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Optimization of a Cold Forging Die Design Using Simulation Software

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Abstract— *The article presents an approach to predict cold forging product quality by simulation method and AHP method. The modern method to achieve stable product quality and recommend suitable technological parameters is to analyze simulation results. Technological improvements achieved by modifying the geometry of the die and the forging process reduce flow defects and stress concentration in critical areas. CAE simulations such as QForm allow finding optimal interference values that provide compressive stress states in complex but fragile inserts under actual forging loads. Plastic strain and defects of forged products can be predicted and minimized by simulation. The presented model is realized in the commercial metal forming simulation software Qform.*

Keywords— *QForm, Cold Forging, CAE, Simulation.*

I. INTRODUCTION

Cold forging is a widely used manufacturing method in automotive engine parts and aerospace components because of its excellent quality, high efficiency, and less scrap generated in the process compared to other production methods [1] . Cold forging dies are usually designed based on forging manuals and standards, for example, GOST 7075-89, GOST 7505-89 …The advantage of this traditional design method is that the design process is transparent, and the resulting products often meet quality requirements. However, this method also has many significant disadvantages. First, the die must be tested, and then modified many times before being applied to the actual production process. Second, cold forging requires a large forging force, so the die is often damaged quickly. This means increased production costs and reduced economics. For these reasons, simulation software is often used to calculate cold forging die optimization to reduce design time and improve product economics [2].

This article presents a method to predict the quality of cold forging products by simulation method. [3]. FE simulation allows for finding the optimal die design and suitable workpiece geometry. The simulation also generates the profile geometry of the die to compensate for the elastic deformation of the die and produces precise geometrical accuracy of the forging products. Plastic cracks in forgings can be predicted and minimized by simulation [2]. The presented model is realized in the commercial metal forming simulation software QForm. The results of this work allow the prediction of loops, forging forces required for the actual process, and the determination of incomplete defect locations as well as different stress and deformation positions in the die cavity afterwards. offer solutions to replace suitable materials for each region.

II. MATERIALS AND METHODS

CAE software, like as QForm was implemented to simulate and predict the complex forging in this research project. First, create a forging object model with some CAD/CAE software such as Inventor, Solidworks, etc. Next, use the software with the function of forming the die cavity based on the forging object model, for example, NX to Create upper and lower dies. Depending on the structure of the product, it is possible to create other tools to coordinate shaping during the forging process, in the research with the details of the spur gear being forged 3 options to find the most optimal… Finally, input the data of the object model, the forging die, the remaining tools, and QForm software, set up the parameters, and then conduct a simulation of the forging process. Simulation results are analyzed and compared with reality to check the accuracy of simulation software.

2.1 Materials of workpieces and dies

The initial workpiece and die materials are JIS S45C low-carbon steel and JIS SKD61 steel alloy. The chemical composition of the workpiece material is shown in Table 1[4].

TABLE 1. Chemical composition of S45C carbon steel in a percent :

C	Si	Mn	P	S	Ni	Cr
0.42 ÷ 0.50	0.15 0.35	0.5 0.8	0.025	0.025	0.20÷0.40	0.2

The process of the cold forging of spur gear is carried out in 2 steps. The workpiece is shaped in the upsetting step and the product finishing step.

TABLE 2. Chemical composition of SKD61 in percent

C	Si	Mn	P	S	W	Cr	Ni
< 0.07	< 1	< 2	< 0.045	<0.015	<0.11	17.5÷19.5	8÷10.5

In this work, the forging process is carried out at a room temperature of 20^{o}C. The forging parameters are selected based on expert recommendations and actual mechanical forging machines at the workshop. The variant data used in this project are shown in Table 3.

