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# ANALYSIS OF THE INFLUENCE OF HOT FORGING PROCESS PARAMETERS ON TOOL WEAR USING THE FINITE ELEMENT METHOD

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***Abstract:*** *The aim of the research is to determine the influence of variable parameters of the hot forging process on tool wear. The research was conducted using the finite element method, software used for simulating the forming process was Simufact.forming. The case study of hot forging of an artillery shell body was analyzed. Data on the dimensions and material of the shell were taken from official literary sources. The influence of four parameter was analyzed: lubrication, blank temperature, tool temperature and tool hardness. Each of the four listed factors has three levels, so the experimental plan was made according to the Taguchi matrix L9. By applying the statistical Taguchi method, the simulation results such as tool wear, forming load, etc. will be analyzed. The less-the-better analysis forms were used to analyze the results. The total amount of tool wear was not analyzed, but rather one place on the tool where the wear value is the highest.*

***Keywords:*** *hot forging, tool wear, finite element method, Taguchi method*

## 1. INTRODUCTION

Hot forging is one of the most important technologies for bulk metal forming. Despite the progress of modern technologies such as micro-casting or 3D metal printing, hot forging is very important for the production of parts that are exposed to high loads. Hot forging has an important place in the military and automotive industries due to the good mechanical properties of the manufactured parts. By heating the workpiece, lower values of the yield stress are achieved, but due to high temperatures, it is very difficult to provide lubrication. In the hot forging process, the tools are loaded due to high temperature, friction that occurs due to sliding of the material on the tool surface and, in the case of hammer forging, impact load. The wear of forging dies is the subject of numerous studies. The aim of technologists is to determine the optimal parameters of the process to ensure the least possible wear of the dies and thus extend their service life. The service life of the dies is important for reducing production costs and increasing productivity. About 70% of die damage is related to wear. An analysis of the influence of forging slopes, radius of curvature and other geometric parameters on die wear is presented in [1]. Numerical experiments were performed numerically using the DEFORM software and the Archard wear model. By choosing the values of the geometric parameters according to the recommendations, the wear of the tool is reduced.

In this paper, the influence of several process factors on the wear of forging dies is analyzed. The influence of lubrication, blank temperature, die temperature and die hardness is considered. The research was conducted numerically using the Simufact.forming software. Archard wear model was used. Results were analyzed using the Taguchi method.

During forging, the tools are exposed to thermal stress at temperatures from 80°C to 600°C as well as mechanical load where stress reaching 1200 MPa [2]. Due to the consideration of the influence of thermal load on tool wear, the values of the blank temperature and the tool temperature were varied. Since it is forged from low-carbon steel, the temperature range is between 1050°C and 1200°C. Tool temperature is between 150ºC and 250°C.

The Archard model provide consideration of tool hardness ranging from 45 to 55 HRc. During the hot forging process, three wear models occur: thermal, mechanical and abrasive [3, 4].

The effect of lubrication was analyzed by taking different values of the friction factor. When applying lubricant, in addition to the amount, the method of application is also important. Different types of lubricants were analyzed by the ring compression test [5] and it was concluded that graphite-based lubricants gave better results. Based on the results of this test, the values of the friction factor used in the numerical experiment were defined.

## 2. DESCRIPTION OF EXPERIMENT

The analysis of the influence of factors was carried out using the finite element method on the example of hot forging of the artillery shell body. The artillery shell production process consists of cutting out the appropriate blanks, heating to the appropriate temperature, hot forging by piercing and then continuing with the cold forming and finally by cutting the final dimensions are achieved. The tool wear in the first forging operation was analyzed. In this paper, the total amount of tool wear was not analyzed, only one place where the tool wear have maximum value. The dimensions and shape of the forging were taken from the material [6]. The shape of the part after the forging operation is shown in Figure 1.

