Modeling and simulation of forging processes

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Abstract*: Forging is an experience-oriented technology. The physical phenomena that describe the forging operations are difficult to express with quantitative relationships. In order to avoid the trail-and-error method, we use numerical simulations for studying the forging process. With the help of these simulations, the engineers are able to uncover the potential defects which may happen during the forging process. Concurrent Engineering (CE) helps in making the forging process more effective. In the CE system, each modification of the product represents a taxonomical relationship between specifications, outputs, and the concept it represents. In the study, the forging process of a disc shaped part is analysed. Thanks to numerical simulations it is determined that the dimensions of the billet are larger than needed. This resulted in overfilling the flash of the tool, thus the simulation was unsuccessful. After correcting the dimensions of the billet, the simulation ran with no interruptions.*
KEYWORDS*: FORGING PROCESSES, NUMERICAL SIMULATIONS, CONCURRENT ENGINEERING*

1. Introduction

In the forging process, initially a simple part – ingot is transformed into more complex part geometry, meanwhile, the tool forms the needed geometry and transfers pressure to the material which is deformed in the tool's interface. The forging processes usually produce little to none scrap and generate the final part geometry in a short amount of time, usually in one or a few strokes of a hammer or press. In addition, for a given weight, parts produced with forging show better mechanical and metallurgical properties than those produced by casting or machining. Forging is an experience-oriented technology. Throughout the years, a great deal of experience has been accumulated in this field, mainly through trial-and-error methods. Modern serial forging production is done with special forging tools. According to metal flow properties, closed-die forging can be done with or without flash; of the two, the latter is a more sophisticated method. Closed-die forging with hammers is done in a few strokes, whereas forging on a press is done in one slow stroke [1].

The physical phenomena that describe the forging operations are difficult to express with quantitative relationships. The material flow, friction between the tool and the material, the heat generation and transfer during the plastic flow, and the relationship between microstructure/properties and process conditions are difficult to predict and analyse. A forging system comprises all the input variables such as the billet (geometry and material), the tooling (geometry and material), the conditions at the tool/material interface, the mechanics of plastic deformation, the equipment used, the characteristics of the final product, and finally the plant environment where the process is being conducted. The key to a successful forging operation, to obtain the desired shape and properties, is the understanding and control of the metal flow [1].

2. Modeling and simulation of a forging tool

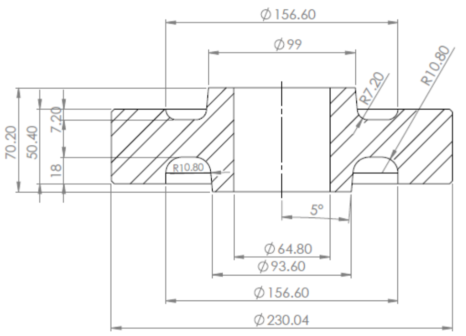

Figure 1. *Final part drawing*

The forged part design is developed by using the part drawing and following the guidelines found in the EN DIN 10243-1 standard. This standard covers hot forgings made from carbon and alloy steels with a mass up to 250 kg.

2.1. Category of steel used

The type of steel used takes account of the fact that steels of high carbon and high alloy content are more difficult to deform and cause higher die wear than steels with lower carbon content and lower alloying elements. The category of steel used is determined as being one of the following:

- Group M1: Steel with carbon content not greater than 0.65% and total of specified alloying elements (Mn, Ni, Cr, Mo, V, W) not greater than 5% by mass;
- Group M2: Steel with carbon content above 0.65% or total specified alloying elements (as mentioned above) above 5% by mas;

To determine the category in which a steel belongs, the maximum permitted content of the elements in the steel specification will be used.

Table 1. Chemical composition

C	Si	Mn	Ni	V	Cr	Mo
0.42 - 0.50	max 0.37	0.5 – 0.8	1.3 – 1.8	0.10 – 0.18	0.3 - 0.6	0.2 - 0.3

The steel 45Х2МФА: ГОСТ 4543 has carbon mass fraction of up to 0.50% and a total mass fraction of its alloying elements of 4.18%. This places the steel in the group M1.