TABLE 3. Forging process parameters

	Upsetting step	End forging
Workpiece material	S45C	S45C
Workpiece temperature	20ºC	Inherited from Weasel step
Punch	SKD61	SKD61
Die temperature	200 °C	200 °C
Machines	Mechanical press 10MN	Mechanical press 10MN
Bottom die	SKD61	SKD61
Lubrication	Graphite + water	Graphite + water
Stop condition: Distance from upper die to lower die	23.4mm	15mm

2.2 Simulation process in QForm.

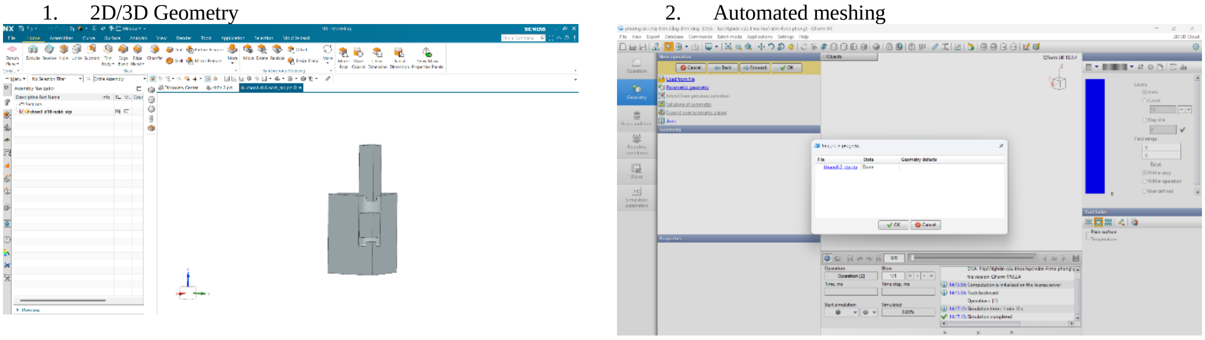
The four main steps of the simulation process in QForm are shown in Figure 4.

- In the first step, geometric data of the upsetting process and die are prepared and imported.

-In the second step, the initial technology parameters are filled in corresponding to the process parameters, including the workpiece, die, and stopping conditions.

The workpiece material is S45C. The properties and characters of the S45C are illustrated in Figure 6 .

1. 2D/3D Geometry
2. Automated meshing



3. Initial technological data
4. Results

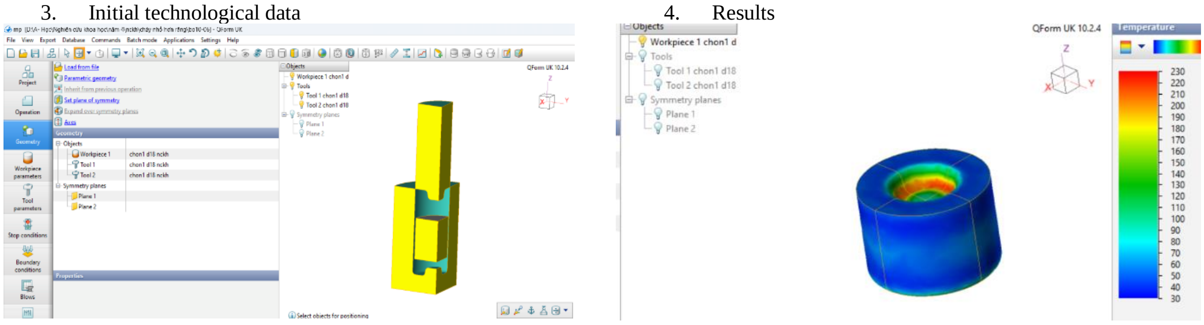


Figure.4. Simulation process in QForm software

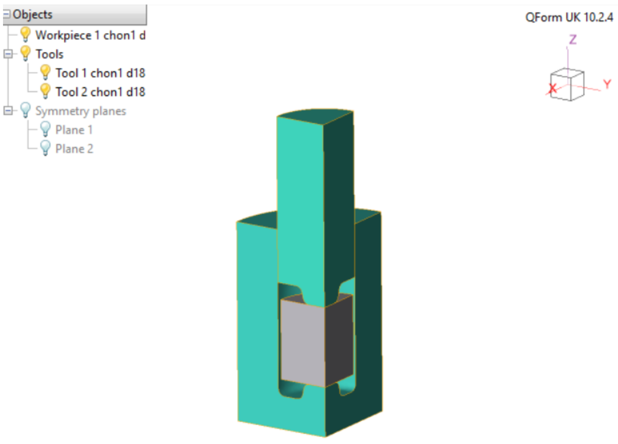
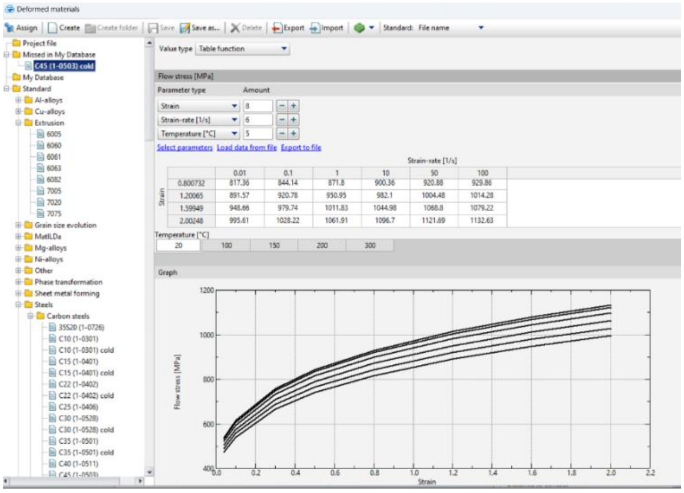


