International Journal on Advanced Science Engineering Information Technology

Vol.12 (2022) No. 2
ISSN: 2088-5334

Investigation on Billets and Tools Geometry in Cold Forging of the Straight Bevel Gear

Duy Dinh Van [a], Duc Quang Vu [b,*]

[a] School of Mechanical Engineering, Hanoi University of Science and Technology, Hanoi, 100000, Viet Nam
[b] Mechanical Engineering Department, University of Economics - Technology for Industries, Hanoi, 100000, Viet Nam
Corresponding author: *vuquang@uneti.edu.vn

***Abstract*— Straight bevel gears are an essential component of mechanical transmissions; they are widely used in the automotive, aerospace, shipbuilding industries and are made by shaping methods such as metal forming, casting, or machining. To market products, with proper function and properties, at a low cost, this gear component is usually fabricated by precise cold forging (the billet is forged in a closed-die at room temperature). In cold forging, the geometry of the billet and the forming tool plays an important role. It determines the ability to fill the die cavity, creating a finished product profile that meets the required geometric parameters. In this study, by 3D numerical simulation, some geometric shapes of workpieces and tools were investigated to find the optimal parameters. The results obtained from the simulation method were determined that a cylindrical workpiece with a tapered end and a die bottom with a convex profile will increase material flow velocity, improving cavity filling, uniform distribution stress in the forming specimen, and forging products without defects. Experimentally also verified the simulation results, which were cold forging with optimized workpiece and tool geometry, the straight bevel gear part was fully shaped, ensuring geometrical accuracy. The result of this study is a suggestion to apply to the design of a cold forging die for similar features.**

***Keywords*—Cold forging; FEM; bevel gear; billet's geometry; closed-die.**

Manuscript received 6 Aug. 2021; revised 9 Sep. 2021; accepted 14 Dec. 2021. Date of publication 30 Apr. 2022.

I. INTRODUCTION

Cold forging is one of the methods of metalworking by pressure. The metal billet is formed at room temperature, and the plastic deformation of the material is low. This forming method requires a high forging force, which causes the material to harden. However, it has advantages that hot or warm forging do not have to be cold forging produce high-quality machine components concerning surface quality and dimensional accuracy. This forging method also saves material, enhances mechanical properties, good microstructure through deformation, and reduces secondary operations [1]–[5]. Bevel gears are subjected to varying dynamic loads during operation (different stresses), so they need a hard surface and a tough core to ensure longevity. If the bevel gear is fabricated by the cutting method, the metal threads/grains are/are cut by the cutting tool, whereas this problem does not occur when manufactured by the bulk metal forming process [6]. Therefore, forged bevel gears show a wide range of working effectively with different stress types.

Improving the quality of forging products is an issue that all manufacturers want. Many different research works have been in this issue [7]–[12]. The commonly used research methods are numerical simulation combined with experiments [9], [13]–[19]. Lee et al. [20] conducted a study to change the forging process of bevel gear components by using three-dimensional finite element analysis. The obtained results proved that the design and addition of a pivot pin in the center of the die cause better material flow and complete fill of the die cavity, especially at the gear angles. Song and Im [21] carried out closed die design studies to fabricate forging bevel gears using the finite element method. The obtained results demonstrate that incorrect placement of punch and die during forging and the unbalanced distribution of force acting on the die will cause crack formation in the punch and die. By designing the die correctly, balancing the material flow, and increasing the force of the punch and die, the production process will be improved.

This study focuses on investigating the influence of billets and tools geometry on the filling capacity of the die cavity. The most common workpiece geometries have been studied, combined with the variable cavity profile to ensure uniform material flow, ensuring fast filling speed. By numerical simulation, it is also possible to analyze the distribution of damage factors, effective strain, effective stress, and load-stroke of the forming process. From the investigation results of the workpiece's geometrical parameters and the tools in four cases of simulation and cold forging experiments, this study has come to some important conclusions for serving for the manufacturing process of straight bevel gears from A5052 material.