2.2. Shape complexity factor

The shape complexity factor takes account of the fact that in forging thin sections and branched components, as compared to components having simple compact shapes, larger dimensional variations occur which are attributable to different rates of shrinkage, higher shaping forces and higher rates of die wear. The shape complexity factor of a forging is the ratio of the mass of the forging to the mass of the enveloping shape necessary to accommodate the maximum dimensions of the forging.

$$S = \frac{m_{forging}}{m_{enveloping \quad shape}} = \frac{\rho \cdot V_{forging}}{\rho \cdot V_{enveloping \quad shape}},$$

where: S – complexity factor, $m_{forging}$ – mass of forged part, $m_{enveloping\ shape}$ – mass of enveloping shape, ρ – material density, V – volume.

The resulting shape complexity factor is determined as falling within one of the following categories:

- S4: up to and including 0.16;
- S3: above 0.16 up to and including 0.32;
- S2: above 0.32 up to and including 0.632;
- S1: above 0.63 up to and including 1;

$$V_{forging} = V_{part} \cdot K_P$$

$$m_{forging} = m_{part} \cdot K_P$$

where, $K_p = 1.5 \div 1.8$ – shape coefficient for round forged parts (gears, flanges, discs, etc.).

The parts mass and volume can be determined by using any CAD software while using the density of the material in question (Figure 2).

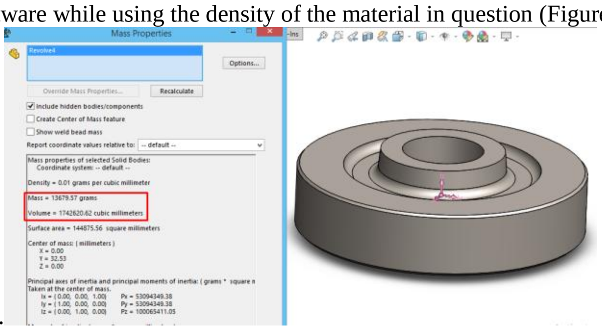

Figure 2. *Mass properties for the final part – SolidWorks*

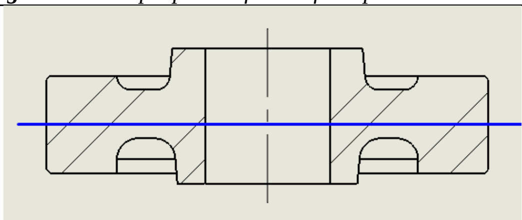

Figure 3. *Parting line*

$$V_{forging} = V_{part} \cdot K_P = 1742620.62 \cdot 1.5 = 2613930.93\ mm^3$$

$$m_{forging} = m_{part} \cdot K_P = 13679.57 \cdot 1.5 = 20519.355\ kg$$

The enveloping shape of a circular forging is the circumscribing cylinder the volume of which is calculated by increasing the maximal width and height of the final part by 5% to accommodate the increased size of the forging.

$$V_{enveloping\ \ shape} = \frac{(D_{max} \cdot 1{,}05)^2 \cdot \pi}{4} \cdot (H_{max} \cdot 1{,}05)$$

where, D_{max} [mm] – largest diameter; H_{max} [max] – largest part height.

$$V_{enveloping\ \ shape} = \frac{(230.04 \cdot 1{,}05)^2 \cdot \pi}{4} \cdot (70.2 \cdot 1{,}05) = 3375836.34\ mm^3$$

$$S = \frac{\rho \cdot V_{forging}}{\rho \cdot V_{enveloping\ \ shape}} = \frac{2613930.93}{3375836.34} = 0.7743$$

The complexity factor S = 0.7743 falls in the S1 category. It is important to emphasize that the initial complexity factor is an estimated value due to the estimation of the forgings and enveloping shapes mass. The estimated degree of complexity should be refined after calculating the exact envelopes and forging mass.

2.3. Parting line configuration

The part has a plain parting line configuration located at the half point of the thickness at the largest diameter (as shown in Figure 3).