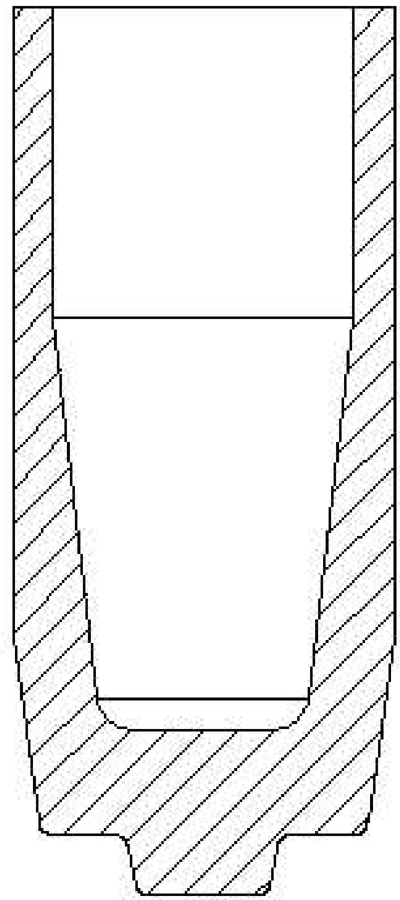

**Figure 1.** Forged shell body after hot forging

The experiment was planned according to the Taguchi matrix L9. Four parameters with three levels each were considered. Lubrication conditions were considered using different values of the friction factor.

The values of the factor m are 0.3, 0.45 and 0.6. The factor 0.6 corresponds to the case with little or no lubrication, 0.45 to the case when a graphite-free lubricant is used and the value 0.3 to a graphite-based lubricant. The values were taken for the average values of the lubricant amount according to the results presented in the paper [5].

Three values of the blank temperature were considered: 1050°C, 1100°C and 1150°C. The considered tool temperature values were 170°C, 210°C and 250°C.

Three values of the tool hardness were taken into consideration: 47 HRc, 50 HRc and 53 HRc. The experimental plan is shown in Table 1.

**Table 1.** Experiment plan

| Exp no. | Lubrication | Blank temp. | Tool temp. | Tool hardness |
|---|---|---|---|---|
| 1 | m=0,3 | 1050ºC | 170ºC | 47 HRC |
| 2 | m=0,3 | 1100ºC | 210ºC | 50 HRC |
| 3 | m=0,3 | 1150ºC | 250ºC | 53 HRC |
| 4 | m=0,45 | 1050ºC | 210ºC | 53 HRC |
| 5 | m=0,45 | 1100ºC | 250ºC | 47 HRC |
| 6 | m=0,45 | 1150ºC | 170ºC | 50 HRC |
| 7 | m=0,6 | 1050ºC | 250ºC | 50 HRC |
| 8 | m=0,6 | 1100ºC | 170ºC | 53 HRC |
| 9 | m=0,6 | 1150ºC | 210ºC | 47 HRC |

## 3. TOOL AND NUMERICAL SIMULATION PARAMETERS

According to the reference [6], the tool consists of three parts: cabbage, die and punch. The workpiece material is AISI 1064 and the tools are made of tool steel H11. The numerical simulation was performed as a 2D simulation because the workpiece and the tools are axisymmetric. In order to be able to analyze tool wear, it is necessary that the working elements of the tool, the punch and die, be defined as deformable. The tools ready for simulation are shown in Figure 2.

The Simufact.forming software uses the Archard model to estimate tool wear. The Archard model is used to calculate the abrasive wear of bodies in contact. In the finite element method, the calculation of wear according to the Archard model is done according to the formula:

$$w = \int \frac{K}{H} \cdot \sigma_N |V_{rel}| dt. \quad (1)$$

The wear parameter w represents the length of reduction of the tool dimensions perpendicular to its surface. Wear is equal to the product of the normal stress (MPa), the relative velocity (m/s) and the wear coefficient in relation to the material hardness (MPa).

