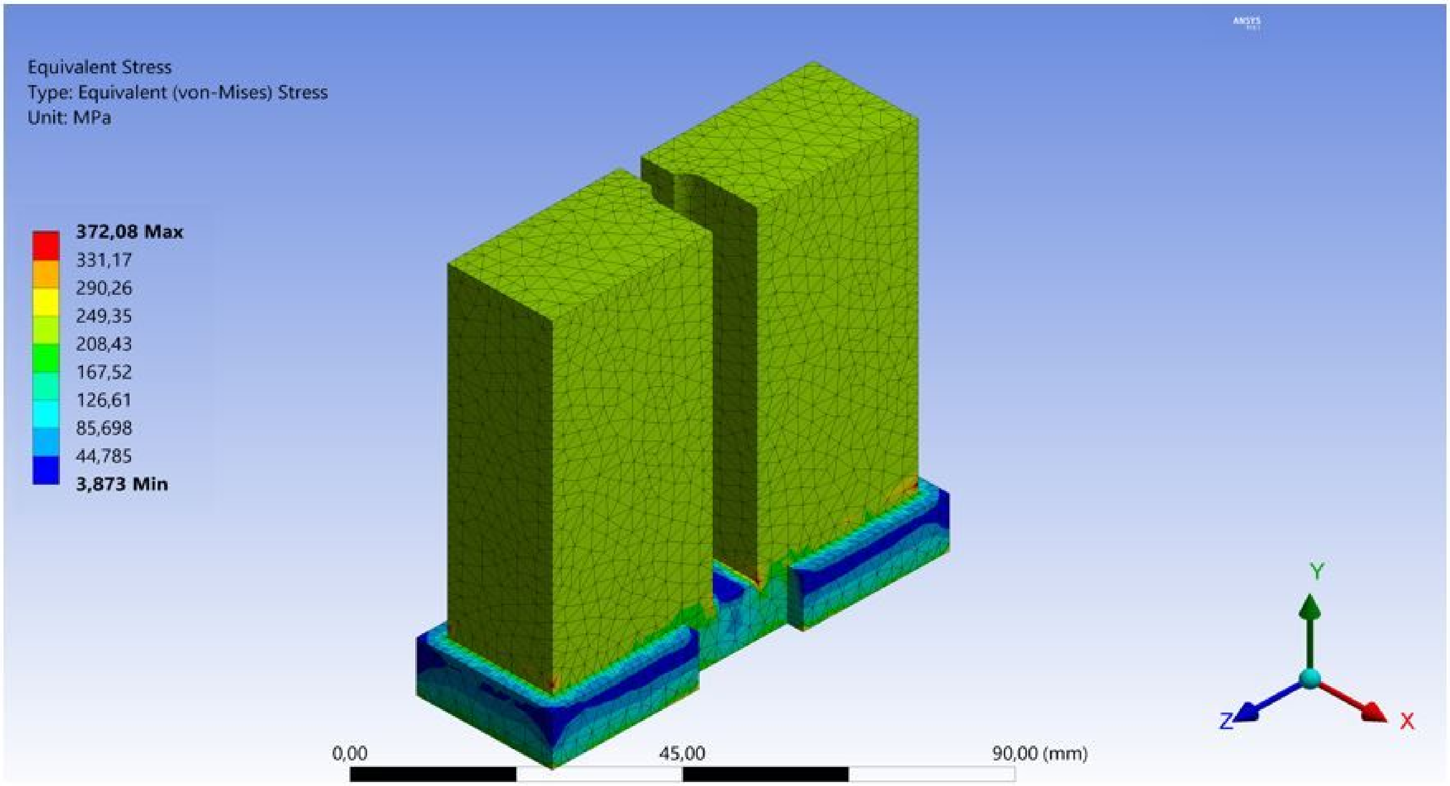

Figure 8

Von-Mises stress of Notching punch