2.4. Forging equipment selection

In order to begin the forging design, we must first select a forging machine by doing a control calculation to determine the plausibility of the technological process on the available equipment by estimating the needed machine force.

- For power-drop steam hammers:

$$G = 10(1 - 0{,}005D_{fmax})(1{,}1 + \frac{2}{D_{fmax}})^2(0{,}75 + 0{,}001{D_{fmax}}^2)D_{fmax} \cdot \sigma_m$$

- For mechanical presses:

$$F = 8(1 - 0{,}001D_{fmax})(1{,}1 + \frac{20}{D_{fmax}})^2 A \cdot \sigma_m$$

where, G [kg] – hammers falling mass; F [kg] – mechanical press force needed for forging circular forgings; $D_{fmax} = D_{max} \cdot 1{,}05$ – largest forging diameter; $\sigma_m \left[\frac{kg}{mm^2}\right]$ – material strength in the final forging stages; $A = \frac{{D_{fmax}}^2 \cdot \pi}{4}$ $[mm^2]$ – projection of the forging in the horizontal plane.

The steel 45Х2МФА: ГОСТ 4543 can be classified in the second type according to table 2. From there we select the values for σ_m for the forging hammers and mechanical presses for the calculations.

Table 2. *Steel strength σ_m [kg/mm²] in the final forging stages*

	Type of steel	Forging hammers	Mechanical presses	Horizontal forging machines
1.	Carbon steel with carbon content up to 0,25 %	5,5	6	7
2.	Carbon steel with carbon content above 0,25 %, or Alloyed steel with carbon content up to 0,25 % and alloying element content up to 5%	6	6,5	8
3.	Alloyed steel with carbon content above 0,25 % and alloying element content up to 5%	6,5	7	9
4.	Alloyed steel with alloying element content above 5%	7,5	8	10
5.	Alloy tool steel	9 - 10	10 - 12	12 - 14

$$G = 10(1 - 0{,}005D_{fmax})(1{,}1 + \frac{2}{D_{fmax}})^2(0{,}75 + 0{,}001{D_{fmax}}^2)D_{fmax} \cdot \sigma_m = 2.4\ t$$

$$F = 8(1 - 0{,}001D_{fmax})(1{,}1 + \frac{20}{D_{fmax}})^2 A \cdot \sigma_m = 13800\ t = 138\ MN$$

Since the estimated value for the needed force on the power-drop hammer is reasonable, it is selected as the forging machine used to manufacture the forging of the part. All the tolerances and machining allowances will be selected to suit the forging process on steam hammers.

2.5. Defining the forged part dimensions

All of the tolerances and machining allowances for the forged part were selected from the tables 1 to 6 from the standard DIN EN 10243-1. The standard identifies two grades of tolerances. Forging grade F with tolerances providing adequate standard of accuracy for the majority of applications and capable of being complied with by commonly used forging equipment and production methods. Forging grade E providing closer tolerances to assist in accommodating those instances in which the normal manufacturing standards are inadequate. The forging grades “E” and “F” were allocated to the measures, depending on the particular surface roughness and tolerances designated in the part drawing. The standard also identifies four major types of dimensions and several minor ones and classifies them in 4 groups.

All of the allocated allowances and tolerance grades for the inner and outer forging dimensions are given in table 4. Finally, the resultant dimensions are modified by a factor η that takes into account the thermal expansion while heating. The outer dimensions are increased and the inner ones are decreased by a specific amount that corresponds to the forging temperature. This way we ger the correct hot forging part design with measurements ready for creating the die geometry. $\eta = 1{,}025$ – thermal expansion coefficient for steel alloys at forging temperatures of ~1200 °C.

2.6. Forging draft angles

Draft is an angle allowance added to surfaces parallel to the direction of die closure to facilitate release of the part form the die after forging. In general, draft allowances on inside surfaces are greater than those on outside surfaces, because of the tendency of the part to shrink onto projections in the die as cooling takes place [2]. For power drop steam hammers the chosen normative draft angles are as follows: $\alpha = 7°$ - external draft angle; $\alpha_1 = 10°$ - internal draft angle.