Figure.5. Original geometry data of the workpiece and upsetting die



Value type: Table function

Flow stress [MPa]

Parameter type	Amount
Strain	8
Strain-rate [1/s]	6
Temperature [°C]	5

Select parameters Load data from file Export to file

Strain	Strain-rate [1/s] 0.01	0.1	1	10	50	100
0.800732	817.36	844.14	871.8	900.36	920.88	929.86
1.20065	891.57	920.78	950.95	982.1	1004.48	1014.28
1.59949	948.66	979.74	1011.83	1044.98	1068.8	1079.22
2.00248	995.61	1028.22	1061.91	1096.7	1121.69	1132.63

Temperature [°C]: 20 100 150 200 300

Figure.6. Workpiece parameters

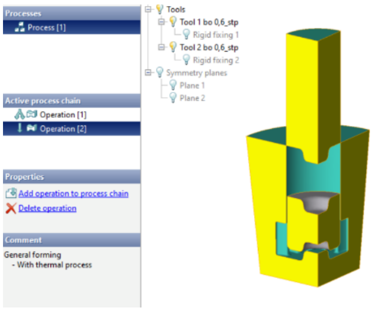
-The material of the upper die and lower die is H13 (SKD61 steel). In the case where the upper die can move on the OZ+ axis while the lower die is fixed, in this simulation the die is heated to 200˚C as actual manufacturing conditions.

Tools parameters	
Drive	
Tool 1 spur gear_stp	10MN
Tool 2 spur gear_stp	+OZ
Lubricant	Cold forging\Steels\Graphite + water
Tool 1 spur gear_stp	Cold forging\Steels\Graphite + water
Tool 2 spur gear_stp	Cold forging\Steels\Graphite + water
Material	H13 HRC50
Tool 1 spur gear_stp	H13 HRC50
Tool 2 spur gear_stp	H13 HRC50
Temperature [°C]	200
Tool 1 spur gear_stp	200
Tool 2 spur gear_stp	200
Put in contact	move backward first
Tool 1 spur gear_stp	move backward first
Tool 2 spur gear_stp	move backward first
Friction between tools	Steel-steel no lubricant
Coupled tools simulation	☐
Tools deformation model	Separate
Tool 1 spur gear_stp	☐
Tool 2 spur gear_stp	☐
Heat transfer to workpiece	Simple
Tool 1 spur gear_stp	Simple
Tool 2 spur gear_stp	Simple
Spring loaded tool	☐
Tool 1 spur gear_stp	☐
Tool 2 spur gear_stp	☐
Movement of a tool by another connecting tool	☐
☐ Springs between tools	

Stop conditions	
Minimum share of free surface [%]	1
Condition 1	Distance
Distance [mm]	23.4
Individually for each blow	☐
From tool	Tool 1 chon1 d18 nckh
To tool	Tool 2 chon1 d18 nckh
Point 1	☑
X [mm]	-4.07172
Y [mm]	-10.705
Z [mm]	10
☐ Additional records	

Figure.7. Die parameters and stop conditions

- In step 3: Finishing forging



General forming
- With thermal process

Figure.8. Geometry data after the upsetting step

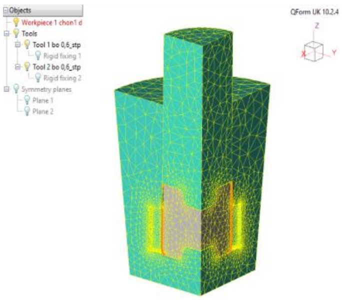


Figure.9. Meshing original geometry data with the adaptive meshing tool

- The mesh properties of the workpiece and the die before the performing step are shown in Table 4.

