DOI: 10.21062/mft.2023.102 http://www.journalmt.com

Precision Forming Process Analysis and Forming Process Simulation of Integrated Structural Gear for New Energy Vehicles

Liyong Zhang (0000-0003-3960-1121)[1*], Tianle Zheng (0009-0007-1524-6336)[1], Tongjie Li (0009-0009-7228-4026)[1], Juan Wang (0009-0006-2902-9028)[1], Changlu Wang (0009-0004-8727-7519)[2], Yehu Jiang (0009-0009-1729-247X)[3], Chengyu Li (0009-0009-4943-4284)[3], Fengxia Yuan (0009-0003-3280-6623)[1], Zhihua Yao (0009-0001-2720-6098)[1]
[1]Anhui University of Science and Technology Chuzhou 233100 China
[2]Jiangsu Zhonggong High end Equipment Research Institute Co., Ltd. Taizhou 225300 China
[3]Anhui Zhongxin Technology Co., Ltd. Chuzhou 233100 China
Corresponding author email: zhangly@ahstu.edu.cn

New energy vehicles driven by electric motors have higher requirements for the lightweight and high reliability of their gear transmission devices. It is now necessary to optimize the precision forming process of their structural gears. The integrated structure gear without undercut produced by precision forming technology can reduce axial size while improving the strength and reliability of gear parts. Based on the performance requirements of integrated structural gear parts in practical applications, a process plan of "hot forging forming +cold trimming tooth shape" was developed, and compared with existing hot extrusion forming plans. Simulation analysis was conducted on the hot forging forming process of integrated structural gears. Through the improvement and optimization of the process plan, the extrusion stress during the filling process of the formed gear teeth was reduced by about 29%, achieving a good forming effect, in order to provide data reference for the forming of this type of gear.

Keywords: Gear forming, precision forming, cold extrusion, simulation analysis, extrusion stress

1 Introduction

In recent years, new energy vehicles have developed rapidly. New energy vehicles driven by electric motors have imposed higher requirements for lightweight and high reliability of their gear transmission systems [1, 2]. Gears with an integrated structure devoid of any tool removal slots, produced using precision molding technology, can reduce axial dimensions while enhancing the strength and reliability of the gear parts [3]. Gear precision forming is a near-net gear forming process that is highly efficient and, while reducing cutting operations, ensures the integrity of metal flow lines in the gear tooth region, enhancing component performance [4]. Domestic scholars have proposed numerous improvements regarding mold filling. Feng Wei [5] researched the effects of different floating die speeds and male mold pressing speeds on the microscopic structure evolution of helical gears, concluding that increasing the pressing speed of the male mold leads to a larger average volume fraction of dynamic recrystallization. Studies by Peng Bo et al. [6] have shown the influence of tooth profile deviations during gear rolling. Bu Junwei [7, 8] introduced the idea of a floating die, utilizing the positive friction generated during die movement to promote metal flow and improve the filling of the gear tooth area. This study, through refining the molding process, reduced the extrusion stress during the molding process by approximately 29%. Rui Xu [9] analyzed the influence of tooth surface contact deviations and proposed a modeling analysis method based on TCA, which holds practical significance. Du Peng et al.[10] introduced a method to simplify calculations for the strength of a dual-layer combined extrusion mold. Liu Youyu et al. [11] developed various parametric gear design methods, making gear design and molding more realistic. Research by Kühn Felix et al. [12] employed austempered ductile iron (ADI) components for economic process optimization in gear molding design, leveraging computer-aided force measurement to reduce molding wear tests.

This article analyzes the forming process of gears with an integrated structure devoid of tool removal slots, proposing a process plan of blanking → rough upset → hot forging temperature extrusion → cold trimming [13]. Based on the molding results, the process was optimized using the method of simultaneous motion of the upper and lower male molds for bidirectional extrusion, which can promote metal flow, achieving full filling of the gear tooth area. Numerical simulations were conducted for the hot forging temperature extrusion-cold trimming process of the integrated structure gear. The force status, load distribution, and metal extrusion flow direction in the molding process under different steps were summarized and analyzed, aiming to provide references for the molding process of such gears.

2 Materials and Methods

2.1 Gear component structure and process plan analysis

2.1.1 Gear Component Structure

The structure of the researched gear is shown in Fig. 1(a). The gear design integrates the tooth portion with the hub using a design without tool removal slots, reducing the axial size, which is beneficial for the lightweight design of the transmission device. The tooth parameters for this integrated gear component are: modulus m=2.8mm, number of teeth Z=30, and pressure angle α of 30°. The specific structure and related dimensions can be seen in Fig. 1(b).

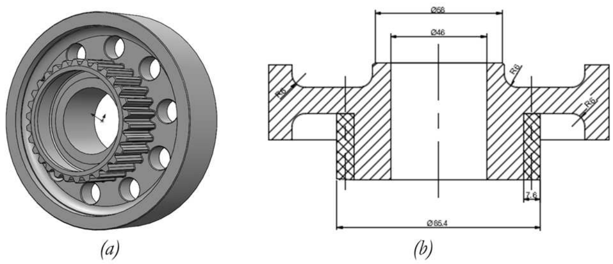


Fig. 1 *Main dimensions and 3D model of gear*

The material used for the gear is carburized steel 20CrMnTiH, and its main mechanical properties are listed in Table 1:

Tab. 1 *Mechanical properties of materials*

Grade	Steel Type	Density (g/cm3)	Tensile Strength (Mpa)	Yield Strength (Mpa)	Elongation (%)	Tempering Temperature (℃)	Hardness (HB)
20CrMnTiH	Carburized Steel	7.85	≥1080	≥835	≥10	200	≤217

