Hot and Cold Precision Forging Of Straight Bevel Gears in Closed Die: Experimental and Simulated Investigation

Duy Dinh Van, Duc Quang Vu, Anh Quan Tran, Trung Kien Le

***Abstract*— This paper has been drawn from fundamental research on precise hot and cold forging based on numerical simulation and experiments for straight bevel gear (SB-gear) made of aluminium A5052. The study was undertaken by using the finite element (FE) method and experiments. The utilization of such techniques provides a better insight into the deformation mechanics during the hot or cold forging process by giving an accurate description of the material flow, filling conditions, scalar damage index, and corresponding geometrical profiles. The finite element method also enables the prediction of stresses and forces exerted on tools and the distribution of the grain direction variables in the hot or cold forged parts. Numerical results, once compared with the experimental ones, have shown a good agreement. The straight bevel gears have been successfully fabricated by the precise forging process in a closed die. The results showed a close agreement between the numerical simulation and experimental analysis of straight bevel gears.**

***Index Terms*— Precision Forging, Closed Die, Straight Bevel Gears.**

I. INTRODUCTION

The straight bevel gears are widely used in machinery to transmit movement between intersection axes. Gears are mainly manufactured by metal cutting or combining conventional hot forging with metal cutting, which is expensive and requires a lot of manufacturing time. In the forging industry, newer achievements enable direct making gears with precision forging technology [1]. Compared with machining, forging is a high efficiency, high material utilization, and low-cost manufacturing method. The right one brings in continuous metal flow and refined microstructure for the gear parts, thus improving the mechanical property of the gear parts [2].

Numerical simulation of the precision forging gears using 3D finite element models is truly state of the art [3,4,5]. The three-dimensional FE analyses have been used to investigate the effect of some critical geometrical parameters such as initial billet diameter and height, gap height, and working conditions such as friction during the process [6,7,8]. These studies focus on studying the influence of technological parameters on the quality of stamping products in hot forging or cold forging [9,10], without an analytical comparison between these two technologies, for a case-by-case assessment.

The study performed numerical analysis for two types of the precise forging of straight bevel gears with nine teeth and encompasses the experimental investigation of the hot and cold precision forging gear parts (from A5052) on the same die. This paper aims to present theoretical and experimental research in the cold precision forging of straight bevel gear. The theoretical analysis consists of utilizing virtual prototyping techniques based on the finite element method to characterize the material flow, obtain a better insight into the deformation mechanics, and predict the mechanical properties of the shaped parts. Theoretical predictions are also used for designing and manufacturing a laboratory tool. The experimental analysis was undertaken to verify the theoretical assumptions and further develop the flexible tool system.

II. MATERIAL AND METHODS

A. Simulation Process

As a high efficiency and low-cost analytical method, the finite element simulation is employed in this research to analyze the precision forging process of the straight bevel gears (SB-gear). In this study, the hot and cold forging processes of the SB-gears are simulated so that the differences between these two forging processes can be recognized.

The numerical simulation performs one type of workpiece; the forging die was calculated based on the principle of precise forging process and dimension of the designed product. The work-pieces would be meshed of quadrilateral elements, suitable for die full-filled process.

In these FE models, the material of the billet is A5052. To ensure the accuracy and convergence of numerical simulation of bevel gear forging, the billet is set as plastic-type and meshed by tetrahedral elements with absolute mesh type. To accurately predict the temperature field, the dies are meshed by tetrahedral elements with absolute mesh type, and the heat transfer boundary condition between billet and dies is reasonably set. Furthermore, the shear friction model is employed to describe the friction between billet and dies. The friction factor for lubricated hot and cold forging processes is adopted based on the software recommendation. The main parameters of the hot and cold forging processes of the SB-gear are listed in Table 1.

Table 1. Process parameters of hot and cold forging processes of the SB-gear.