-In step 4, the workpiece parameters and stop condition are set the same as in step 2.

-In the final step, the necessary results are analyzed to investigate the actual product quality and find ways to change the die or technological parameters.

TABLE 4. Mesh properties of original geometry data

Object	Buttons on the surface	Internal button	Total number of buttons	Surface elements	volume factor
Workpiece	1548	1044	2592	3092	11028
Upper die	691	207	898	1378	3191
Die below	11265	10167	21432	22526	97877
Total	**13504**	**11418**	**24922**	**26996**	**112096**

TABLE 5. Mesh properties of the geometry data after finishing the forging step

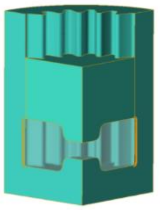
Object	Buttons on the surface	Internal button	Total number of buttons	Surface elements	volume factor
Workpiece	9121	8778	17899	18238	82543
Upper die	691	207	898	1378	3191
Bottom die	11265	10167	21432	22526	97877
Total	**19885**	**17739**	**37624**	**39758**	**171043**

-After finishing the forging step, the simulation results can be analyzed to modify the die or predict the quality of the forged product.

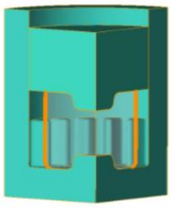
III. COMPARATIVE METHODS AND RESULTS

3.1.Simulation options

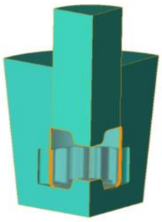
1. Option 1: Plan of tooth punch for cold forging



2. Plan of round punch with a diameter equal to tooth tip diameter

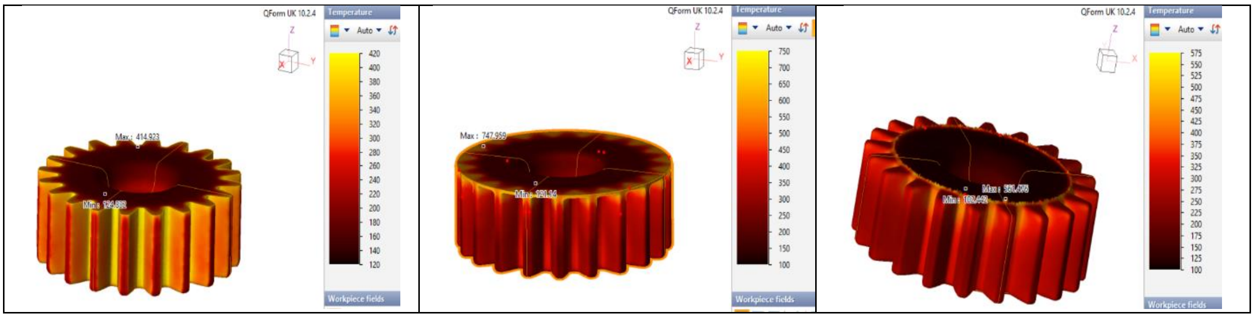


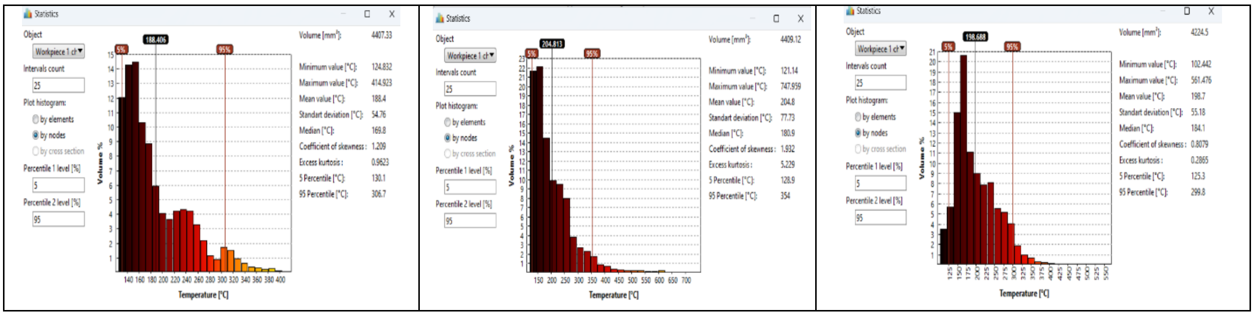
3. Plan of round punch with a diameter smaller than the tooth tip diameter