II. Materials and Method

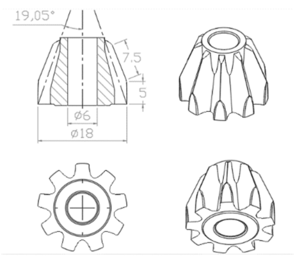
A. Bevel Gear Component and Initial Metal Workpiece

The component selected for this study is a straight bevel gear with material properties and parameters, as shown in Tables 1 and 2. A straight bevel gear is a type of gear used to transmit rotational motion between two intersecting axes. It is an indispensable component in the operating system of a vehicle or a system of industrial machinery.

TABLE I
MECHANICAL PROPERTIES OF WORKPIECE A5052 [22]

Temperature (°C)	Yield strength (MPa)	Ultimate tensile strength (MPa)	
24	90	193	
Elongation (%)	**Young's modulus (Gpa)**	**Poisson's ratio**	**Density (kg/m^3)**
25	70	0.35	2680

TABLE II
STRAIGHT BEVEL GEAR PARAMETERS



Parameters	Symbol/unit	Value
Module	m	2.25
Number of teeth	z	9
Pitch Angle	δ (^{0})	19.5
Teeth face width	B (mm)	7.5
Pitch diameter	D_p (mm)	18
Outside diameter	D_{max} (mm)	18
Bore diameter	d (mm)	6

Metal workpieces are determined according to the principle of volume conservation. Thus, the workpiece volume is determined from the component volume and the machining allowance. Based on this volume, the team studied two types of billet shapes, including the cylindrical and the tapered cylindrical billet, as shown in Fig. 1.

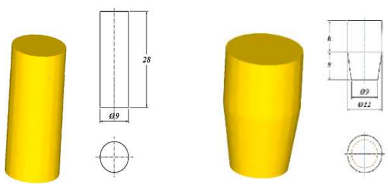
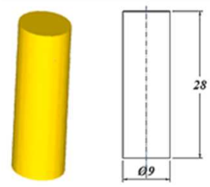
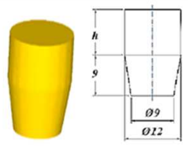
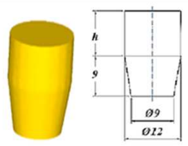
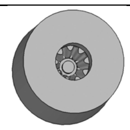
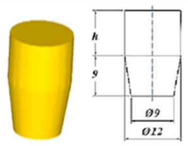
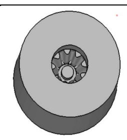


Fig. 1 Geometric geometry of the workpiece used for simulation and experiment

B. Numerical Simulation

The numerical simulation method as a highly efficient and low-cost analytical method is used in this study to analyze the cold forging process in a closed die when forming a bevel gear detail. Simulations were conducted to forge straight bevel gear components from two A5052 workpiece geometries, as shown in Fig. 1. The geometries of the tools and workpieces were modeled to be consistent with the geometries of experimental tools and workpieces. In the present analysis, only the deformation behavior of the workpiece was studied, so the portion of the die and punch surface contact with the workpiece was modeled as 3D surfaces. The models were built in four components: workpiece, rigid die, rigid punch, and rigid ejector (Fig. 2). Workpieces were set as plastic deformation types and meshed by 20.000 to 25.000 tetrahedral elements with absolute mesh patterns. The shear friction model was used to describe the friction between the workpiece and the die. The friction coefficient for the lubricated cold forging process is used according to the recommended Deform-3D software. The case studies and surveys are listed in Table 3.