2.1.2 Determination of the process plan

Structurally, this gear component belongs to the disc-type forgings and has a center-symmetric shape. The projection of this kind of forging on the parting surface is approximately circular. During die forging, the axis direction of the blank coincides with the direction of the forging press, and the metal undergoes plastic deformation in the length, width, and height directions simultaneously. The die forging process for this type of forging typically consists of blanking → rough upsetting → hot forging billet → cold extruding teeth [14, 15]. For symmetric gear components, like our subject of study, during the forming of the gear part, there is a need for full extrusion filling to achieve the component's usage precision. The warm forging primarily takes advantage of the material's good plasticity after heating. The deformation resistance of the material during the deformation process is relatively small, which facilitates forming parts that require significant deformation and are challenging to form. Subsequent trimming in the cold state benefits from the high accuracy of cold deformation to improve the precision of the gear teeth [16]. Therefore, the die forging method adopted in this experiment is blanking → heating → rough upsetting → hot forging → warm extrusion → cold trimming → mechanical processing. Blanking and rough upsetting should be carried out before die forging to significantly reduce the initial extrusion time during forming. Choosing hot forging and warm extrusion methods make the billet fill the mold cavity more easily [17]. Subsequently, precise trimming is needed in the cold state, and after the end forging, trimming the burrs from the formed results ensures the best effect of the gear teeth, meeting the part's performance requirements under various working conditions.

2.1.3 Continuous extrusion

To investigate whether the adopted process plan can meet the working requirements, a set of experiments were conducted using the continuous extrusion forming method to observe the forming effect and analyze the results and data. Continuous extrusion involves the direct forming of the billet to the finished product, encompassing rough upsetting, hot forging, and the crucial tooth filling process. The specific steps are as follows:

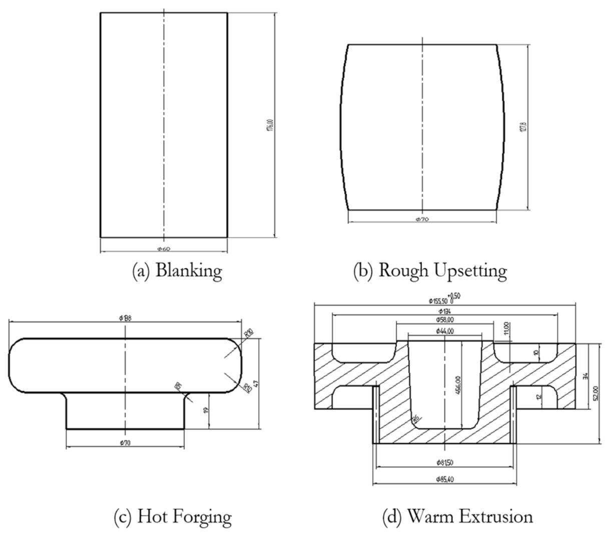


Fig. 2 *Forging process*

Continuous extrusion simulation follows the steps of blanking → rough upsetting → hot forging → warm extrusion → cold trimming → mechanical processing. The method in this forming plan involves placing the forging in the mold and pressing the hot-forged part with a male mold. Throughout the process, there's no need to modify the forging, and it can directly form in the die, closely resembling the overall shape of the gear component and the crucial gear tooth position. The process flow is shown in Fig. 2.

Given the conditions, a model was established through SolidWorks 3D software. Under the premise that the cavity of the retaining mold is consistent with the actual mold, it was converted into an STL format and imported into the DEFORM-3D software. The conditions used during the extrusion process, such as the forging material and temperature, were set, and a simulation analysis was conducted to judge the tooth filling effect and simulation results. This part can serve as a preprocessing part for numerical simulation. The results of the simulation are shown in Fig. 3(a).

From the side view, it can be clearly seen that there are multiple obvious gaps in the molding of the gear teeth. This is because, during the extrusion process, the forging is subjected to the extrusion of the male mold and the reverse extrusion collision of the female mold, forming dead angles that cannot be fully filled. This results in a large extrusion stress, with the maximum value reaching 734kN, as shown in Fig. 3(b). This simulation result is not ideal, and issues such as dead angles during extrusion and excessive elastic forces during extrusion need to be addressed.

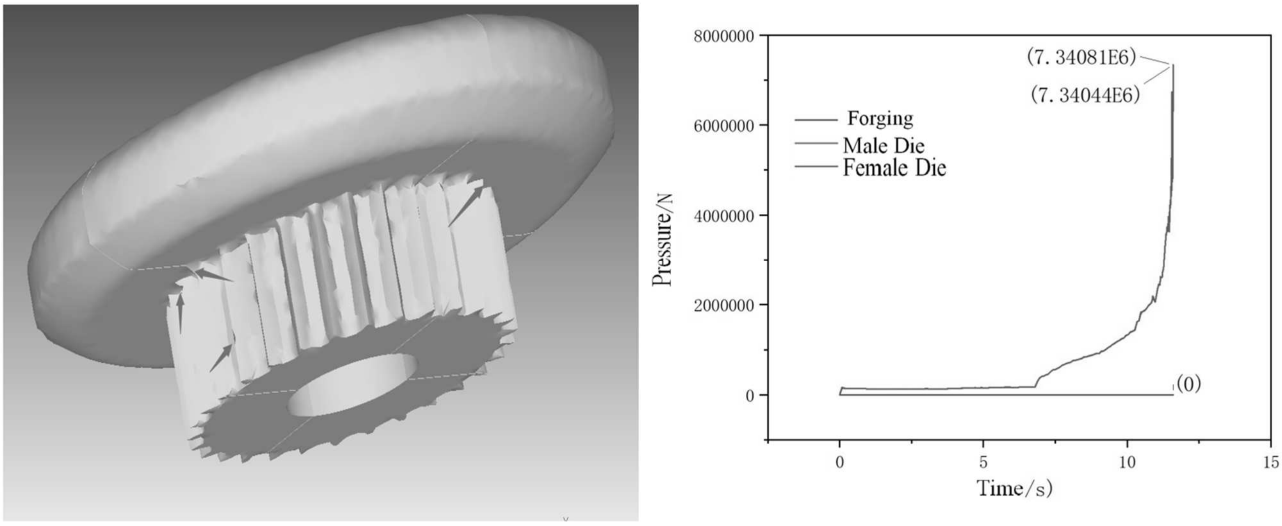
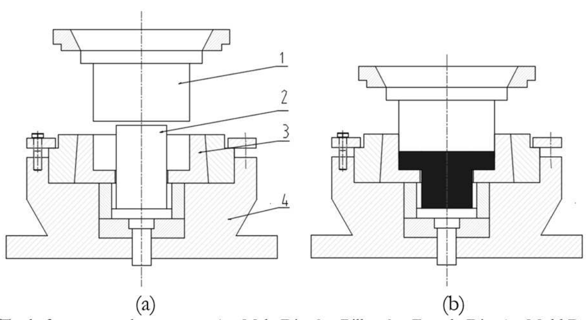