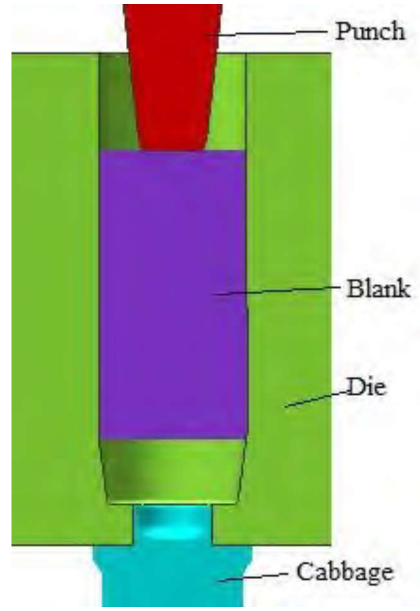


**Figure 2.** Tools in Simufact.forming software

The initial value of the wear coefficient is 1e-5. The value w is a relative value and to obtain absolute values it is necessary to calibrate the simulation, that is, to compare the numerical results with the experimental ones and thus correctly define the parameters of the numerical simulation. In this paper, attention is paid to the assessment of wear based on the results of the numerical simulation and the calibration of the simulation will be left for future research.

The finite element mesh on the deformable tools was created using the Advancing front quad mesher, with the element type Quads (10) and the element size 5 mm. The Refinement boxes were set so that the mesh was refined at all points where there was contact. Refinement boxes were made with refinement level 4. The Quadtree mesher with the element type Quads (10) was used to discretize the workpiece. A constant friction model was used and a friction factor was defined.

## 4. RESULTS OF NUMERICAL SIMULATION

The value of the wear parameter w on the punch and the die was considered. Then, results were analyzed using the Taguchi method. Since the result w was considered, the less is better approach was chosen.

Numerical simulation showed that the forging process was successful. The distribution of the normal stress values on the forging is shown in Figure 3.

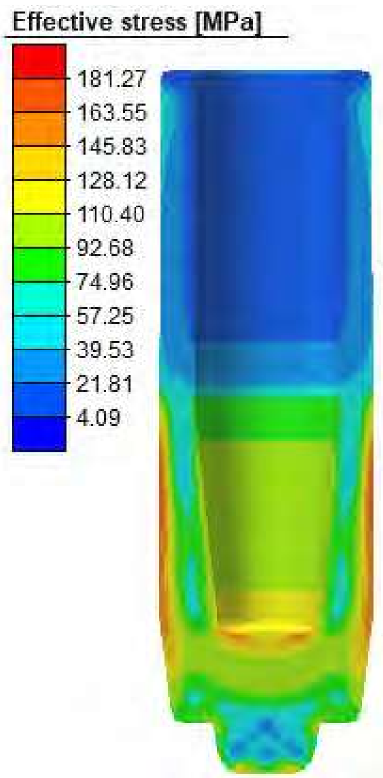


**Figure 3.**Distribution of effective stress on the workpiece (forging) in experiment 1

Figure 4 shows workpiece temperature at the end of the forging process in experiment 1. The temperature of the part is highest in the middle part of the forging, which is in contact with the punch the longest. On the outside of the part, the temperature has a value between 770°C and 950°C.

The results that will be analyzed separately are the wear values of the punch and the die. As mentioned earlier, only the highest wear value was considered, that is, one critical point with the highest wear.

The distribution of the wear values of the punch is shown in Figure 5. The greatest wear of the punch is on the upper radius above the conical part. Considering the results, it is concluded that if the design requirements allow, the radius should be increased to facilitate the flow of the material.