3.2. Simulation results

3.2.1. Workpiece temperature





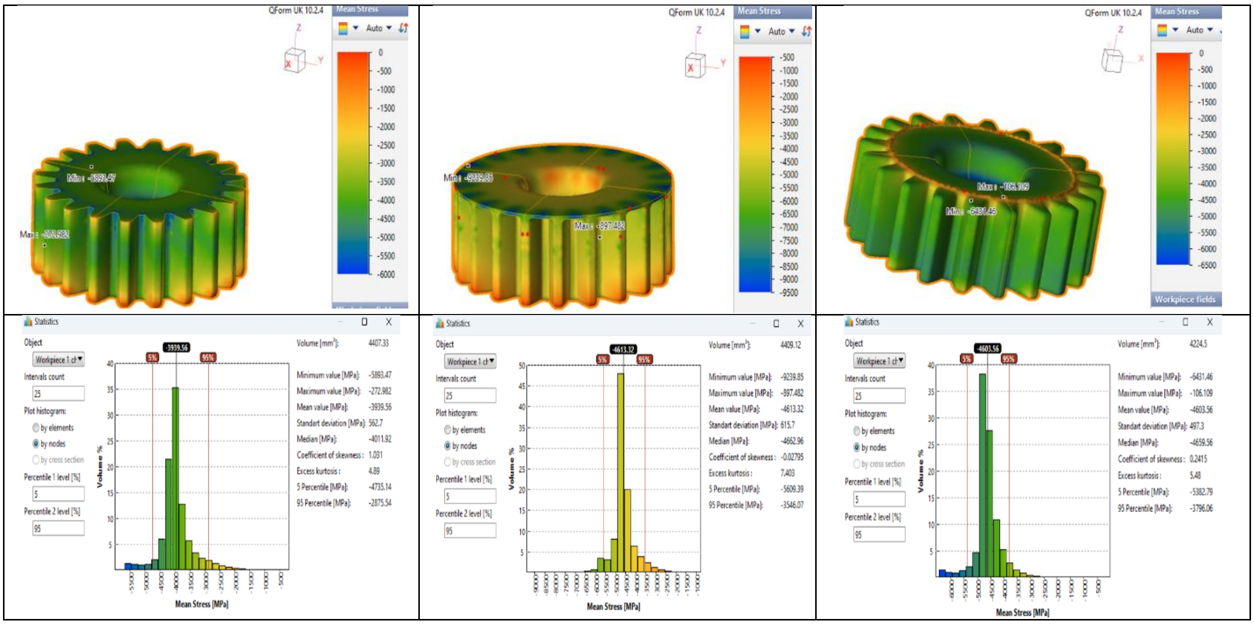
Volume [mm³]: 4407.33
Minimum value [°C]: 124.832
Maximum value [°C]: 414.923
Mean value [°C]: 188.4
Standart deviation [°C]: 54.76
Median [°C]: 169.8
Coefficient of skewness : 1.209
Excess kurtosis : 0.9623
5 Percentile [°C]: 130.1
95 Percentile [°C]: 306.7

Volume [mm³]: 4409.12
Minimum value [°C]: 121.14
Maximum value [°C]: 747.959
Mean value [°C]: 204.8
Standart deviation [°C]: 77.73
Median [°C]: 180.9
Coefficient of skewness : 1.932
Excess kurtosis : 5.229
5 Percentile [°C]: 128.9
95 Percentile [°C]: 354

Volume [mm³]: 4224.5
Minimum value [°C]: 102.442
Maximum value [°C]: 561.476
Mean value [°C]: 198.7
Standart deviation [°C]: 55.18
Median [°C]: 184.1
Coefficient of skewness : 0.8079
Excess kurtosis : 0.2865
5 Percentile [°C]: 125.3
95 Percentile [°C]: 299.8