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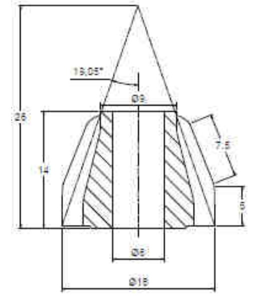
Parameters	Hot forging	Cold forging
Material of workpiece	AA5052	
Temperature of billet (°C)	400	24
Material of dies	SKD61	
Friction factor	0.3	0.08
Feed speed of punch (mm /s)	10	
Punch stroke (mm)	10.8	

The part selected for hot and cold forging is a straight bevel gear, mounted on hand tools with the material and gear specifications given in Tables 2 and 3:

Table 2. Material properties of work-piece [11]

Material	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m^3)
AA5052	70	0.35	2680

Table 3. 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

The equations governing the material flow in the precision forging process of A5052 consist of the conservation equations of the power law, flow stress, which are defined as [12]:

Power law: $\bar{\sigma} = c\bar{\epsilon}^n \dot{\bar{\epsilon}}^m + y$ (1)

Flow stress: $\dot{\bar{\epsilon}} = A[sinh(\alpha\bar{\sigma})]^n e^{-\frac{\Delta H}{RT_{abs}}}$ (2)

Where: $\bar{\sigma}$ = Flow stress, $\bar{\epsilon}$ = Effective plastic strain, $\dot{\bar{\epsilon}}$ = Effective strain rate, c = Material constant, n = Strain exponent, m = Strain rate exponent, y = Initial yield value, A = Constant, α = Constant, ΔH = Activity energy, R = Gas constant, T_{abs} = Absolute temperature.

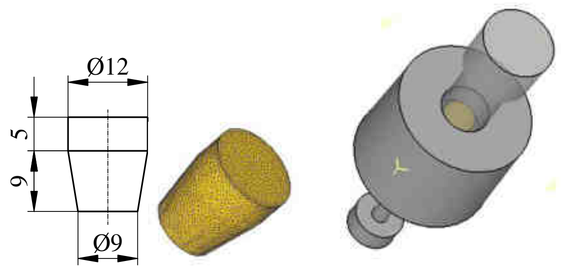


Fig. 1. Model of Workpiece and tools

As mentioned above, SB - gear is an important component for shaft drive. Nowadays, there are many methods to manufacture SB - gear products, primarily by forging technique. Work-pieces used for the experiment were A5052 tapered shapes. The shape of the workpiece and the setting of the tool components when simulated are shown in Figure 1.

B. Experiment

Through theoretical calculations, the original workpiece has been determined, and the die forging was designed with the help of CAD software. Next, the workpieces were machined on a turning machine to ensure their same initial geometrical shapes and sizes (figure 10a). After being machined to pre-determined dimensions, the workpieces were polished and lubricated before being shaped.

The punch and die were made of SKD61 steel, as shown in Figure 2a. The die was lubricated with a graphite mixture.

a) Punch (left) and die (right) *b) Assembled dies*

Fig. 2. Forging dies of the driven SB-gear.

The forging die was manufactured by the CNC EDM machining centre and fitted on a hydraulic testing machine, Figure 3b. Hydraulic press with maximum compressive force up to 125 tons is used in this machine.

To investigate the forging load in the forming process, a measuring system has been designed and manufactured (Figure 3):

Fig. 3. System for measuring force and stroke

III. Results and Discussions

A. Metal flowing in Deformation Process

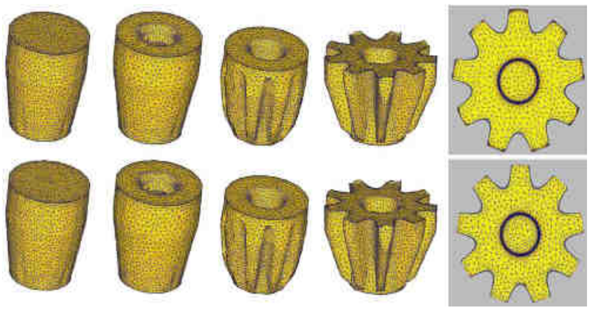


Fig. 4. Metal flowing in hot forging (up) and cold forging (down) of the SB-gear

Due to the complicated shape of the gear, the resistance for metal to flow into the die will be high, so it is necessary to investigate the metal's flowing process to evaluate the forming ability. Fig. 4 shows the filling processes in the hot and cold forging processes of the SB-gear with forging stages.