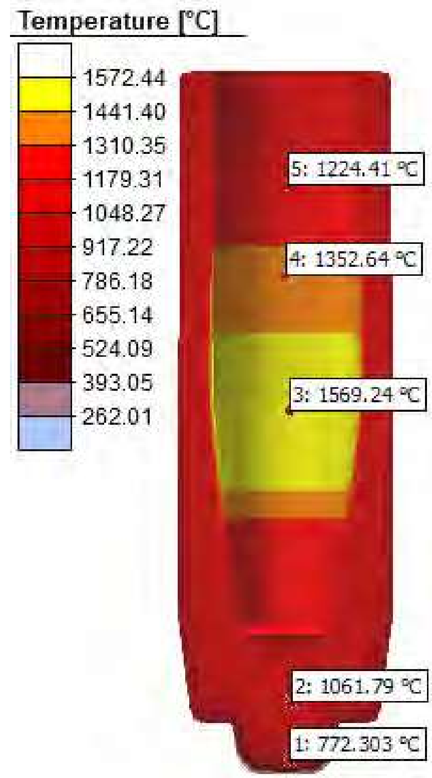


**Figure 4.**Temperature distribution in experiment 1

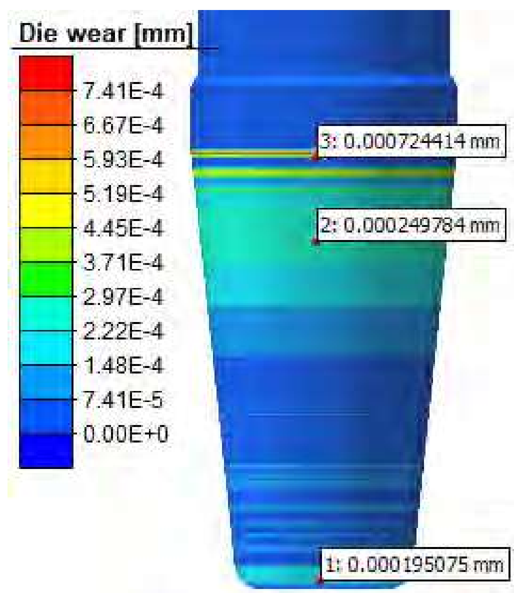


**Figure 5.**Wear distribution on the punch in experiment 1

It is interesting to look at the temperature distribution on the punch in experiment which is shown in Figure 6.

Highest temperature value is precisely in the part where the highest wear value occurs.

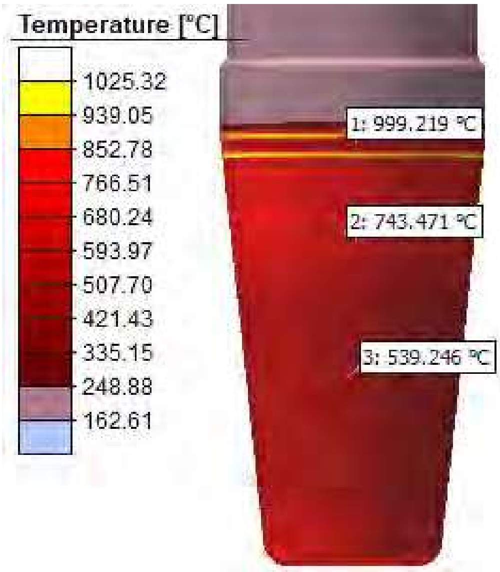


**Figure 6.** Temperature distribution on the punch in experiment 1

The wear distribution on the die is shown in Figure 7. The wear is significantly less than on the punch. The highest wear value is on the lower radius as well as on the part that is in contact with the material the longest.

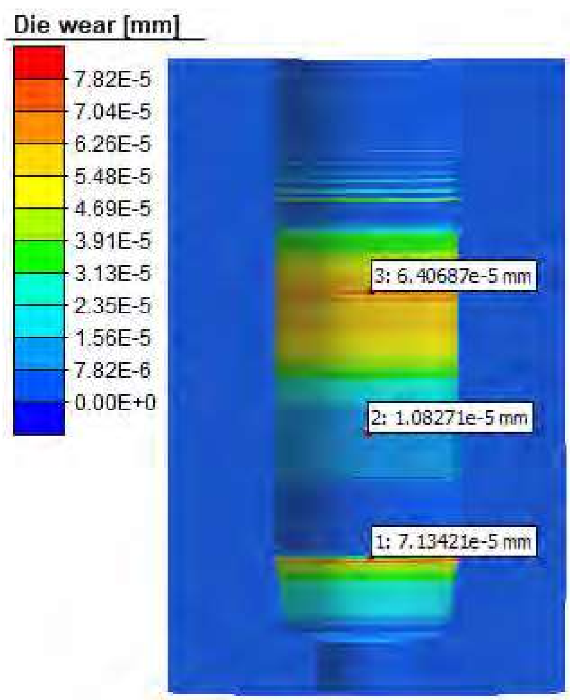


**Figure 7.** Die wear distribution in experiment 1

After defining the zones of the die that are most exposed to wear, it is important to consider the temperature and effective stress distribution on the die. The temperature distribution is shown in Figure 8. As with punch, the zone of highest temperature coincides with the zone of highest wear.