-Remarks: High temperature can affect the mechanical and structural properties of C45 steel as follows. Deformation and hardness: High temperatures can increase the deformability of C45 steel, making it easier to bend or permanently deform. At the same time, high temperatures can also reduce the hardness of steel. Changing the crystal structure, high temperatures can change the crystal structure of C45 steel. At that time, there will be a change in the size and shape of the crystal, reducing the hardness and strength of the steel. Magnet properties: High temperature can also reduce the magnetism of C45 steel, causing it to be susceptible to magnetic fields or loses its magnetic properties. Therefore, it is necessary to limit the temperature of the workpiece during the forging process.

3.2.2. Mean Stress



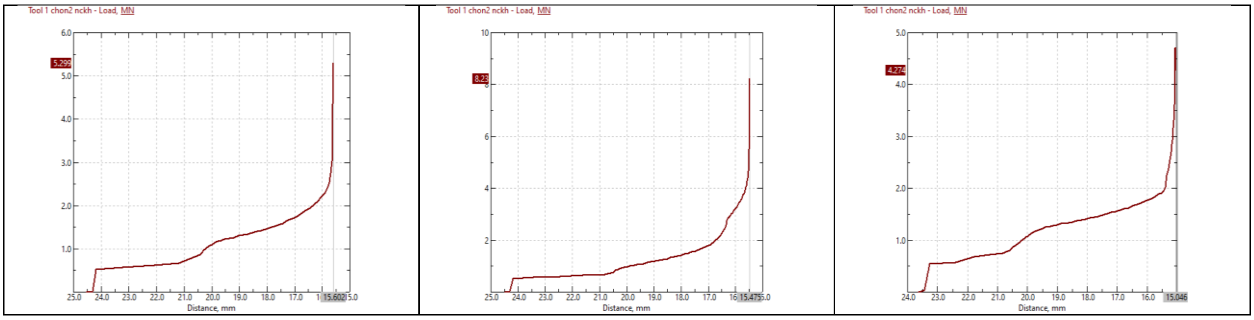
Volume [mm³]: 4407.33
Minimum value [MPa]: -5893.47
Maximum value [MPa]: -272.982
Mean value [MPa]: -3939.56
Standart deviation [MPa]: 562.7
Median [MPa]: -4011.92
Coefficient of skewness : 1.031
Excess kurtosis : 4.89
5 Percentile [MPa]: -4735.14
95 Percentile [MPa]: -2875.54

Volume [mm³]: 4409.12
Minimum value [MPa]: -9239.85
Maximum value [MPa]: -897.482
Mean value [MPa]: -4613.32
Standart deviation [MPa]: 615.7
Median [MPa]: -4662.96
Coefficient of skewness : -0.02795
Excess kurtosis : 7.403
5 Percentile [MPa]: -5609.39
95 Percentile [MPa]: -3546.07

Volume [mm³]: 4224.5
Minimum value [MPa]: -6431.46
Maximum value [MPa]: -106.109
Mean value [MPa]: -4603.56
Standart deviation [MPa]: 497.3
Median [MPa]: -4659.56
Coefficient of skewness : 0.2415
Excess kurtosis : 5.48
5 Percentile [MPa]: -5382.79
95 Percentile [MPa]: -3796.06