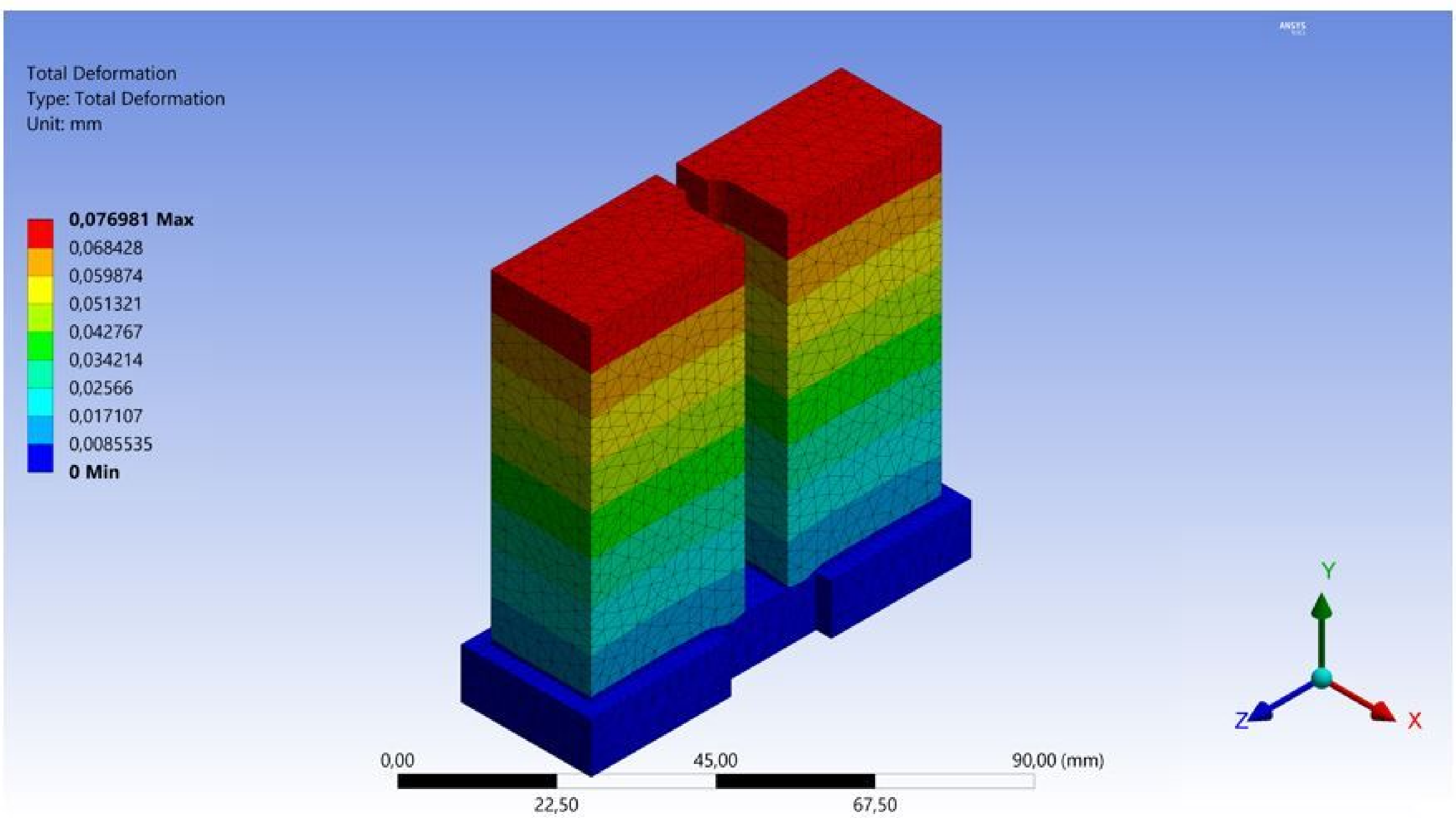

Figure 9

Deformation of Notching punch