Fig. 3 *Simulation results*

2.1.4 Segmented extrusion

To achieve a more ideal tooth filling situation, after reviewing the literature, a segmented extrusion molding method was conceived. The molding process was segmented, with the plan being: first, the forging undergoes upsetting to resemble the overall features of the gear component. Then, a reverse extrusion forms an annular groove. Finally, hot forging → warm extrusion → cold finishing → mechanical processing is used for the molding of the gear teeth. The main idea behind segmented extrusion is that the entire molding process is carried out separately. By using the male and female molds moving towards each other to extrude the forging, the forging's extrusion stress is divided into forces acting from above and below, reducing the need for extrusion stress.

The first initial step involves blanking and rough forging, shaping the upper flange section. The diameter of the bar stock is selected based on the root circle of the tooth profile, which should be 1-2mm smaller than the root circle. It is then heated to 800-850℃[18], placed in the mold, and as the male mold moves downward, force is applied to the billet, causing the material to flow and fill the female mold cavity.



Tools from top to bottom are: 1—Male Die; 2—Billet; 3—Female Die; 4—Mold Base

Fig. 4 *Upsetting forming*

Subsequently, the rough-forged billet undergoes reverse extrusion to form a ring groove as shown in Fig. 4. After the first step, the component appears "T"-shaped, and the male mold has a hole in the middle. The ring-shaped portion of the material is extruded and deformed, forming the ring groove as shown in Fig. 5. A challenge arises with the gap between the inner hole of the male mold and the outer circle of the billet. If the gap is too large, metal flows into the gap, resulting in burrs. If the gap is too small, it may interfere with the smooth movement of the mold. Typically, a 1mm allowance is left on one side.

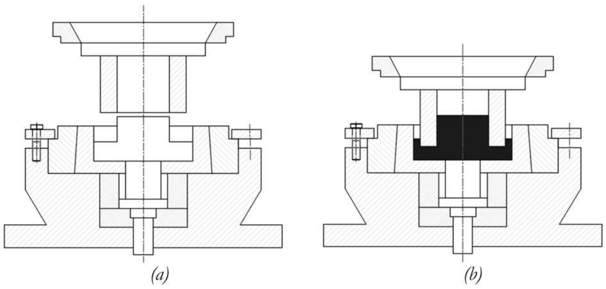


Fig. 5 *Upsetting forming*

The final step involves warm extrusion molding. To aid in filling, bidirectional extrusion is employed, as illustrated in Fig. 6. The lower end of the male mold is tooth-shaped and can move within the toothed female mold. Since the upper end is connected to the flange section, a toothed male mold can't be used. Force is applied directly to the flange surface, which may result in insufficient filling at the upper end. During numerical simulation, a floating female mold approach can be used, wherein the female mold can float freely based on friction during the molding process. This primarily leverages the friction to drive metal flow [19-22], molding areas that are difficult to fill.

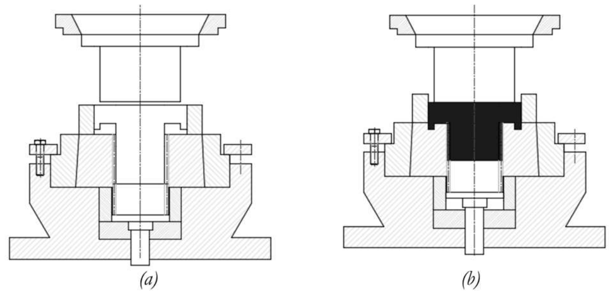


Fig. 6 *Extrusion molding*

The results of this segmented extrusion are depicted in Fig. 7.