2.7. Forging fillet radii

All edges and corners in the part must have added fillets. These fillets are necessary to aid material flow and ensure good die filling. In addition, sharp corners in dies can lead to premature die failure due to fracture as a result of associated high stress concentrations. In general, larger radii are recommended for the more difficult-to-forge materials [2]. The outer radii are selected depending on the mass of the forging and the largest depth of the die impression that is calculated according to the position of the parting line; $R_{outer} = 2.5\ mm$.

The inner radii are calculated using this formula:

$$r_{inner} = (2{,}5 \div 3{,}5)R_{outer} + 0{,}5$$

$$r_{inner} = 3 \cdot 2.5 + 0.5 = 8\ mm$$

2.8. Defining the position, shape and dimensions of the barrier plates for all through holes in the forged part

In the forging process, holes are not punched through because this would make the ejection of the part more difficult. This way the dies are separated by a barrier plate in each hole. The thickness of the plate is calculated using the following equation:

$$s = 0{,}45\sqrt{d - 0{,}25h - 5} + 0{,}6\sqrt{h}$$

where, s [mm] – plate thickness, d [mm] – diameter of the hole at the topmost surface, h [mm] – distance from the plate midline to the topmost surface of the forging.

$$s = 0{,}45\sqrt{d - 0.25h - 5} + 0.6\sqrt{h} = 6.87 \rightarrow 7\ mm$$

The fillet radii for the plate also have to be calculated. Hence, we use the equation: $r_1 = r_{inner} + 0{,}1h + 2$, where, r_1 [mm] – fillet radii for the plate edges, r_{inner} [mm] – inner fillet radii for the forged part.

$$r_1 = r_{inner} + 0.1h + 2 = 14.37 \rightarrow 14\ mm$$

The type of plate depends on the size of the forging part, the diameter and the height of the hole. To determine the type, we need to check the following condition:

$$d - 1.25r_1 = 57.72 - 1.25 \cdot 14 = 39.75$$

The condition $d - 1{,}25r_1 > 26$ requires the use of a Type II plate with a shape shown in Figure 288, page 581, Obrada Metala Plasticnom Deformacijom, Binko Musafija.

$$d_1 = 0.12 \cdot s + 3 = 3.82 \rightarrow 4\ mm$$

$$S_{min} = 0.65 \cdot s = 4.4 \rightarrow 4\ mm$$

$$S_{max} = 1.35 \cdot s = 9.2 \rightarrow 8\ mm$$

where, d_1 [mm] – flat length of the plate, S_{min} [mm] – minimal plate thickness, S_{max} [mm] – maximal plate thickness.

2.9. Control check for the forging mass and the complexity factor S

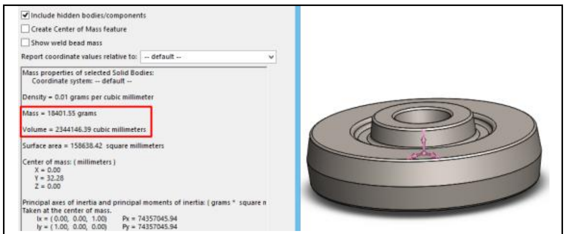

Figure 4. *Mass properties for the development forging part – SolidWorks*

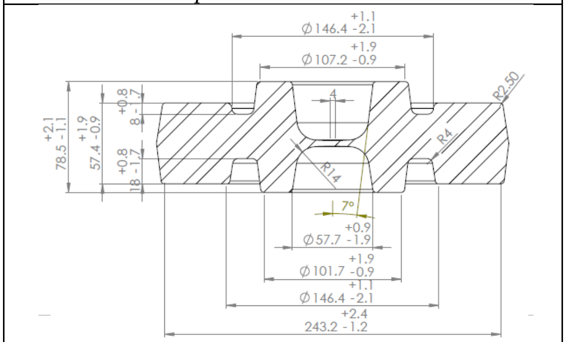

Figure 5. *Drawing of the forged part*

$$V_{enveloping\ \ shape} = \frac{{D_{max}}^2 \cdot \pi}{4} \cdot H_{max} = \frac{243.17^2 \cdot \pi}{4} \cdot 78.5 = 3644566.28\ mm^3$$

where, D_{max} [mm] – largest part diameter (with the added machining allowances), H_{max} [mm] largest part height (with the added machining allowances).