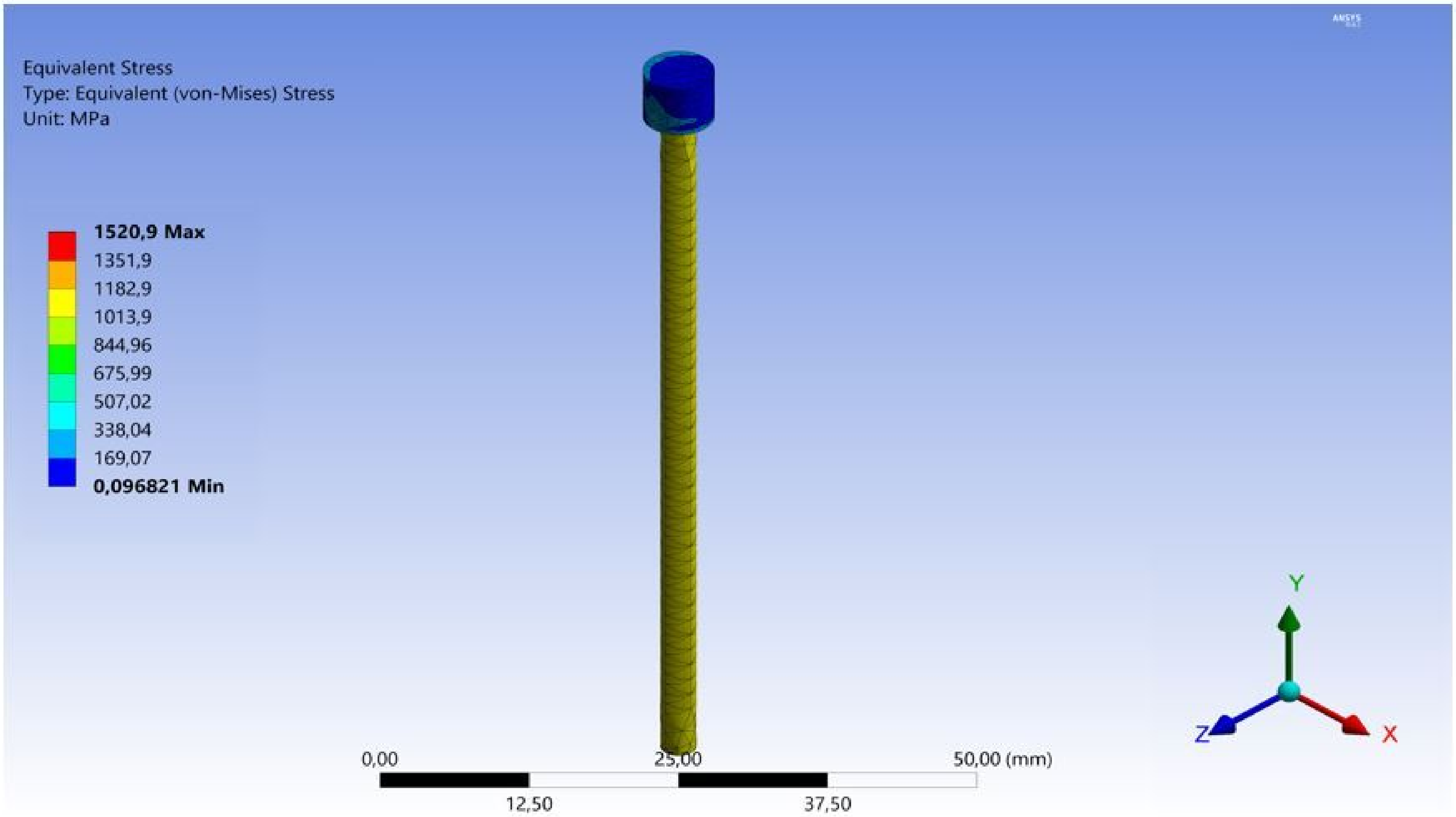

Figure 10

Von-Mises stress of D3 piercing punch