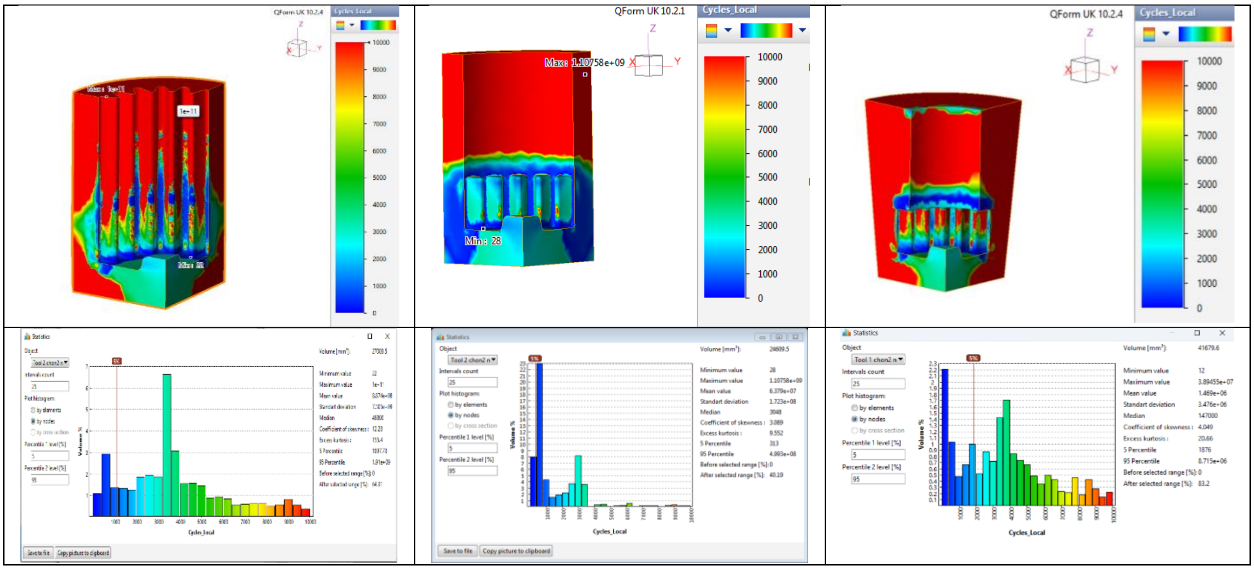
-Remarks: When metal materials are subjected to dynamic loads, one of the important factors to evaluate the strength of the material is fatigue strength. Fatigue strength is the ability of a material to withstand before a load rupture occurs dynamic weight. It depends on many factors, including Mean Stress. If Mean Stress is negative, that is, the mean load per the dynamic cycle is negative, the metallic material will be susceptible to cracking, and fatigue strength will be reduced. Conversely, if Mean Stress is positive, meaning that the average load per the dynamic cycle is positive, the metallic material will have better tolerance and the fatigue strength will increase. So, we can choose option 3 because it is the best option .

3.2. 3.Max load



-Remarks: The max load index is used to measure the bearing capacity of a metal material before it is permanently deformed during manufacturing. When the max load index is higher, the metallic material will have a better bearing capacity and the durability of the product will be improved. The product will have higher rigidity, and no permanent deformation or breakage during use, which is very important, especially in applications where high precision and durability are required. However, if the forging pressure or speed is too high, it can cause stress in certain areas of the product and lead to other defects, such as cracking or deformation. Therefore, it is necessary to control the forging pressure and speed to ensure that the Cold Forging process is carried out safely and efficiently and that the final product meets the specifications and quality requirements.

3.2. 4. Die fatigue cycles



Volume [mm³]: 27003.5
Minimum value 22
Maximum value 1e+11
Mean value 8.874e+08
Standart deviation 7.305e+08
Median 46800
Coefficient of skewness: 12.23
Excess kurtosis: 155.4
5 Percentile 1097.73
95 Percentile 1.91e+09
Before selected range [%]: 0
After selected range [%]: 64.31

Volume [mm³]: 24609.5
Minimum value 28
Maximum value 1.10758e+09
Mean value 6.379e+07
Standart deviation 1.723e+08
Median 3048
Coefficient of skewness: 3.089
Excess kurtosis: 9.552
5 Percentile 313
95 Percentile 4.993e+08
Before selected range [%]: 0
After selected range [%]: 40.19

Volume [mm³]: 41679.6
Minimum value 12
Maximum value 3.89455e+07
Mean value 1.469e+06
Standart deviation 3.476e+06
Median 147000
Coefficient of skewness: 4.049
Excess kurtosis: 20.66
5 Percentile 1876
95 Percentile 8.715e+06
Before selected range [%]: 0
After selected range [%]: 83.2

According to the 3 solution results, the third solution is the best because of the highest quality and lowest forging loads. The design of 3rd solution will be used to continue optimising by modifying geometry.