$$S = \frac{m_{forging}}{m_{enveloping\ \ shape}} = \frac{\rho \cdot V_{forging}}{\rho \cdot V_{enveloping\ \ shape}} = \frac{2344146.39}{3644566.28} = 0.64$$

The complexity factor S = 0.64 falls in the S1 category, same as the initially calculated value. Since the mass is within the previously selected range and the refined complexity factor matches the initial calculation, the added allowances are considered correct.

2.10. Determining the flash land geometry

The flash produced during closed-die forging is scrap material and may in many cases have a volume that is more than 50% of the final part volume. The amount of flash produced increases with the complexity of the part. However, the production of the flash is a necessary part of the process, and its control is essential to ensure good die filling [2]. The choice of the appropriate width and thickness of the flash land is an important part of the forging design. If the geometry is wrong, the dies may not fill completely or the forging loads may become excessive. In addition, the projected area of the flash in the flash land is usually included in the total projected area of the part for estimation of the forging loads required and therefore is a determining factor in equipment selection for processing. In order for vertical flow to occur in the die, the resistance to flow in the flash gap must be higher than that required for vertical flow in the die. The material must not flow into the flash gap until the die cavity is completely filled. The resistance to flow in the flash gap depends upon the ratio of flash land width to flash land height. The flash land height can be calculated approximately using the following expression [3]: $c = 0{,}015\sqrt{A}$

where, c [mm] – flash land height, A [mm^2] – projected area of the forging (including allowances and draft).

$$c = 0{,}015\sqrt{46775.67} = 3.244\ mm$$

The flash land width is calculated with the help of a coefficient that takes into account the way the die is filled during the forging process: $K = 1{,}5 + 0{,}3\,\frac{H}{B_{avg}}$

where, K – coefficient that takes into account the way the die is filled, H [mm] – largest die depth, B_{avg} [mm] – average width of the die at the location of the flash land.

$$K = 1.5 + 0.3\frac{42.8}{237.24} = 1.55$$

According to the calculated values for the bridge height *c* and the coefficient *K* we choose the nearest standard flash land size. All relevant dimensions are given in table 3 below and figure 293, page 596 in Obrada Metala Plasticnom Deformacijom, Binko Musafija [4].

Table 3. Standard flash land and gutter dimensions

$c\ [mm]$	$c_1\ [mm]$	$R\ [mm]$	$b\ [mm]$	$b_1\ [mm]$	$A_f\ [mm^2]$	$R_1\ [mm]$	$R_2\ [mm]$
4	6	2	11	30	268	6	2

Finally, we need to determine the flash volume in order to be able to calculate the dimensions of the initial workpiece. The flash volume is calculated by the following expression: $V_f = \xi \cdot A_f \cdot P$, where, V_f [mm^3] – flash volume, ξ = 0.5 – coefficient of gutter fullness for axisymmetric forged parts, A_f [mm^2] – flash gap cross section area, $P = D_{max} \cdot \pi$ [mm] – perimeter of the forging in the parting plane (parting line length).

$$V_v = \xi \cdot A_f \cdot P = 0{,}5 \cdot 268 \cdot 237.24 \cdot \pi = 99821.1\ mm^3$$

2.11. Determining the initial workpiece dimensions

The volume of the workpiece is the sum of the forging and the flash volume, while taking into account the scale losses that occur during heat treatment processes. Oxide scales discolour the metal surface and hinder subsequent finishing operations and therefore need to be removed from the heated stock, either before or during forging operations.

$$V_{wp} = (V_{FP} + V_f)(1 + \Delta)$$

where, V_{wp} [mm^3] – workpiece volume, V_{FP} [mm^3] – forging volume, V_f [mm^3] – flash volume, Δ - scale loss.