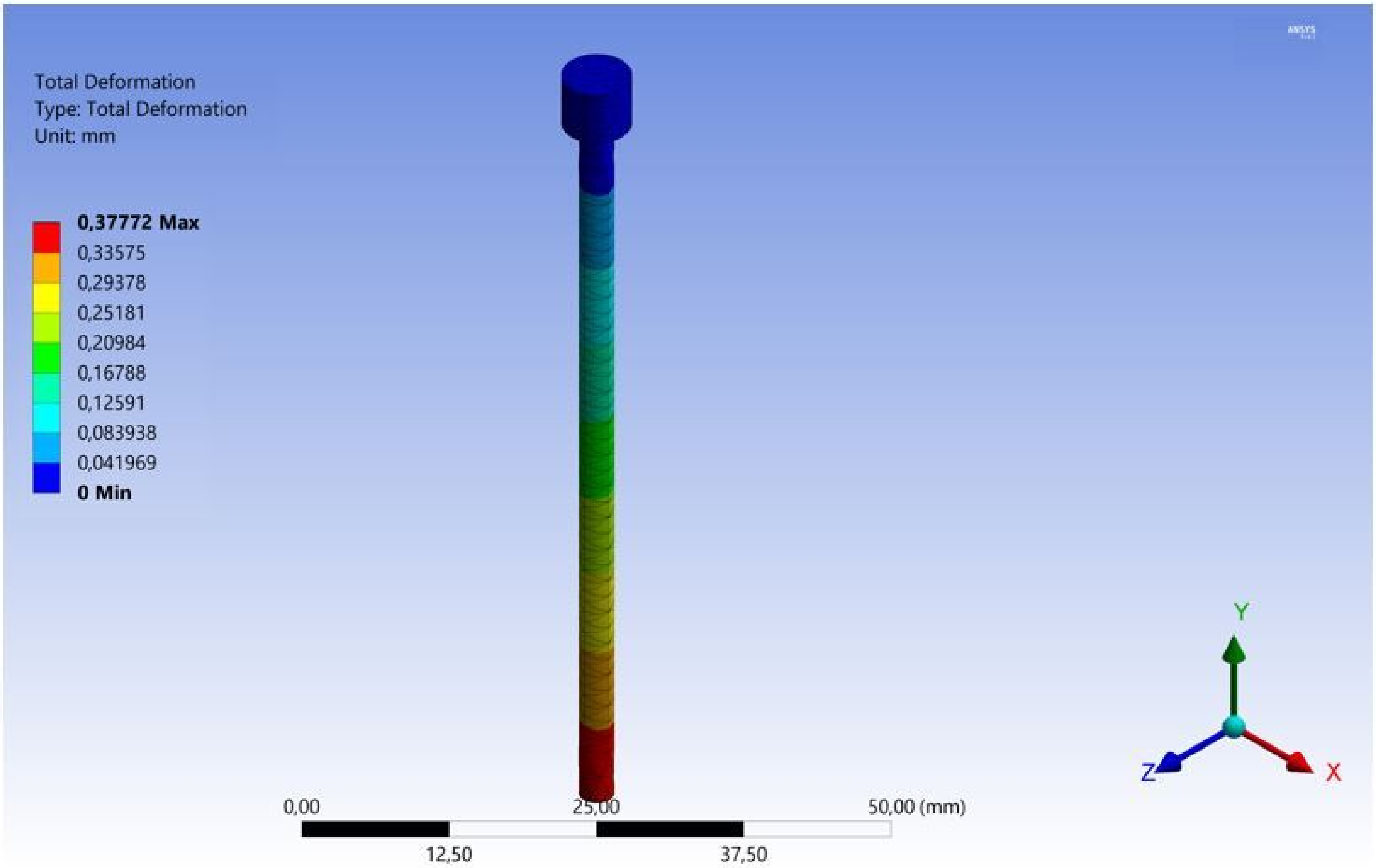

Figure 11

Deformation of D3 piercing punch