TABLE III
GEOMETRIC PARAMETERS OF THE WORKPIECE AND PROFILE OF THE DIE CAVITY

Case study	Geometric parameters of the workpiece	Profile of the die cavity
1		 The bottom of the die is flat
2	 Cylindrical workpiece with h = 8mm, with one taper end	 The bottom of the die is flat
3	 Cylindrical workpiece with h = 8mm, with one taper end	 Raise the ejector 2 mm from the bottom of the die
4	 Cylindrical workpiece with h = 5 mm, with one taper end	 Raise the ejector 4 mm from the bottom of the die

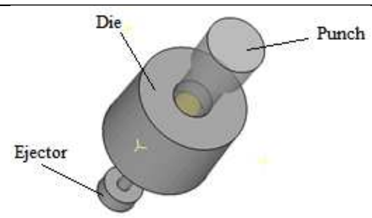


Fig. 2 Workpiece and tools used for finite element simulation

C. Build Experimental System

The experimental system was built to survey and evaluate the influence of the geometrical parameters of the workpiece and the tools determined from the numerical simulation. The system has three components: a die set, forging equipment, and a load-stroke meter. Because of cold forging in a closed die, the forging force is large, and the pressure inside the die is high. Therefore, the forging die has been designed to ensure durability, the punch and die material was made of alloy steel and was heat-treated to ensure rigidity. The punch and die are coupled to the die base by stress rings. These stress rings provide sufficient compressive prestress of the mounted die and mounted punch, leading to die and punch life improvements and fabricated metal savings [2]. The 3D model and components of the die set are designed and fabricated, as shown in Fig. 3.

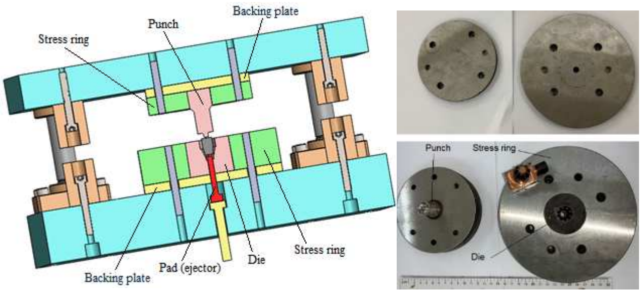


Fig. 3 3D model and components of the designed and fabricated die set

A 125-ton hydraulic press was selected for this cold forging process, thanks to the advantages can adjust the stroke and the force. The forging device has the parameters as listed in table 4.

TABLE IV
PARAMETERS OF THE 125-TON HYDRAULIC PRESS

No	Specifications	Unit	Value
1	Nominal pressure	kN	1250
2	Maximum stroke	mm	710
3	Slide head speed	mm/s	5/10
4	Table size of the machine	mm	500x 500
5	Master cylinder diameter	mm	220
6	Maximum hydraulic system pressure	MPa	32
7	Drive	Below	

A measuring device was designed and manufactured to determine the load-troke parameters during the experiment, as shown in Fig. 4.

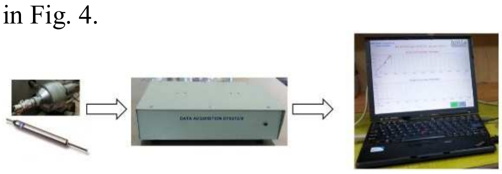


Fig. 4 Load-stroke measuring device

III. Results and Discussion

A. Simulation and Experimental Results

1) *Case study 1:* As shown in Fig. 5, it is shown that the die cavity was not filled with the cylindrical workpiece during the cold forging process. After step 200 to the end of the pressing stroke, the workpiece material did not fill the die cavity, and the material flowed back up at the edges until the end of the press stroke.