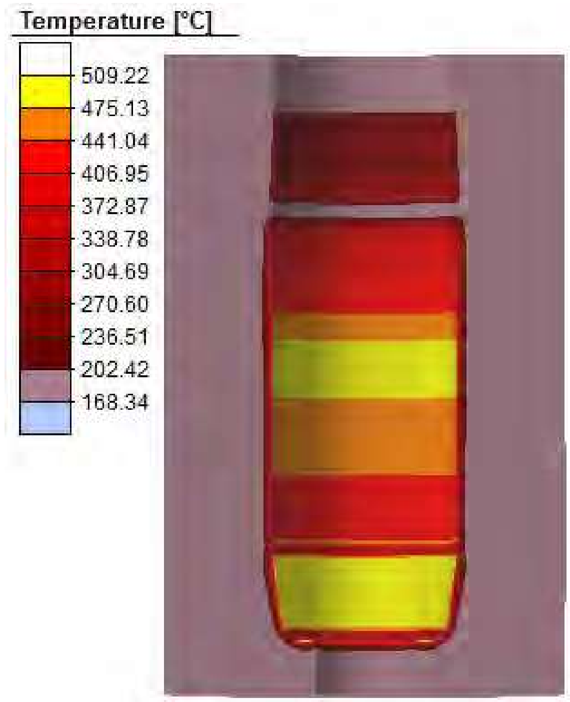


**Figure 8.** Temperature distribution on the die in experiment 1

Plastic strain does not occur on the die and the punch, the effective stress distribution on the die is shown in Figure 9. The stress is less than 800 MPa on most of the die, only higher values occur at the bottom of the die, more precisely on the radius and amount to slightly more than 2000 MPa. The explanation for this phenomenon is the nature of the process, which, although it belongs to hot forging, is similar in nature to combined extrusion.

All results shown are from experiment number 1. The wear distribution in all cases is similar, only the values differ. The results of the experiments are given in Table 2.

**Table 2.** Experiment results

| EXPER. | Wear-punch, mm | Wear - die, mm | Forming load, t |
|---|---|---|---|
| 1 | $7{,}41\cdot10^{-4}$ | $7{,}82\cdot10^{-5}$ | 1450,06 |
| 2 | $5{,}79\cdot10^{-4}$ | $6{,}77\cdot10^{-5}$ | 1357,59 |
| 3 | $5{,}13\cdot10^{-4}$ | $4{,}87\cdot10^{-5}$ | 1219,83 |
| 4 | $4{,}99\cdot10^{-4}$ | $4{,}45\cdot10^{-5}$ | 1799,32 |
| 5 | $5{,}65\cdot10^{-4}$ | $5{,}06\cdot10^{-5}$ | 1554,12 |
| 6 | $5{,}44\cdot10^{-4}$ | $3{,}7\cdot10^{-5}$ | 1550,26 |
| 7 | $3{,}21\cdot10^{-4}$ | $3{,}35\cdot10^{-5}$ | 2256,25 |
| 8 | $2{,}61\cdot10^{-4}$ | $2{,}61\cdot10^{-5}$ | 2139,16 |
| 9 | $3{,}53\cdot10^{-4}$ | $2{,}84\cdot10^{-5}$ | 1998,52 |