It can be seen from Fig. 5, in the forging process of SB-gear, the filling processes of all gear-teeth are similar for axis-symmetrical SB-gear. Figure 6 shows the velocity vector of metal flow during the deformation process. Quickly see that the metal flow ran more uniformly and stably during the hot forging process, forming metal grains.

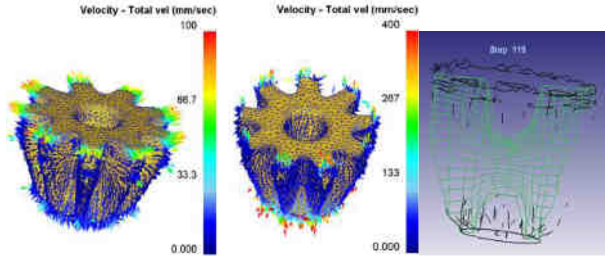


Fig. 5. Velocity in hot forging (left) and cold forging (right) of the SB-gear (a), deformation mesh (b)

Based on numerical simulation, we can study the metal flow by forging technique and other metalworking methods to make comparisons and judgments about compressive force and metal flow in each case.

B. Effective strain distribution and evolution on forged SB-gear

The complicated metal flowing of the hot forging process of the driven SB-gear would lead to inhomogeneous plastic deformation. The effective strain distribution and growth of forged driven SB-gear in hot and cold forging processes are shown in Fig. 6:

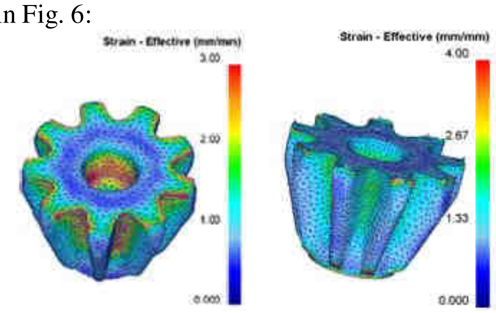


Fig. 6. Effective strain distribution and evolution of the driven SB-gear in hot and cold forging process

As shown in Fig. 6, with gear-tooth die feeding, the effective strain gradually accumulates on the billet. The effective strain on gear-teeth regions increases more obviously than that on other areas, which means that the plastic deformation mainly occurs on the gear-teeth. This result is because that high metal flowing resistance is caused by the complicated gear-teeth cavities, the plastic deformation is more severe on the gear-teeth regions. Secondly, the effective strain on the surface of each gear-tooth is higher than that inside the gear-tooth, which is attributed to the high friction resistance on the surface of each gear-tooth. Furthermore, the effective strain gradually increases from addendum to dedendum on each gear-tooth; the cause is the metal flowing is more intricate near the dedendum region because of the complicated die cavity.

During hot forging and cold forging processes of the driven SB-gear, the different velocity vectors of metal flow during deformation processes (introduced in section 3.1) leads to inhomogeneous effective strain on other SB - gears. The earlier the gear-tooth is filled, the shorter the deformation period the metal should undergo, less effective strain would be accumulated. It is well known that the inhomogeneous effective strain distribution would lead to non-uniform mechanical property, so it should be avoided. Compared with Fig. 6 (right), the effective strain homogeneity on hot forged gear is improved in Fig. 6 (left). It is because that the hot forging process has effectively allocated the metal.

C. Effective stress distribution on forged SB-gear

Stress is a characteristic parameter for energy process development in the forging technique. In deformation areas that have large strain impedance will occur high-stress field. Stress field distribution on workpieces of the two different processes is shown in Figure 7.