Due to the fact that scale loss cannot be included in the simulation, for the purpose of this report, the scale loss coefficient is not taken into account ($\Delta = 0$).

$$V_{wp} = (V_{FP} + V_f)(1 + \Delta) = 4252707.32 + 99821.1$$
$$= 4352528.42\ [mm^3]$$

Round parts are forged from cylindrical billets and before the dimensions are calculated we need to determine the relation between the height and the diameter of the workpiece.

$m = \frac{h_{wp}}{d_{wp}}$, where, $m = 1{,}5\ \div 2{,}8 - {}^{h}\!/_{d}$ ratio, d_p [mm] – workpiece diameter, h_p [mm] – workpiece diameter.

This relation is in the range $m = 1{,}5\ \div 2{,}8$. If m < 1.5 then the shearing of the billet to size is more difficult and is accompanied by the forming of big burr formations. For ratios of m > 2.8 there is a risk of buckling. The billet dimensions are determined by the volume and the ratio *m*. The estimated diameter is calculated as follows: $d_{wp} = 1.08\sqrt[3]{\frac{V_{wp}}{m}} = 154.04mm$

The standard dimensions for cylindrical billets are found in Kraut's Mechanical Engineering Handbook: $d_{wp} = 155\ mm$

The billets height is calculated using the expression:

$$h_p = \frac{V_{wp}}{A_{wp}} = \frac{4 \cdot V_{wp}}{\pi \cdot {d_{wp}}^2} \approx \mathbf{145}\ mm$$

The billet for the part forging has the following dimensions:

$$\emptyset\ \mathbf{155 \times 145}$$

2.12. Determining the die block dimensions

The dimensions selected for the die blocks depend on the depth of the cavity. The minimal thickness and height for each block (table 4) were selected according to the recommendations in Metal Forming Practise Processes, page 135, table 13.11 [3].

Table 4. Selected die block dimensions

	h [mm]	a [mm]	H [mm]
Upper block	43.76	56	200
Lower block	34.76	40	160

2.13. Production phases

1. Shearing the initial workpiece with a diameter of $\emptyset\mathbf{155}$ and height of $\mathbf{145\ mm}$.
2. Heating up the workpiece to the forging temperature of $\approx \mathbf{1100\ °C}$.
3. Upsetting the workpiece to a height of $\boldsymbol{h_1 = 83\ mm}$. The upsetting is carried out on a power-drop steam hammer (5t).
4. Finishing forging done on a power-drop steam hammer to the shape and dimensions given in Figure 5.
5. Flash removal using a trimming die and punching the barrier plate for the hole.

3. Simulation of the forging process

Computer Aided Engineering has many benefits when it comes to saving time and expenses, it gives certain important information about the forging process before the part is approved for production. Information as material flow, stress, deformation, temperature etc. are available to the user at any given moment after the simulation is done. This way potential defects as material overlapping, excess or lack of material etc. After all the calculations are finished, the 3D model and the 2D sketches in the CAD software, everything is set for the simulation to begin.

The numerical analysis for this study is simulated in two operations, upsetting and closed die forging with flash, as well as an additional operation for removing the flash and plate.

The first operation as said is upsetting. It is done with a 5t forging hammer. The initial part is heated to 1100 °C for the recrystallization process to occur. In this phase the initial height of the part 145 mm is reduced to 83 mm. This allows the following operation to be completed with ease. The reducing of the height is completed with hammer blows. Figure 6. shows the maximum and minimum effective stress of the part in the first blow of the upsetting stage. The maximum stress is 170.83 MPa. Figure 7. shows the maximum and minimum effective stress of the part in the second blow of the upsetting stage. The maximum stress is 216.18 MPa.