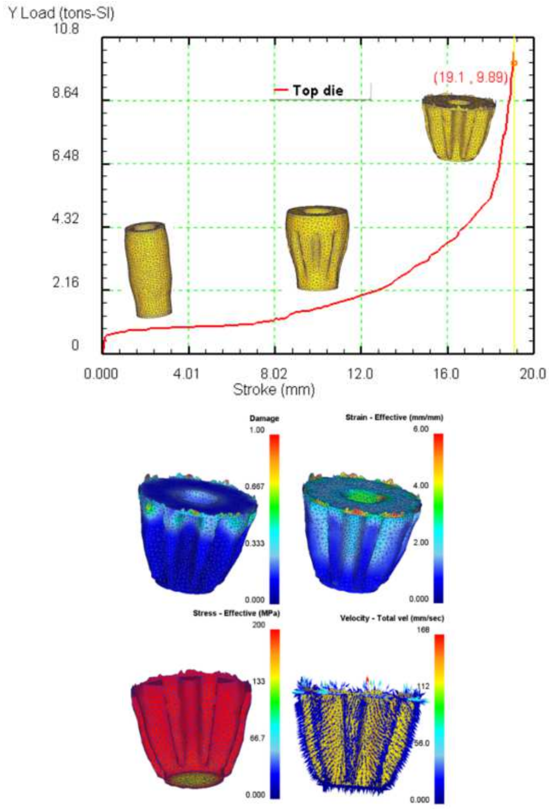


Fig. 5 Simulation result of the case study 1

The straight bevel gear component (Fig. 6) was not successfully formed because the initial workpiece model was not reasonable.

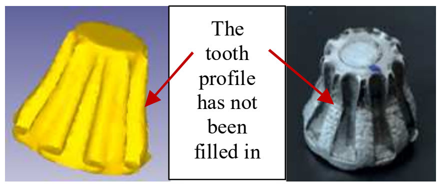


Fig. 6 Experimental results of the case study 1

The instability of the workpiece occurred right from the initial forming steps of the cold forging process. Continuing the simulation in the next steps showed that the metal did not fill the cavity, and it was not possible to shape the product as designed. The reason for this instability is that the ratio $h/D = 28/9 = 3.1 > 2.5$, the initial forming stage of the workpiece is freed, then comes in contact with the die and begins to create a profile of the component, so it is difficult to fill the workpiece material into the die cavity. The new solution has been proposed to use a workpiece with a shape closer to that of the straight bevel gear component, and a cylindrical billet with a tapered end is selected as in case study 2.

2) Case study 2: Observing the simulation results, the final profile of the component inside the die, as shown in Fig. 7, showed that the part has not yet achieved the design profile. The workpiece material has not yet filled the die cavity. The final tooth profile has not been formed yet. From step 222, the material was not filled into the die cavity, and It tends to flow back up at the edges until the end of the press stroke.

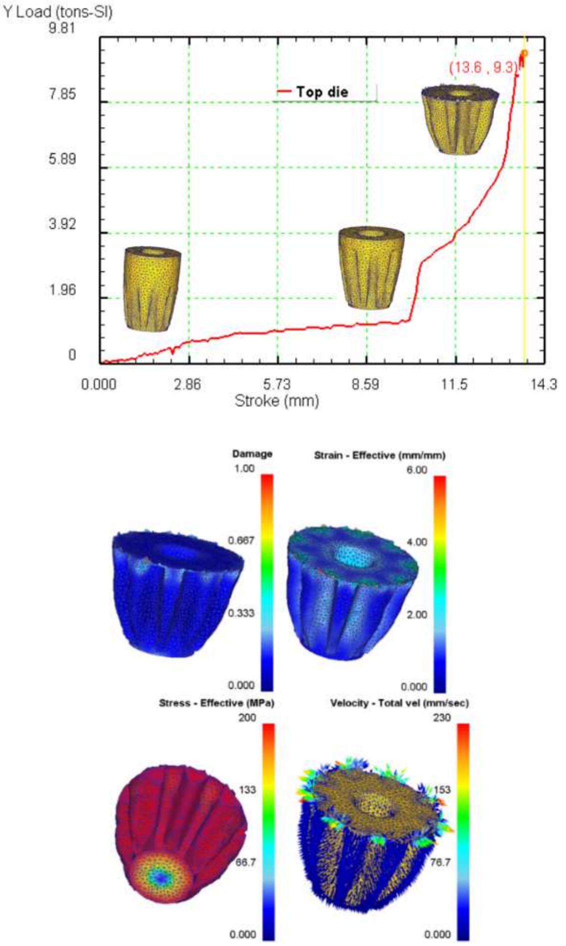


Fig. 7 Simulation result of the case study 2

However, the deformation ability of the workpiece has been improved because it had a preliminary shape of the product. The cylindrical workpiece with taper end is self-locating in the die cavity without the upsetting stage as in case study 1.