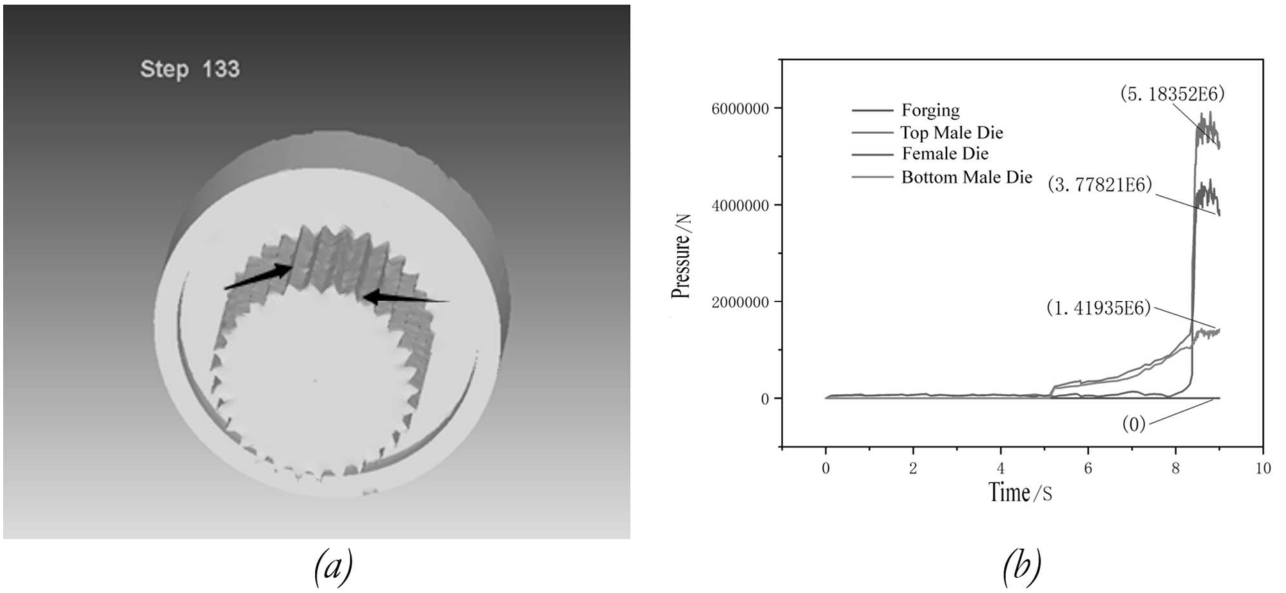


Fig. 7 *Simulation results*

For the segmented extrusion numerical simulation, the simulation results show some burrs on the edges, which can be polished off later. Unlike continuous extrusion simulation, there are no dead spots and large gaps in the tooth-forming area. Moreover, the extrusion stress required during the simulation peaks around 518.3kN, significantly reducing the use of extrusion stress.

By observing the load curve during the simulation process, it can be noted that in the section before approximately 5 seconds: the upper male mold contacts the billet and moves downward, while the lower male mold hasn't yet touched the billet and no force is applied. After 5 seconds, the forging touches the rising lower male mold. Both male molds squeeze the billet simultaneously, causing the billet to expand laterally. The extrusion force gradually rises to 140kN. As the stroke increases, around 8.3 seconds, the billet is squeezed to the inner wall of the female mold, hence the deformation resistance of the upper and lower male molds and the female mold surges, peaking at 518.3kN. During this period, both male molds continue their slow extrusion motion at a steady speed until the molding is complete.

Comparing the tooth-shaping results of the two methods, it's evident that continuous extrusion produces more burrs and has significant molding defects. In contrast, segmented extrusion molding allows for more complete tooth filling, achieving relatively ideal results. Therefore, the segmented extrusion molding method is selected for the experimental process.

3 Discussion of results

3.1 Model and Simulation Parameter Setting

The gear component used in this experiment is a pie-like symmetrical component. To avoid prolonged simulation time for the entire DEFORM extrusion process, a 1/4 model of the entire model is used for simulation experiments. Throughout the experimental process, SolidWorks software is initially used for main model modeling, divided into upper die, lower die, blank, and cavity; subsequently, the processed model is converted to the STL format and then imported into the DEFORM software. In this software, the blank is set as a plastic body, neglecting the force and deformation of the mold during extrusion, setting the mold as a rigid body. The material selected for the blank is AISI-4120 (20CrMnMo steel) from the material library, with the blank divided into 32,000 grids. The initial temperature is set to 850°C. Symmetric boundary conditions are applied on the two cut surfaces of the 1/4 model, and the related movements of the upper and lower dies are defined. Contact friction exists between the upper die, lower die, blank, and cavity, all using shear friction. The friction factor is set to the standard 0.3 for warm forming. Comparing the experimental results, the results of the segmented forming simulation are analyzed. The gear forming conditions under different steps are compared, as shown in Fig. 8:

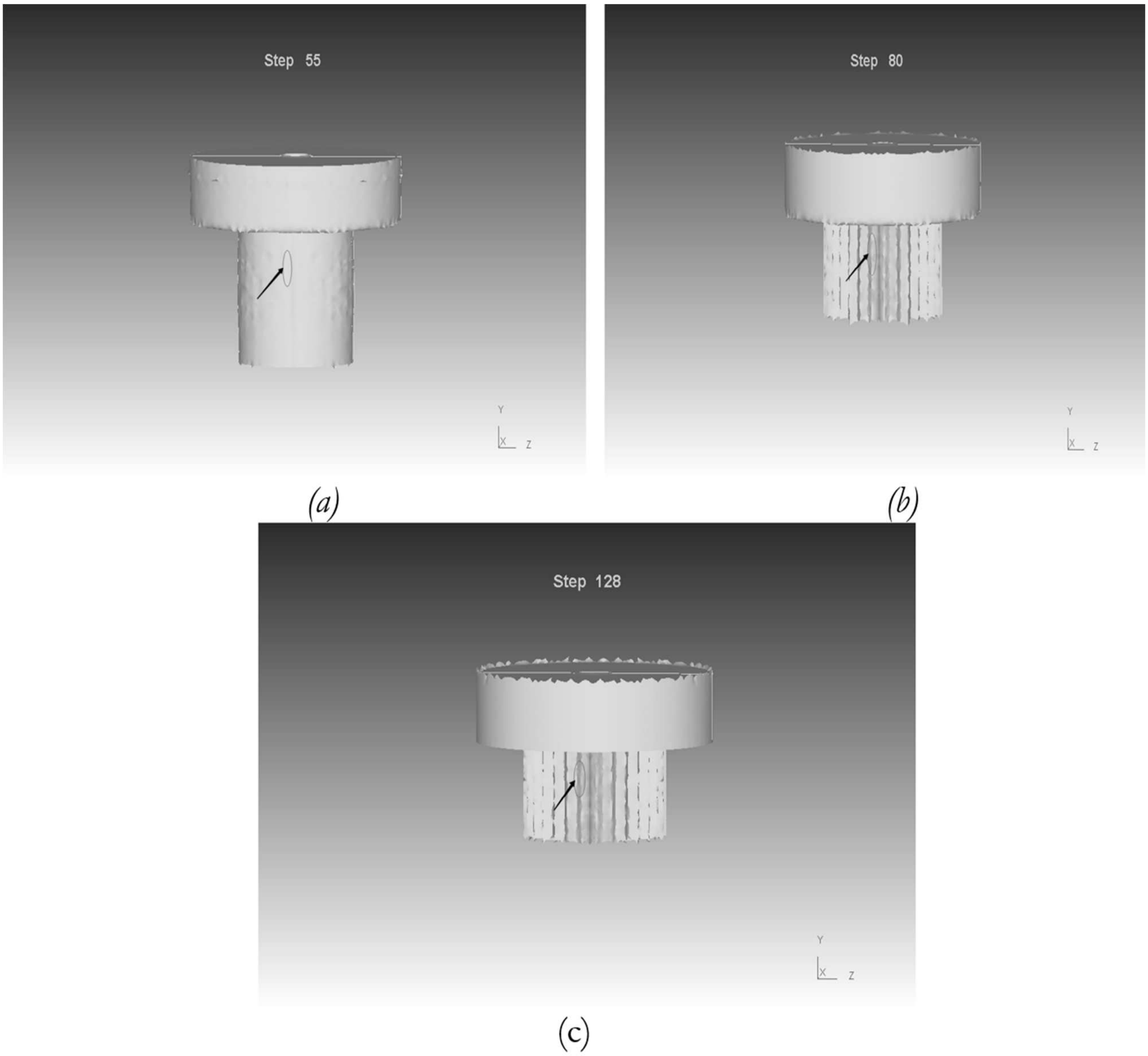


Fig. 8 *Gear forming*

To reduce the squeezing force needed during the extrusion forming process, the center hole is treated in the center of the blank. The goal is to reduce the squeezing force used when the upper and lower dies mutually squeeze the blank. From the extrusion process, we can see that by step 55, the teeth shape has changed due to the squeezing. After the upper die touches the blank, it is slowly pressed downwards. The metal flows slowly and moves downwards without mutual squeezing. By step 80, we can see that the tooth shape is almost formed. At this time, the blank is being mutually squeezed between the upper and lower dies, and the blank is pressed in the cavity to fill the toothed part, with the metal flow spreading horizontally inside the cavity. By step 128, the teeth shape is fully formed and is in good shape. The upper and lower dies have squeezed and filled, and the metal no longer flows. Relative to the load curve, the flow velocity fields corresponding to steps 30/60/90/125 of the parts are shown in Fig. 9:

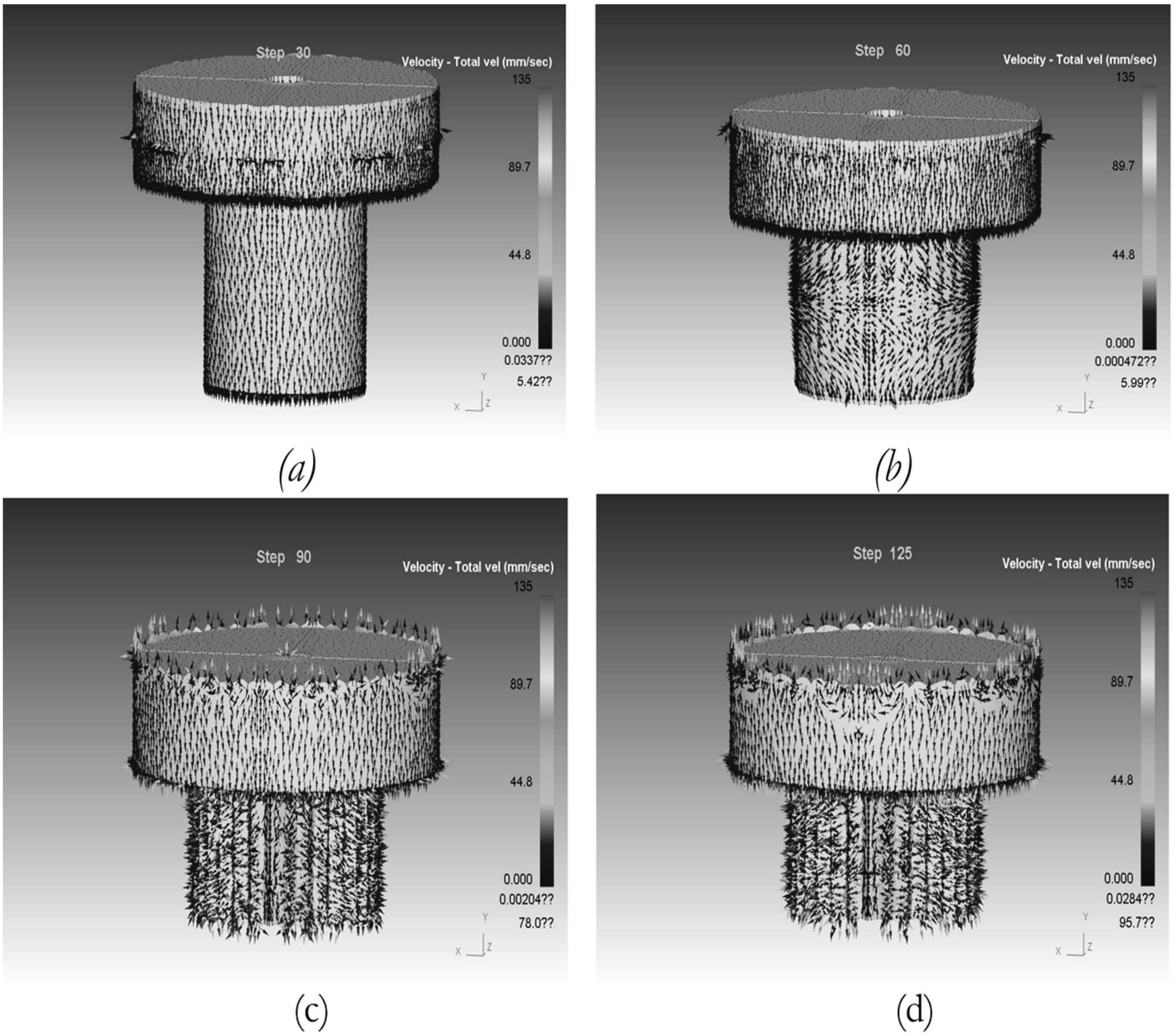


Fig. 9 *Deformation velocity field*

According to the deformation velocity field in Fig. 9, it is not difficult to notice that the first phase's metal flow direction is consistent with the downward movement direction caused by the upper die. The deformation speed shows a regular downward trend, with no speed deformation field conflicts in this phase [15]. In the second phase, forming the annular groove, while the upper die presses, the blank moves slowly around to fill the annular groove type cavity in the corresponding cavity, and the entire process has relatively slow metal flow. Only when forming the tooth part, restricted by the molds of the cavity and the lower die, does the entire metal deformation speed field begin to flow mutually. The whole flows into the tooth-shaped cavity of the cavity, gradually filling it, making the external surface of the tooth part of the component slowly smooth. Fig. 10 below shows the stress distribution during the forming process, from which the force changes in different parts of the component during the simulation process can be seen:

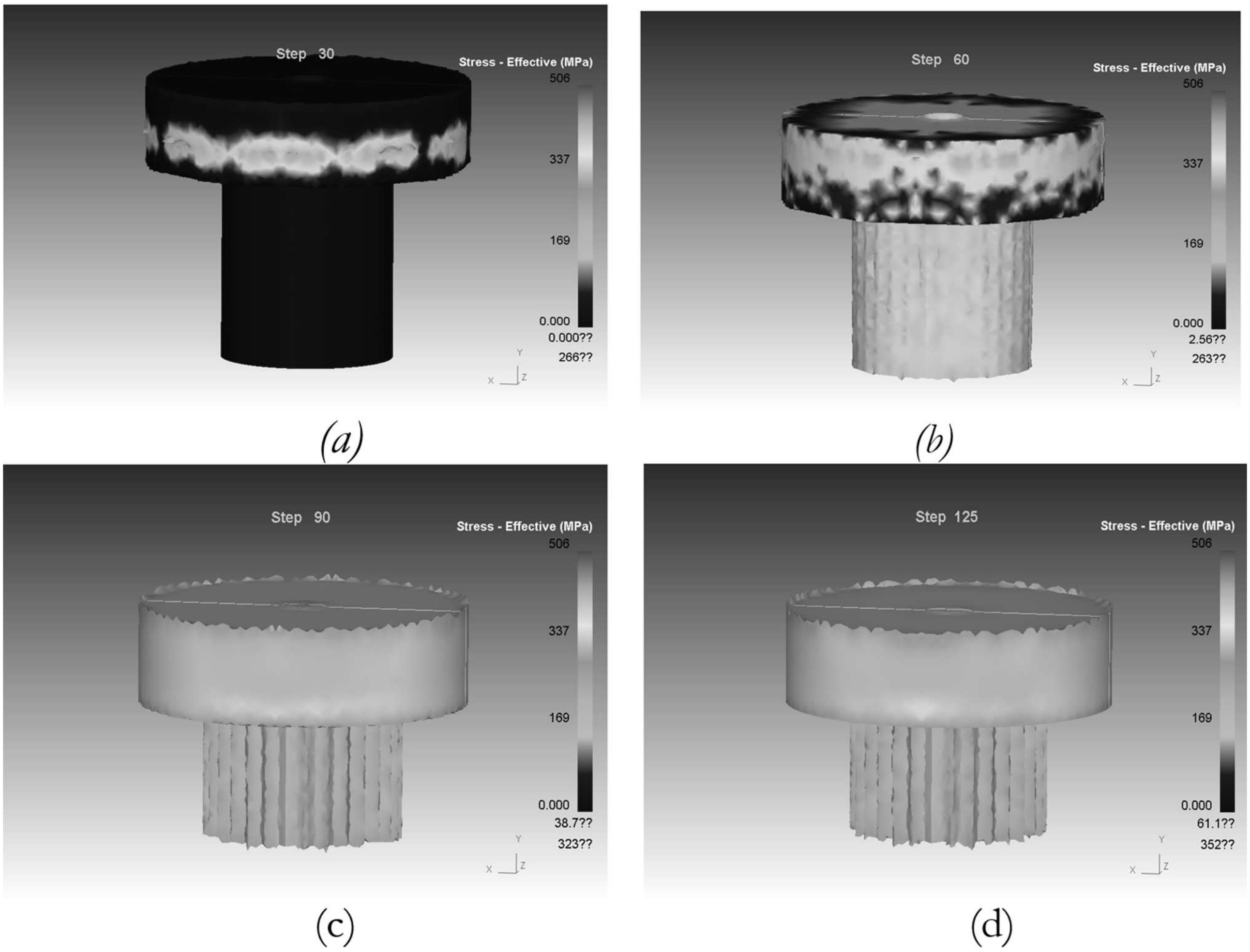


Fig. 10 *Equivalent stress nephogram*

From the equivalent stress cloud diagram in Fig. 10, it can be concluded that during the forging and formation of the annular groove phase, the stress experienced by the blank mainly distributes at the top force position of the blank and the position caused by the friction between the blank's sidewall and the cavity. This is because the blank is first subjected to the squeezing force of the upper die and the friction between the sidewall of the blank and the cavity. During the forming process, if the squeezing speed is too fast and the stress output is too large, a dead-angle situation may occur in the annular groove forming process. Therefore, by controlling the size of the squeezing stress, this is one way to avoid the occurrence of dead angles. In the final phase, the blank mainly undergoes relative moving squeezing from the upper and lower dies. The stress concentrates on the teeth where deformation occurs after forming the annular groove. Although the squeezing speed is slow, the squeezing stress on the blank is gradually increasing. Also, due to the small size of the tooth structure, it's not easy to fill during squeezing. It takes a long time to slowly squeeze and fill the cavity, so the stress eventually concentrates on the tips of the teeth.