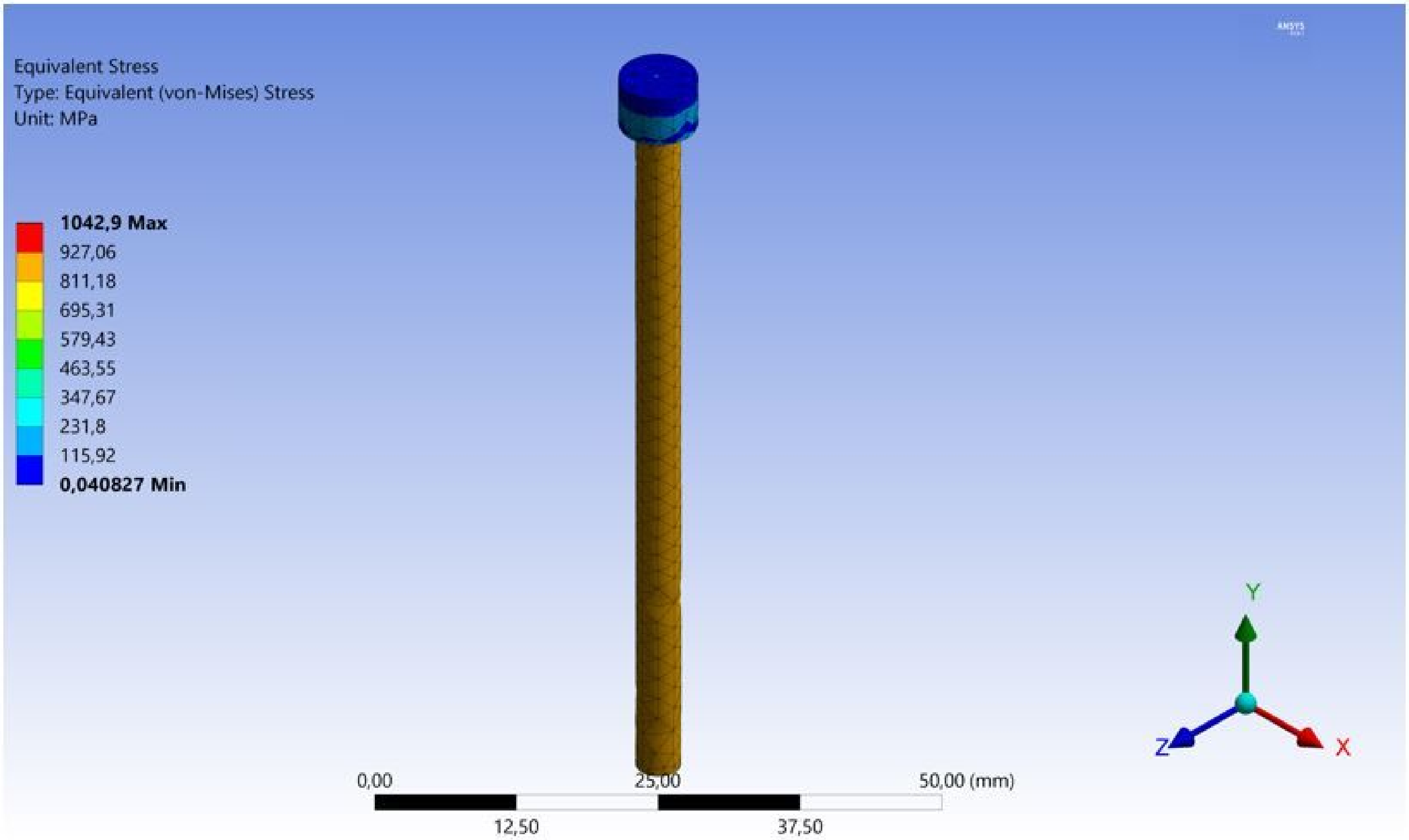

Figure 12

Von-Mises stress of D4 piercing punch