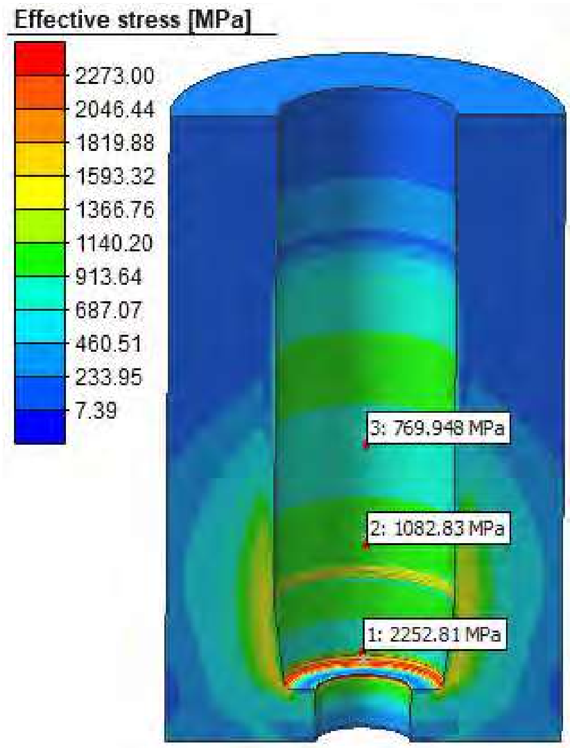


**Figure 9.**Distribution of effective stress on the die in experiment 1

## 5. DISCUSSION OF RESULTS

Since the influence of four factors with three levels each was considered, the experiment was organized according to Taguchi's L9 matrix. Since the aim of the analysis was the influence of wear, the less is better approach was used.

For each experiment, the signal-to-noise ratio (S/N) was calculated. This ratio is a logarithmic function of the output, and serves as the object of an optimization function, its task being to assist in data analysis and prediction of optimal results. There are three forms of the ratio (S/N) for optimization problems: smaller is better, larger is better, and nominally best. It is calculated according to the formula:

$$n = -10log_{10}\begin{bmatrix} average\ of\ the\ sum\ of \\ squares\ of\ measured \\ values \end{bmatrix}.$$

It is used in the calculation of some losses or defects where the desired ideal value is zero (e.g. wear analysis, etc.). The results of the response by the less-better model are shown in Table 3.

**Table 3.**Response results

| Експ. | S/N-punch wear | S/N- die wear | S/N-press force |
|---|---|---|---|
| 1 | 62.6036 | 82.1359 | -63.2277 |
| 2 | 64.7464 | 83.3882 | -62.6554 |
| 3 | 65.7977 | 86.2494 | -61.7260 |
| 4 | 66.0380 | 87.0328 | -65.1022 |
| 5 | 64.9590 | 85.9170 | -63.8297 |
| 6 | 65.2880 | 88.6360 | -63.8081 |
| 7 | 69.8699 | 89.4991 | -67.0677 |
| 8 | 71.6672 | 91.6672 | -66.6049 |
| 9 | 69.0445 | 90.9336 | -66.0142 |

Based on the response results shown in Table 3, the delta value was calculated, which represents the difference between the highest and lowest response values. Based on the delta value, the influence of the considered parameters was determined, the higher the delta value, the greater the influence of the considered parameter.

The greatest influence on the wear of the punch is friction, followed by the hardness of the punch, and then the blank temperature and punch temperature. The best result, the lowest wear value, is achieved for the friction factor value m=0.6 as shown in Table 4. The most suitable blank temperature is 1150ºC, the tool temperature is 250ºC and the tool hardness is 53 HRc.

**Table 4.** Punch wear results

| Level | Friction | Billet temperature | Die temperature | Die hardness |
|---|---|---|---|---|
| 1 | 64.38 | 66.17 | 66.52 | 65.54 |
| 2 | 65.43 | 67.12 | 66.61 | 66.63 |
| 3 | 70.19 | 66.71 | 66.88 | 67.83 |
| Delta | 5.81 | 0.95 | 0.36 | 2.30 |
| Rank | 1 | 3 | 4 | 2 |

The results of die wear by levels and delta factors are shown in Table 5. As with the punch, friction has the greatest influence and the most favorable result was achieved for the friction factor m=0.6. The second parameter in terms of influence on die wear is blank temperature, which is explained by the significantly larger contact surface between the blank and the die.

The third in terms of influence is the hardness of the die and die temperature has the least influence.

**Table 5.** Die wear results

| Level | Friction | Billet temperature | Die temperature | Die hardness |
|---|---|---|---|---|
| 1 | 83.92 | 86.22 | 87.48 | 86.33 |
| 2 | 87.20 | 86.99 | 87.12 | 87.17 |
| 3 | 90.70 | 88.61 | 87.22 | 88.32 |
| Delta | 6.78 | 2.38 | 0.36 | 1.99 |
| Rank | 1 | 2 | 4 | 3 |

Finally, the influence of factors on the required forming load was analyzed. The results are shown in Table 6. The results show that the friction conditions have the greatest influence.