From the variation of the equivalent strain cloud map shown in Figure 11, it can be observed the degree of deformation of the billet in different parts during the extrusion process. The most important deformation area during the simulation process is the gear-shaped forming process at the lower part of the component, with its corresponding maximum strain value being approximately 5.79mm/mm. The central part of the billet has relatively low extrusion flowability, and its corresponding strain value is almost 0. Throughout the entire forming process, the strain cloud map peaks when the billet is being extruded into the gear tooth. This part of the forming relies on the slow extrusion and filling of the female mold's tooth cavity by the two male molds from above and below. The distribution of the equivalent stress cloud map corresponds accordingly. The overall trend of the strain cloud map indicates that the degree of strain variation is based on the deformation level of the billet and the stress it experiences. During the extrusion simulation process, friction between the molds may lead to burrs and other irregularities on the edges and the tip of the teeth of the billet by the end of the extrusion, necessitating further refinement.

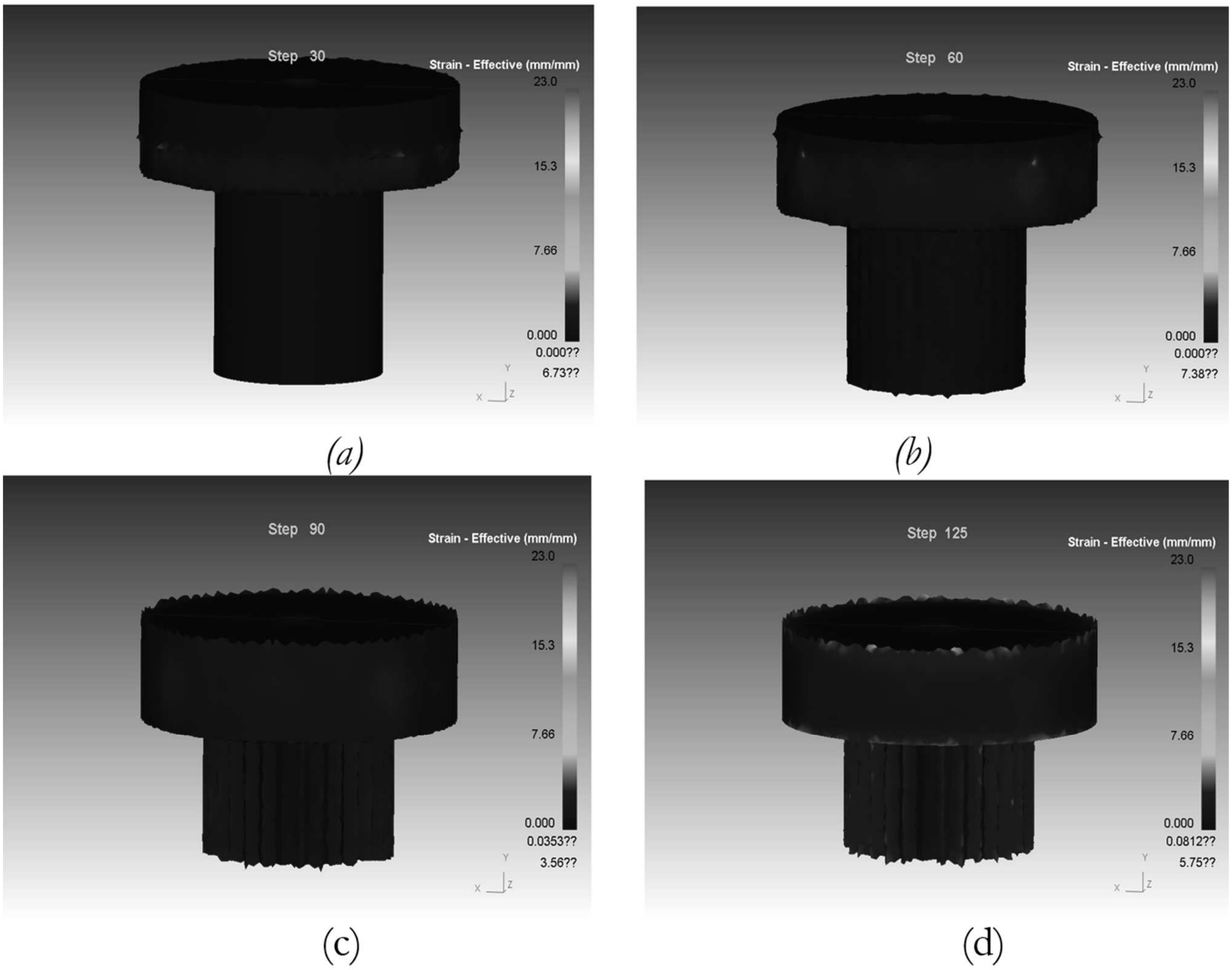


Fig. 11 *Equivalent strain cloud map*

4 Conclusion

This paper studies the precise forming issues of integrated structure gears, exploring the application of extrusion molding technology. We used the Deform-3D software to simulate the extrusion molding plan for structured gears, arriving at the following conclusions:

- Comparing the results of continuous extrusion molding with segmented extrusion molding, segmented extrusion shows better results when filling the female mold cavity. It can also reduce extrusion stress by 29%, meeting the requirements for precision molding of integrated structure gears.
- Throughout the simulation process, the major stress distribution is on the edges of the billet and the pointed areas of the gear teeth. This is due to the outward diffusion of internal stress caused by the upper and lower male molds pressing the billet.
- After the simulation process, burrs can be observed on both the flat surface at the top of the gear's coupling teeth and on the gear teeth. These need to be machined and refined to perfect the part's extrusion molding.