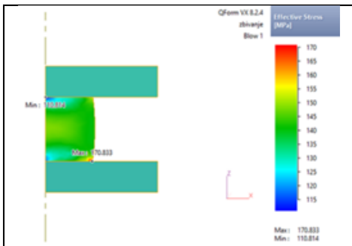

Figure 6. *Effective stress during the first blow*

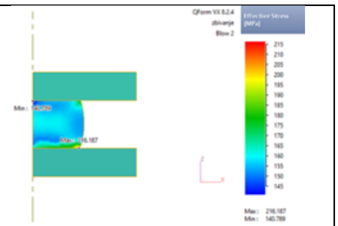

Figure 7. *Effective stress during the second blow*

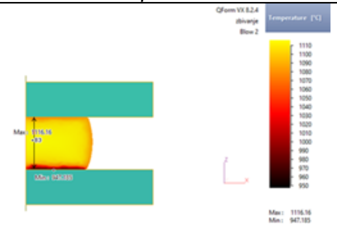

Figure 8. *Part temperature after the upsetting phase*

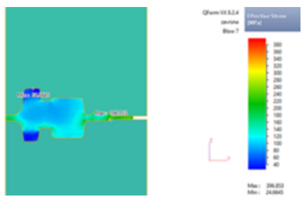

Figure 9. *Unsuccessful closed die forging simulation*

Figure 8. shows the temperature of the part after the upsetting. It is clear that the inside of the part will have its temperature (1116.16 °C) increased due to the deformations.

The second operation, closed die forging with flash, is completed with 5 hammer blows. The part is still heated, and graphite + water is used as a lubricant. In this operation the part gets its final geometry, and this is the phase where the most defects happen. During the simulation, there were a few unsuccessful attempts due to excess material, as it is shown is figure 9.

Figure 10, 11, 12 and 13 show the four needed blows for the operation. The figures show that the cavity fills in the first, second and third blow, and the fourth blow is for filling the flash.

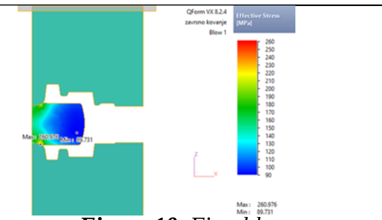

Figure 10. *First blow*

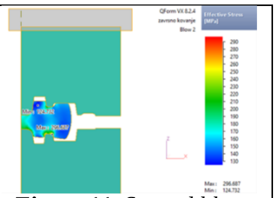

Figure 11. *Second blow*

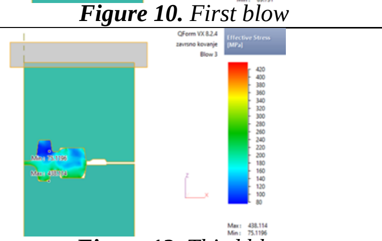

Figure 12. *Third blow*

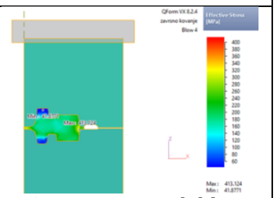

Figure 13. Fourth blow

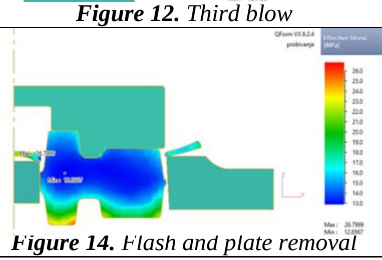

Figure 14. *Flash and plate removal*

The additional operation, removal of flash and plate, is completed on a mechanical press (6.3 MN). The goal of this operation is to remove the excess material which was necessary during the forging process. This operation is done with one blow, simultaneously removing the flash and plate (Figure 14).

4. Conclusion

Forging simulation offers significant advantages by providing detailed insight into the forging process before tool selection and process decisions are made on the shop floor [5]. Thanks to the numerical simulations, the initial error in the study is avoided, and the simulation was successful. Because of the complexity of metal flow, the friction between the tool and part, the temperature generation, CAE software is needed to analyse the initial idea of how the process should look like. In the process of making a product, it is very important in getting to know the characteristics of certain structures and their behaviour in exploitation.

5. References

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