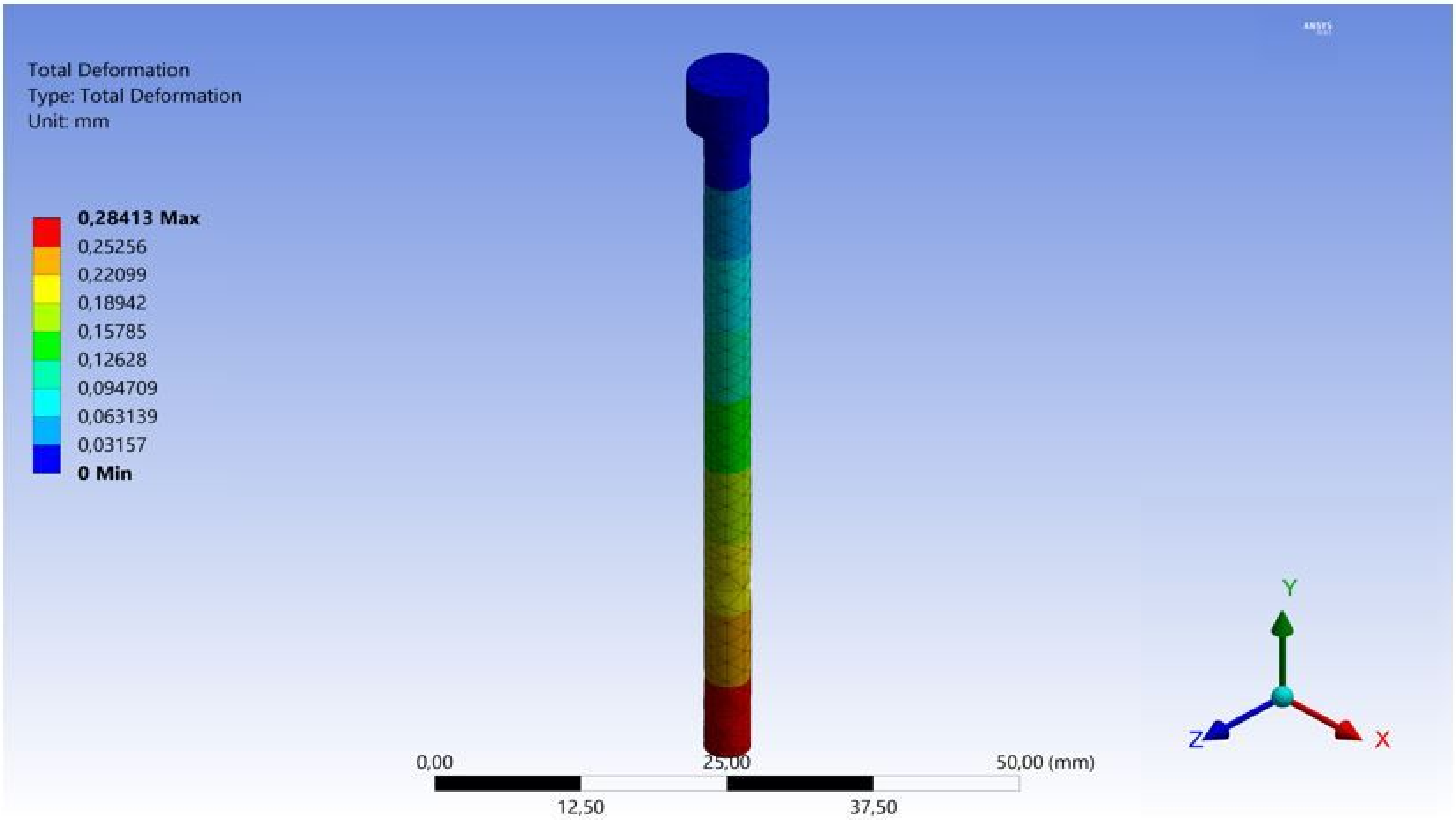

Figure 13

Deformation of D4 piercing punch