By comparing the two techniques and through simulation, we verified the feasibility of this extrusion molding plan, which can reduce production costs and optimize the lightweight design of integrated structure gears. This study aims to provide a reference for the extrusion molding process of such components.

Acknowledgement

This project is funded by the following projects: Anhui Provincial Science and Technology Department Key R&D Project (2022a05020063); Tianchang Intelligent Research Institute Project (tzy202101); Anhui Provincial Department of Economic and Information Technology Agricultural Machinery Shortcomings Project (No.JB23802); Anhui University of Science and Technology Support Project (RCYJ201904) and

Fengyang County Science and Technology Project (No. 2023TPY05).

References

[1] JEONG, M.S., LEE, S.K., YUN, J.H., SUNG, J.H., KIM, D.H., LEE, S., CHOI, T.H., (2013). Green manufacturing process for helical pinion gear using cold extrusion process. *International Journal of Precision Engineering and Manufacturing,* 14, pp.1007-1011.

[2] TANG, Y., WANG, Z., CHEN, G., ZHANG, S., YUAN, W., (2022). Research on Key Technologies of Low-Cost Cold Precision Finishing of Cycloid Gears. *Journal of Mechanical Engineering*, Vol. 58, No. 14, pp. 154-160.

[3] LI, L., YIN, Q., CHEN, X., (2018). Optimization Design and Simulation Analysis of Half-Axis Gear Forging Process Based on DEFORM-3D. *Forging Technology,* Vol. 43, No. 03, pp. 26-30.

[4] LU, H., (2012). Analysis and Application of Modern Cold Extrusion Forming Technology. *Foreign Investment in China,* Vol. 20, pp. 288.

[5] FENG, W., LI, M., (2017). Analysis of Deformation Rule of Cylindrical Helical Gear in Precision Forming with Floating Die. *Precision Forming Engineering,* Vol. 9, No. 01, pp. 35-40.

[6] PENG, B., LUO, Y., WANG, H., NIU, T., WANG, Y., (2023). Investigation on the effects of tooth profile deviation in gear rolling process. *The International Journal of Advanced Manufacturing Technology,* Vol. 126, No. (5-6), pp.1877-1887.

[7] BU, J., CAI, Y., (2021). Precision Forging Process of Straight Cylindrical Gear Based on DEFORM. *Forging Technology,* Vol. 46, No. 11, pp. 43-48.

[8] JIANG, X., FAN, D., FAN, S., XIE, X., CHEN, N., (2021). High-precision gyro-stabilized control of a gear-driven platform with a floating gear tension device. *Frontiers of Mechanical Engineering,* Vol. 16, No. 3, pp.487-503.

[9] XU, R., ZHANG, J., WANG, J., LI, R., HUANG, K., (2021). Nonlinear dynamic modelling and analysis for a spur gear pair considering tooth profile deviation based on tooth contact analysis. *Journal of Vibration Engineering & Technologies,* pp.1-19.

[10] DU, P., WU, X., (2018). Strength Calculation of Double-layer Combined Extrusion Die. *Mechanical Engineering & Automation,* Vol. 03, pp. 120-121.

[11] LIU, Y., LI, Y., MA, L., CHEN, B., LI, R., (2022). Parametric design approach on high-order and multi-segment modified elliptical helical gears based on virtual gear shaping. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* Vol. 236, No. 9, pp.4599-4609.

[12] FELIX, K., JENS, B., THOMAS, B., (2021). Process design for gear shaping of austempered ductile iron (ADI) components. *Procedia CIRP,* 99.

[13] WANG, T., ZHANG, Y., SUN, H., WANG, Z., LIU, H., (2022). Research on deformation coordination of composite metal gears in the process of cold extrusion. *Journal of Physics: Conference Series,* Vol. 2338, No. 1, pp. 012048.

[14] CHEN, J.H., (2012). Optimal Design Method of Gear Molding. *Advanced Materials Research,* Vol. 1673, No. (479-481).

[15] HAO, Z., (2020). Research on the Plastic Forming Process of Bevel Gear with Arc Teeth. *Chemical Design Communications,* Vol. 46, No. 07, pp. 63-64.

[16] WANG, M., (2022). Numerical Simulation Study on Warm Extrusion of Cone Liner of Spring Cone Crusher Based on DEFORM-3D. *Mold Technology,* Vol. 237, No. 03, pp. 38-43.

[17] LONG, K., (2018). Cold Forging Forming Process and Mold Design of Flange Shaft Components. *Manufacturing Technology & Machine Tool,* Vol. 09, pp. 148-150.

[18] ROHRMOSER, A., KIENER, C., HAGENAH, H., MERKLEIN, M., (2019). Influence of tribological conditions on application relevant component properties of cold forged gears. *Production Engineering,* Vol. 13, pp.579-588.

[19] PETER, G., BENJAMIN, H., (2014). Friction control for accurate cold forged parts. *CIRP Annals - Manufacturing Technology,* Vol. 63, No. 1, pp. 285-288.

[20] ZHANG, Y., ZHU, L., REN, J., (2021). Numerical Simulation Study on Cold Extrusion Forming of Two-end Gear Parts Based on Deform-3D. *Chinese Equipment Engineering,* Vol. 24, pp. 272-273.

[21] ŠMERINGAIOVÁ, A. (2021). Elimination of resonant phenomena adverse effect in the process of experimental operation of gears. *Manufacturing Technology*, 21, 842-8.

[22] KOREČEK, D., SOLFRONK, P., SOBOTKA, J. (2020). Numerical Simulation as a Tool to Predict Sheet Metal Forming Process of TRIP Steel HCT690. *Manufacturing Technology*, 20, 625-31.