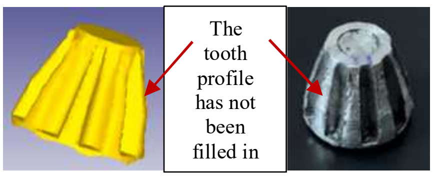


Fig. 8 Experimental results of the case study 2

Experimental results of the cold forging of a straight bevel gear in a closed die, Fig. 8 showed that the tooth apex in the die cavity had not been filled yet, had not achieved the gear shape as designed. Therefore, it had been necessary to change the shape of the die cavity as in case study 3.

3) Case study 3: The initial workpiece, punch, and die were kept as in case study 2 but raised the ejector 2 mm from the bottom of the die. Observing the simulation results and the component's final profile inside the die, Fig. 9 showed that the part had not yet achieved the design profile. The workpiece material had not yet filled the die cavity. The final tooth profile was not yet formed; from step 207, the material was not filled into the die cavity but tended to flow back up at the edges until the end of the press stroke.

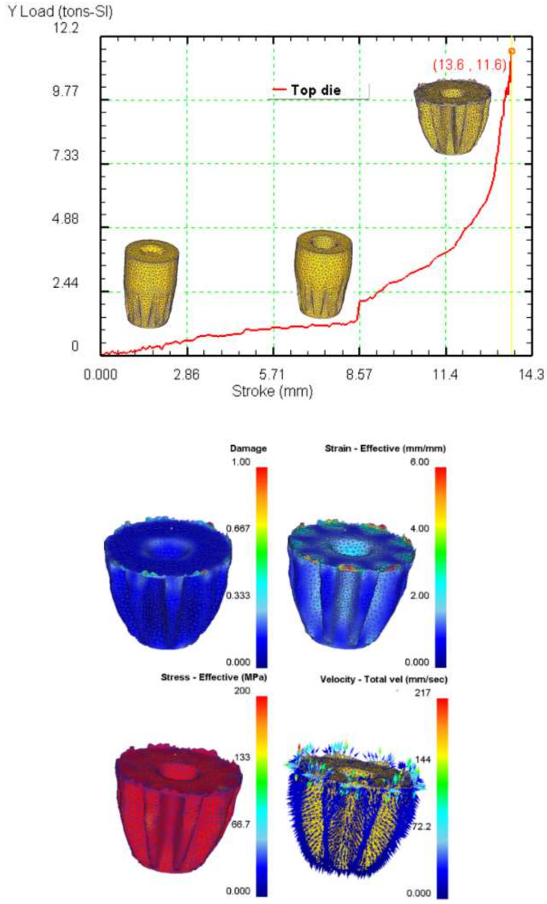


Fig. 9 Simulation result of the case study 3

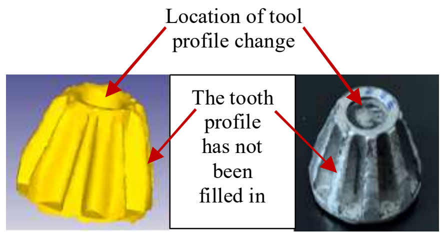


Fig. 10 Experimental results of the case study 3

However, the final profile of the forging component (Fig. 10) showed a better material filling level than the results of case studies 1 and 2 above. The ability to fill the cavity material has been improved compared to the previous cases because the ejector is raised 2 mm from the bottom of the die, creating a jet that pushes the material to flow towards the top of the tooth of the die cavity, increasing the forming capacity. Therefore, the workpiece, punch and die had changed the geometries as in case study 4.