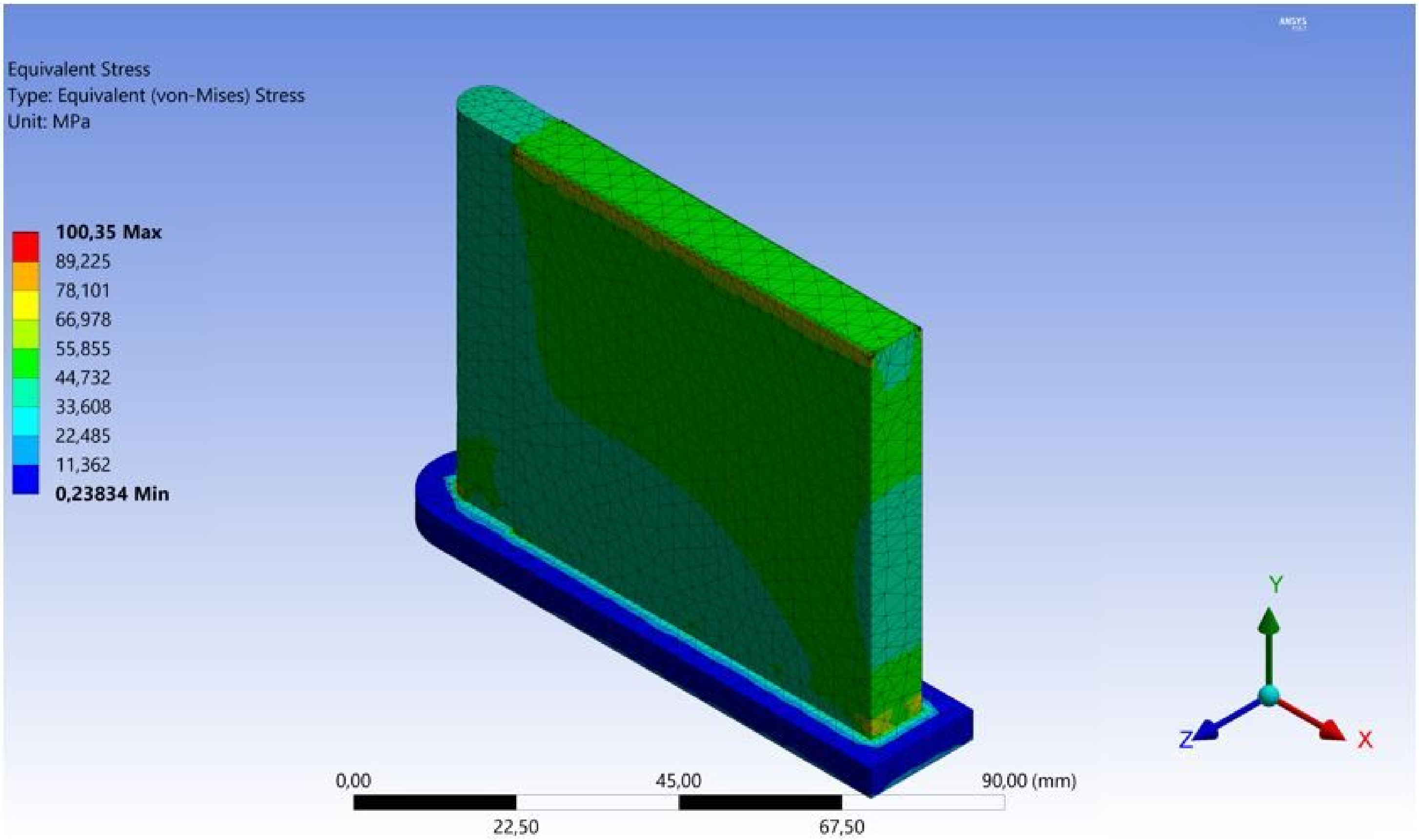

Figure 14

Von-Mises stress of Bending-blanking punch