3.3 Optimization of die geometry.

- From the simulation results of Section 3.2, we can choose option 3 as the one used to optimize the geometry.
- Based on the formula for calculating the angle of the cold forging die. [5]

$R_{max} = 0{,}07.H = 0{,}07.15 = 1{,}05, \quad R_{min} = 0{,}04.H = 0{,}04.15 = 0{,}6$

- From the above formula, we can choose 3 values of the angle r

TABLE 6: Cases of changing the rudder angle

TN Angle r	1	2	3	4	5	6	7	8	9
r_1	0.6	0.6	0.6	0.8	0.8	0.8	1.0	1.0	1.0
r_2	0.6	0.8	1.0	0.6	0.8	1.0	0.6	0.8	1.0

The experiments corresponding to Table 6 will be conducted and the results of forging loads, fatigue cycle and a maximum of plastics strain were shown in Table 7.

The best alternative will be determined using MCDM (Multiple Criteria Decision Making) method namely AHP.

- Use the AHP method to select the plan according to multi-criteria: Load, Plastic strain, and cycles. [6]

Table 7

Alternative	r1	r2	Loads	Cycle	plastic train
A1	0.60	0.60	4.50	3054.00	1.47
A2	0.60	0.80	4.08	3036.00	1.04
A3	0.60	1.00	4.51	3085.00	1.41
A4	0.80	0.60	4.44	3119.00	1.48
A5	0.80	0.80	4.27	3113.00	1.42
A6	0.80	1.00	4.49	3077.00	1.4
A7	1.00	0.60	4.33	3062.00	1.46
A8	1.00	0.80	4.40	3079.00	1.38
A9	1.00	1.00	4.11	3066.00	0.998

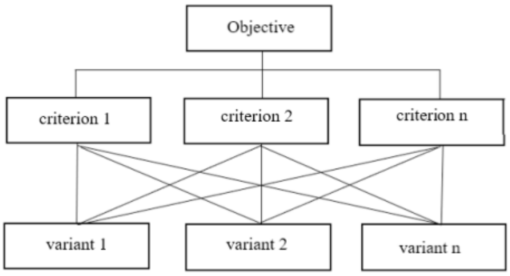


Figure 10. A diagram of the decision-making process in the AHP method.

-The main steps of the AHP method are as follows:

- Hierarchy of the problem - the aim of this stage is a detailed description of the problem, identification of participants, the definition of the main goal and expectations towards it. Then, the decomposition of the problem is carried out in the form of the main goal, main factors and partial factors as well as the considered variants, which generate a certain degree of fulfilment of the objective functions at particular levels of the hierarchical model.

• Assessment of criteria by pairwise comparisons - this is done by the decision-maker who compares the criteria in pairs about the criteria, and the criteria about the overriding goal based on a subjective determination of which of the criteria and to what extent is more important than the other.

• Determining mutual preferences (weights) about criteria and decision variants - after building the matrix, the criterion weights are calculated. The normalized rows of the matrix are summed and the matrix eigenvector is computed.

• Analysis of selected results - selection of the best variant that would correspond to the achievement of the main goal.

TABLE 8: Ranking results of alternatives.

Option	Score	Priority	Rank
OP1	0.065	6.50%	9
OP2	0.071	7.10%	8
OP3	0.085	8.50%	5
OP4	0.076	7.60%	6
OP5	0.162	16.20%	2
OP6	0.074	7.40%	7
OP7	0.100	10.00%	4
OP8	0.114	11.40%	3
OP9	**0.254**	**25.40%**	**1**

- Through the AHP method, we can choose the optimal geometry of the cold forging die as option 9 with an angle $r_1 = r_2 = 1$.

IV. CONCLUSION

The present study highlights the effectiveness of QForm software in predicting the quality of cold forging parts and proposes a modern approach to dying design. Some of the essential findings and recommendations considered in this research paper are:

- The study has demonstrated the application of FE simulation in the prediction of forging details and confirmed the accuracy of this method compared with the actual process.
- The manufacturing forging design process can be reduced in both cycle time and cost by using simulation software. The experimental testing process will be performed on QForm software according to this method. After each cycle, the die and workpiece design will be modified based on the simulation results. This cycle will be repeated until the product meets the specification.
- Simulation can also be applied to many advanced analyzes such as tool life, microstructure, heat treatment or casting and forging processes. This application will be suitable in the production of high-quality products or proactively in calculating tool life and planning maintenance.

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