Case study 4: The initial cylindrical billet had h = 8mm, and a tapered end. The tip of the punch is increased in height to h_{tip} = 5 mm. The ejector is raised 4 mm from the bottom of the die. The simulation results are shown in Fig. 11, showing that the workpiece was completely formed into the product. At the end of the plastic deformation process, the straight bevel gear component achieved the final profile of the component as designed. Therefore, it can be concluded that the cold forging process has been successful, and the shape of the workpiece and tools in this case study is reasonable.

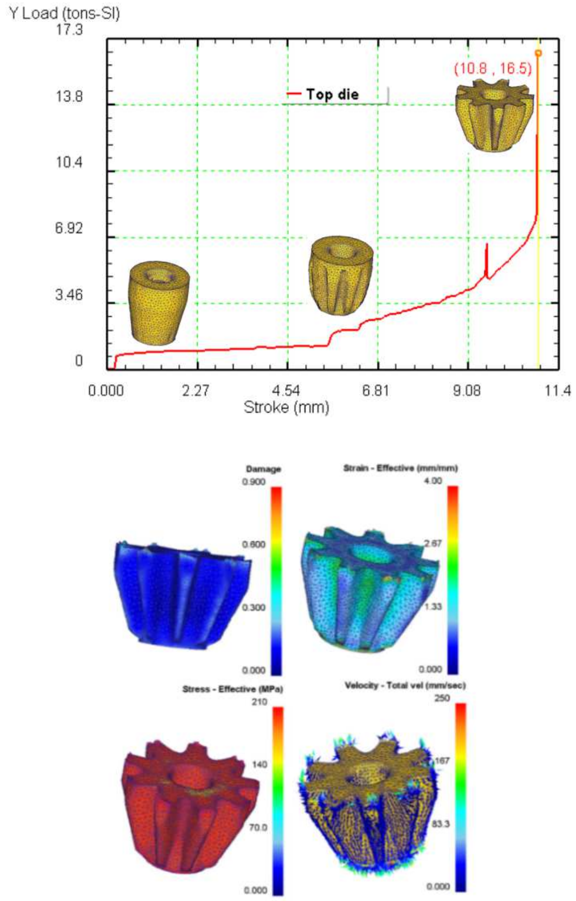


Fig. 11 Simulation result of the case study 4.

Fig. 12 showed satisfactory experimental results, the workpiece material was filled, and the material flow was stable. Therefore, the simulation and experimental results had analyzed all 4 case studies.

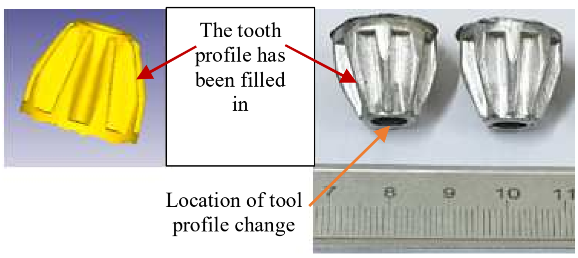


Fig. 12 Experimental results of the case study 4

B. Compare the Distribution of Damage Factor, Effective Strain, Effective Stress, Material Flow Velocity, and Load

From the simulation and experimental results of the four case studies above, the research team compared the distribution of damage factor, effective strain, effective stress, material flow velocity, and load on the load-travel curve in the specimens, calculated by the simulation program and the experimental measurement set.

1) The Distribution of Damage Factor in the Specimen: With the simulation results of case studies 1 (Fig. 5), 2 (Fig. 7), and 3 (Fig. 9), it is shown that the maximum value of the damage factor is 1. This value showed at some portions in the specimen, destruction of the material occurred, and at the same time, the metal flowed back up. It proves that the metal has reached the limit of filling in the die cavity. In addition, the phenomenon of material destruction does not appear in other locations. The simulation results of case study 4 (Fig. 11) showed that the damage factor reached the maximum value of 0.9, proving no material destruction phenomenon in the specimen. The straight bevel gear component was successfully formed without any defects.