**Table 6.** Response results for forming load

| Level | Friction | Billet temperature | Die temperature | Die hardness |
|---|---|---|---|---|
| 1 | -62.54 | -65.13 | -64.55 | -64.36 |
| 2 | -64.25 | -64.36 | -64.59 | -64.51 |
| 3 | -66.56 | -63.85 | -64.21 | -64.48 |
| Delta | 4.03 | 1.28 | 0.38 | 0.15 |
| Rank | 1 | 2 | 3 | 4 |

However, certain shape deviations were observed in the case when the friction factor has a value of 0.6. In all three cases for this value of the friction factor (experiments 7, 8 and 9) a shape deviation was observed. Due to excessive friction, the material flows along the die wall and a smaller geometry deviation occurs. The punch has this geometry so that the friction between the punch and the material is lower and the forming load has a smaller value. The appearance of the part geometry in these cases is shown in Figure 10.

The value of the observed geometric deviation depends on the punch design. The thinning of the body of the punch can be performed in such a way that the difference between the two diameters of the punch is smaller so that the geometric deviation of the part is acceptable and does not affect the height of the piece. After determining that there is a geometric deviation, the simulation was repeated with a different geometry of the punch, when there is no reduction in its diameter. The results of this simulation showed the same trend of the influence of the parameters on wear, and in this case the least wear was measured in the case of the friction factor m=0.6. As expected, in this case there is a significant increase in the forming load, about 50%. A comparison of the forming load -stroke diagram for experiment number 8 for two cases, when the diameter of the punch is reduced and when it is not, is shown in Figure 11.

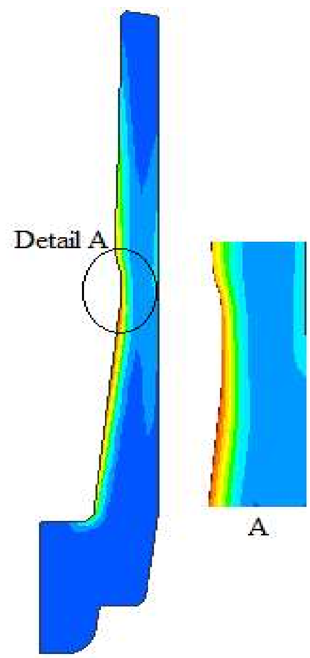


**Figure 10.** Deviation of forging geometry in experiments 7, 8 and 9

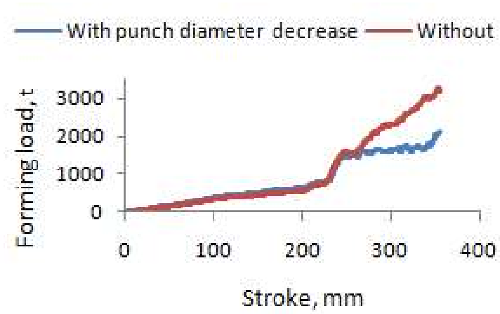


**Figure 11.** Forming load – stroke diagram for experiment no. 8 for two punch geometries

## 6. CONCLUSION

The results of numerical experiments have shown that the process of abrasive wear of tools during shell body forging is most influenced by friction conditions, followed by tool hardness and then the temperatures of the blank and tools. The explanation for such a large influence of friction conditions is the large difference in the values of the friction factors taken from the values from the literature. According to the results, the most favorable case, i.e. the lowest wear intensity, was achieved for the highest value of the friction factor, which does not agree with the theoretical assumptions. The explanation and justification for these results is that the total wear was not observed, but only one small zone with maximum wear. The conclusion is that in the case of forging the artillery shell body, friction is desirable. The explanation for such results lies in the complexity of the process, which belongs to hot forging (punch), but due to the initial position of the blank, it is very similar to combined extrusion. In order to confirm such results, the experiments were repeated with another friction law, combined, and the ratio of influential factors remained unchanged. The application of numerical simulations for wear assessment is increasingly being used in assessing whether the tool design is good. The continuation of the research will be an experimental verification of the considered results.

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