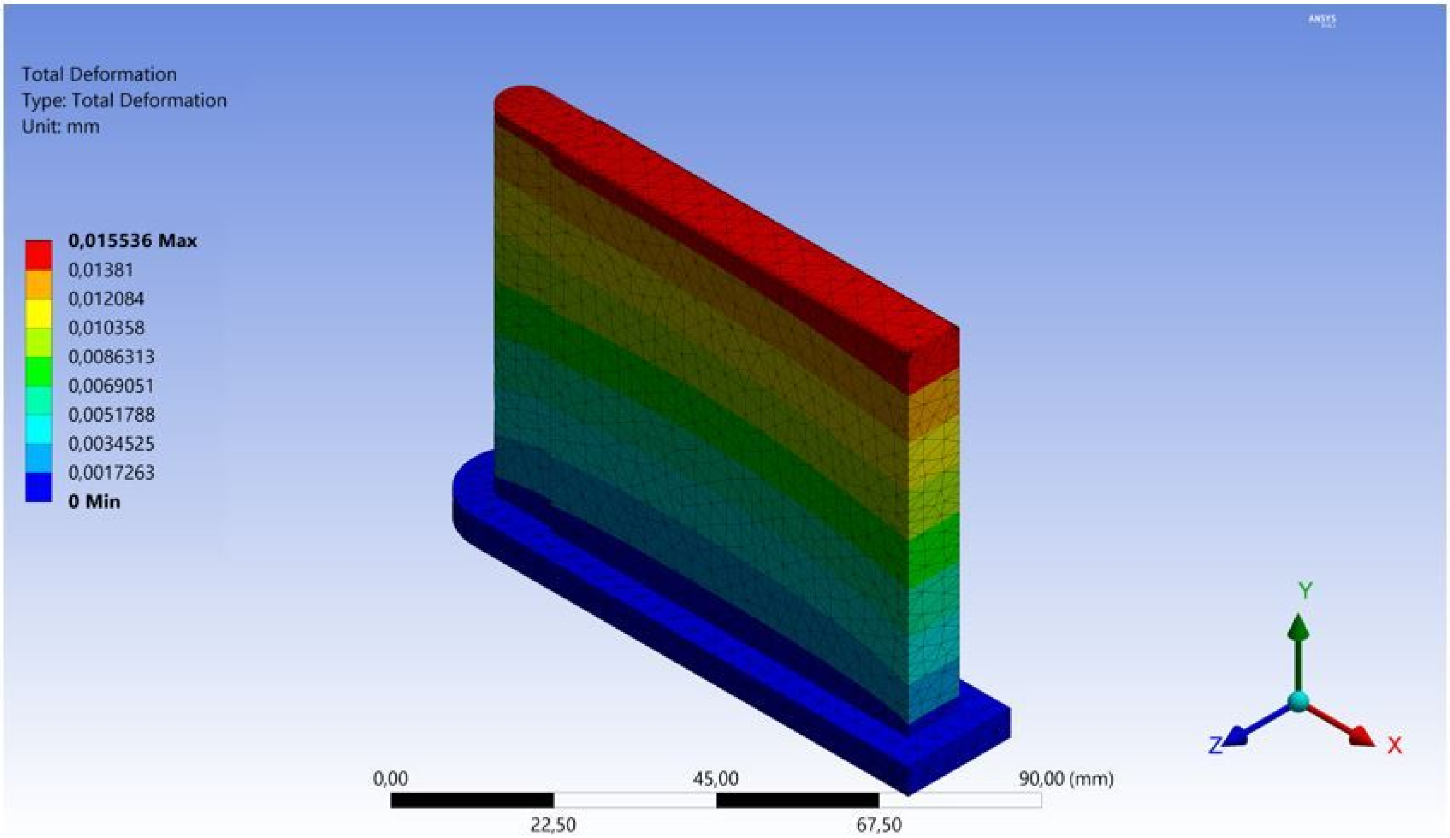

Figure 15

Deformation of Bending-notching punch