2) The Distribution of Effective Strain in the Specimen: The specimen was observed the distribution of effective strain in 4 case studies. Cases 1 (Fig. 5), 2 (Fig. 7), and 3 (Fig. 9), regions of the specimen had the strongest plastic deformation, concentrated mainly in the edge areas, reaching the maximum value of about 6 mm/mm. This value also shows that filling the die cavity was difficult because metal was preferred to flow through locations with lower strain resistance according to the law of least strain resistance. The effective strain had a minimum value of 0 mm/mm, which exists at positions where the surface of the workpiece was in contact with the die cavity. In case of study 4 (Fig. 11), the effective strain distribution reached the maximum value of about 4 mm/mm, which showed the advantage of filling material into the die cavity compared with other research cases.

3) The Distribution of Effective Stress in the Specimen: The effective stress distribution had similar characteristics to the simulation results of the case studies 1 (Fig. 5), 2 (Fig. 7), and 3 (Fig. 9), reaching the maximum value was 200 MPa and was not uniform in the whole forging component with different cases. The difference in effective stress distribution lay at the specimen's bottom when an area with a value of 0 for case studies 1 and 2. Case study 4 (fig. 11) had the most uniform effective stress distribution in the specimen, concentrated at 200 MPa (the maximum value was 210 MPa). This case completely overcomes the problem of distribution difference of effective stress compared to all three previous cases.

*4) The Distribution of Material Flow Velocity in the Specimen*The maximum value of the material flow velocity distribution when the material is filled in the die cavity of : cases 1 (Fig. 5), 2 (Fig. 7), 3 (Fig. 9), and 4 (Fig. 11) were 168, 230, 217 and 250 mm/s respectively. The material flow velocity of case 4 has the largest value in the four cases studied. The direction of material flow was also consistent with the desired filling direction for different positions in the die cavity.

5) The Distribution of Load on the Load-travel Curve in the Specimen: The load-stroke graph of case study 1 (Fig. 5) showed that the load reached 9.89 tons at the stroke of 19.1 mm; the load tended to go to the value infinitely, which indicates that the material did not fill the cavity. In case study 2 (Fig. 7), the load reached the value of 9.3 tons at the stroke of 13.6 mm, and the load had tended to go to infinity. And at the same time, the force graph had appeared the value range was unstable, which indicates that the material was no longer able to fill the die cavity. In case of study 3 (Fig. 9), the load reached the value of 11.6 tons at the stroke of 13.6 mm, and the load had tended to go to infinity, which proves that the material was no longer available the ability to fill the die cavity. In case 4 (Fig. 11), the load reached the maximum value was 16.5 tons at the end of the forging process, and the stroke position was 10.8 mm. The load also had tended to go to infinity, showing that the material data reached the filling limit, and the process of load variation shown in the graph is appropriate. Simulation and experimental loads of case study 4 were 17.8 tons and 17.2 tons, respectively, so these results had not much error. The biggest difference between load theoretical and simulated loads was 7.3%.

The simulation and experimental results as studied above showed that case study 4 had optimized the process parameters and the ability to fill the material into the die cavity. The damage factor distribution in the sample was less than the critical value. The effective stress distribution was uniform in the specimen. The effective strain distribution and the material flow velocity were also increased. The cold forging process of straight bevel gears was successful.

IV. Conclusion

In this work, the cold-forging process of a straight bevel gear in a closed die was analyzed by numerical simulation and experimentally with four case studies to optimize the workpiece and tool design. Research results have shown that the shape of the workpiece and the tool have an important influence on the quality of cold forging products. Optimizing the geometry parameters of the workpiece and tool helped optimize metal flow fill velocity and reduce the risk of failure when cold forging straight bevel gears from A5052 aluminum. Research has shown that the most reasonable geometry of the workpiece to ensure the ability to fill the die cavity without destruction is the workpiece with a cylindrical body and a taped end with suitable dimensions. The tool profile is suitable when lifting the ejector from the bottom of the die to ensure that the metal is filled in the tooth grooves. The results of this study can be applied to the manufacture of similar machine components and help technicians have a better insight into the influence of the geometrical parameters of the workpiece and tools on the results of cold forging in a closed die.

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