It can be seen that the stress distribution of the hot forging process is not uniform. The stress distribution is different in the toe, the middle, and the heel area. From Fig. 7, the stress of tooth toe-end is about 90 MPa, the average stress of middle area near toe-end is 100 MPa, and the stress of tooth heel-end is 125 MPa, respectively. The stress distribution of the cold forging process is more uniform by contrast, and the stress concentration is mainly distributed in the middle tooth and the tooth heel-end; the average stress is close to 175 MPa. By analyzing the effective stress distribution in the forging process, cold forging gives a better micro-structure because the higher pressure helps refine the gear's microstructure.

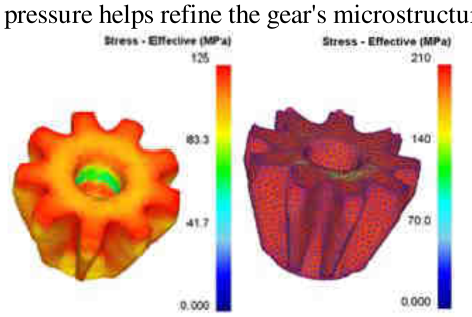


Figure. 7. Stress field of workpiece: hot forging (left), cold forging (right)

D. Forming load

The simulation forming loads of two processes with increasing punch stroke are compared in Fig. 8. It can be seen that the maximum forging load of the hot forming process is relatively small (7.2 tons), approximately 56% of the maximum force of the cold forging process (16.5 tons). So that hot forging process can contribute to tapping the potential of forging equipment; otherwise, the increasing trend in forming load is smooth, which does not cause a sharp increase for the load force of die, and it can also help improve the die service life.

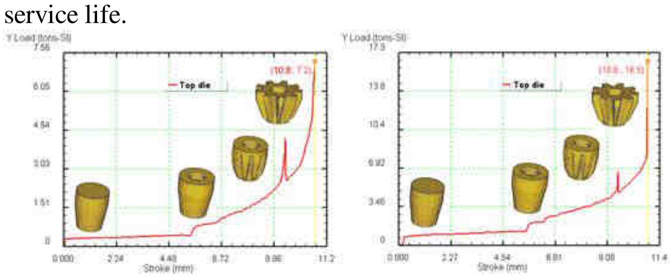


Fig. 8. Forging load curves of forging process: hot forging (left), cold (right)

E. Scalar damage index

From the simulated product in Figure 9, we get the results of evaluating the scalar damage index on the product; for any forged product, the scalar damage index shown on the part reaches a value less than 1. Both simulation products have a scalar damage index much less than 1, with hot forging and cold forging having an average scalar damage index of approximately 0.25 and 0.3, respectively. It can be concluded that the cold forging product has a higher scalar damage index, and the product is successfully formed in both hot forging and cold forging processes without any defects after the forming process.

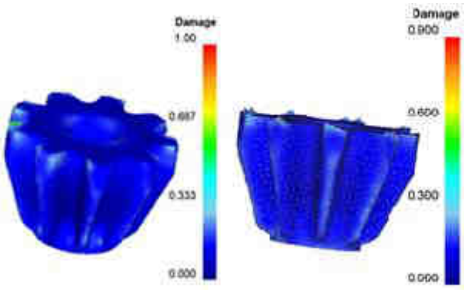
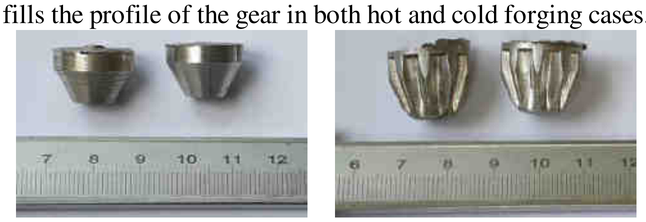


Fig. 9. Scalar damage index: hot forging (left) and cold forging (right)

F. Experiment Results

Based on the FE simulation results revealed above, several cold forging and hot forging experiments were carried out to forge the SB-gear. Experimental results after measurement show that the product meets the requirements in terms of shape and size. Thus, with the designed cavity, the metal fully fills the profile of the gear in both hot and cold forging cases.



a) Workpiece A5052 tapered configuration *b) products (hot forging – left, cold forging – right)*

Figure. 10. Experimental forging of bevel gears in closed die

The maximum experimental cold forging load was 17.2 tons, and the relative error compared with the maximum simulation forging load was 4.2%. Meanwhile, the experimental hot forging load was 7.6 tons and the relative error compared with the maximum simulation forging load was 5.6%. That means both simulation and experimental forging load results are reliable. However, the stamping force in cold forging was much higher than that in hot forging, which leads to the requirement of die design to ensure durability, and the equipment used will consume more energy than hot forging.

CONCLUSION

Forging simulation offers significant advantages by providing detailed insight into the forging process before making production decisions. In this research, the 3D finite element method is used to simulate hot and cold precision forging processes of the straight bevel gear. Based on numerical analysis such as metal flow, effective strain, effective stress distribution, forming load, scalar damage index on SB-gear forging process, suitable parameters were chosen to experiment.

The straight bevel gear has been successfully fabricated by hot and cold precision forging processes. The results showed a close agreement between the numerical simulation and experimental analysis of straight bevel gear. Cold forging shows advantages such as saving materials, reducing machining steps, high productivity, good surface finish and high dimensional accuracy. In particular, compared with conventional methods, the cold forging technique creates products with high mechanical properties due to the uniform, continuous flow and hardening of metal. The research results also offer technicians the possibility of using cold forging technology to replace hot block stamping with suitable materials and strain.

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REFERENCES

[1] T. Altan (1998), Solid forging, *Metal Forming Handbook*, Schuler (c) Springer-Verlag Berlin Heidelberg.
[2] Schuler (c) (1998), *Metal Forming Handbook*, Springer-Verlag Berlin Heidelberg (1998).
[3] Hartley P, Pillinger I (2006*) Numerical simulation of the forging process*. Comput Method Appl M 195(48–49):6676–6690
[4] Satish GD, Singh NK, Ohdar RK (2008*) Preform optimization of pad section of front axle beam using DEFORM*. J Mater Process Technol 203(1–3):102–106
[5] Zhang ZJ, Dai GZ,Wu SN, Dong LX, Liu LL (2009*) Simulation of 42CrMo steel billet upsetting and its defects analyses during forming process based on the software DEFORM-3D*. Mater Sci Eng A 499(1–2):49–52
[6] Lee YK, Lee SR, Lee CH, Yang DY (2001) *Process modification of bevel gear forging using three-dimensional finite element analysis*. J Mater Process Technol 113(1):59–63
[7] Yoon JH, Yang DY (1990) *A three-dimensional rigid-plastic finite element analysis of bevel gear forging by using a remeshing technique*. Int J Mech Sci 32(4):277–291
[8] Saman Khalilpourazary, Abdolrahman Dadvand, Taher Azdast, Mohammad Hossein Sadeghi (2011) *Design and manufacturing of a straight bevel gear in hot precision forging process using finite volume method and CAD/CAE technology*. Int J Adv Manuf Technol 56:87–95
[9] Zhen-Shan Gao, Ju-Bo Li, Xiao-Zhong Deng, Jian-Jun Yang1, Fu-Xiao Chen, Ai-Jun Xu, Lei Li (2017) *Research on gear tooth forming control in the closed die hot forging of spiral bevel gear*. Int J Adv Manuf Technol.
[10] M.L. Alves, J.M.C. Rodrigues, P.A.F. Martins (2001) *Cold forging of gears: experimental and theoretical investigation*. Finite Elements in Analysis and Design 37: 549-558.
[11] William F. Gale, Terry C. Totemeier - *Smithells Metals Reference* Book-Butterworth-Heinemann (2004).
[12] Deform - 3D V6.1: User's Manual (2007).