A Study on the Heading of Spur Gears: Numerical Analysis and Experiments

M.Zadshakouyan, E.Abdi Sobbouhi, H.Jafarzadeh

***Abstract*—**In this study, the precision heading process of spur gears has been investigated by means of numerical analysis. The effect of some parameters such as teeth number and module on the forming force and material flow were presented. The simulation works were performed rigid-plastic finite element method using DEFORM 3D software. In order to validate the estimated numerical results, they were compared with those obtained experimentally during heading of spur gear using lead as a model material. Results showed that the optimum number of gear teeth is between 10 to 20, that is because of being the specific pressure in its minimum value.

***Keywords*—**Heading, spur gear, numerical analysis, experiments.

I. INTRODUCTION

PRECISION forging of gears has been the subject of considerable efforts in the last few decades in the forging industry. Of all the many types of machine elements that exist today, gears are among the most commonly used. For example the cylindrical spur gear is one of the most widely used gears. Two groups of manufacturing methods for gears, i.e. cutting and non cutting, are available in engineering industry. The forging of spur gears is one of the non cutting methods. Compared with the conventional methods such as machining, the forging of gears has many advantages such as great reduction of raw material and energy expenses, considerable improvement of the productivity effect, and significant increase in strength values of the teeth because of the intact microstructure of the forged gear. Giving high production rates and eliminating many time consuming and costly manufacturing processes such as cutting and shaping of gears are the other advantages of this process. For the spur gears, the way to complete filling up of the material in to the die cavity is regarded as the most important aspects for improving the dimensional accuracy of gears. For complete filling up, predicting the power requirement is an important features of the forging process [1-5]. Simply forged gears are used as either keyed to the shaft or force or shrunk fitted on to the shaft; however, heading of the teeth directly over the body of the shaft itself, removes the need for further consideration.

M. Zadshakouyan, Assistant professor of Manufacturing Engineering Department, University of Tabriz, Tabriz, Iran. (corresponding author to provide phone: 0098-411-3393824; fax: 0098-411-3356026; e-mail: zadshakoyan@ tabrizu.ac.ir).
E. Abdi Sobbouhi, MSC Student of Manufacturing Engineering, University of Tabriz, Tabriz, Iran. (e- mail: ehsan.eas@gmail.com).
H.Jafarzadeh, MSC Student of Manufacturing Engineering, University of Tabriz, Tabriz, Iran. (e- mail : hosseinjama@gmail.com).

The development of precision gear forging and heading is an area of important experimental and analytical activities in recent years. Chitkara and Bhutta [1] analyzed the forging and heading of hollow spur gears by two theoretical approaches i.e. upper bound and slab method. They compared estimated results with those obtained experimentally during forging using the model material tellurium-lead. In the other study [2] they analyzed heading of spur gears by upper bound and slab method. J.Choi and Y.Choi [3] classified the forging process of spur gears in two types of operations, guiding and clamping. J.Choi et al. [4] investigated the forging of spur gears by means of upper bound analysis and proposed a new kinematical admissible velocity field. Alves et al. [5] studied cold forging of gears using 2D and 3D finite element method.

In this study numerical analysis of precision heading process of spur gears was investigated and effect of some parameters such as teeth number and module on the metal forming force and material flow were presented. The results are compared with experimental results carried out using lead as a model material.

II. FINITE ELEMENT ANALYSIS

The effect of geometrical parameters of spur gear such as teeth number and module have analyzed using three dimensional finite element program DEFORM 3D^{TM} for comparison. This software has a simulation engine for performing the numerical calculation required to analyze the process, and writing the results to the database file. The simulation engine reads the database file, performs the actual solution calculation and appends the appropriate solution data to the database file. The simulation engine, also works seamlessly with the automatic mesh generation system to generate a new FEM mesh on the workpiece whenever necessary. The program works according to rigid-plastic material behavior model. All of the simulations have been done in the room temperature i.e. 20°. Throughout the analysis a constant friction factor was considered on the die-workpiece contacting surface and the initial diameter of the billet was equal to that of the root circle of the gear.

In order to have an efficient and cost effective three dimensional numerical simulation, the punch and die are assumed to be rigid bodies without meshing and only one gear tooth model is built. Fig.1 shows the schematic illustration of spur gear heading.

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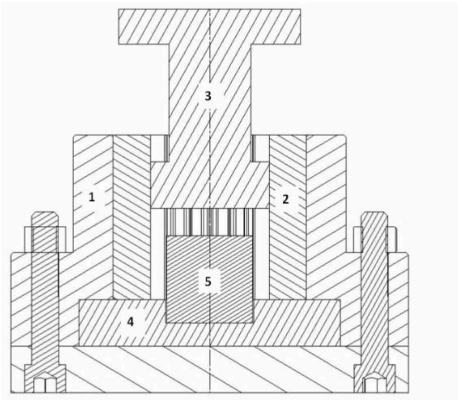


Fig. 1 schematic illustration of spur gear heading
1. Container. 2. Gear shaped die insert. 3. Gear shaped punch.
4 .Bottom plate 5 .Billet

III. EXPERIMENTAL

A. Material properties

Compression tests were performed on commercial lead billets using workpieces of 20 mm in diameters and 30 mm in height (h/d=1.5) to obtain true stress-strain data. Shallow concentric grooves were turned on the ends of the specimens, so as to facilitate the retention of lubricant during compression testing.

The procedure used for the compression test involved lubrication of the ends of the specimens with Alvania grease, so that the lubricant was allowed to retain in the grooves. The test specimen was centralized between the platens of the compression rig before load was applied. Tests were carried out at the ram speed of about 5mm/min. Fig.2 shows the true stress-strain curve for solid lead billet, obtained from a compression test.

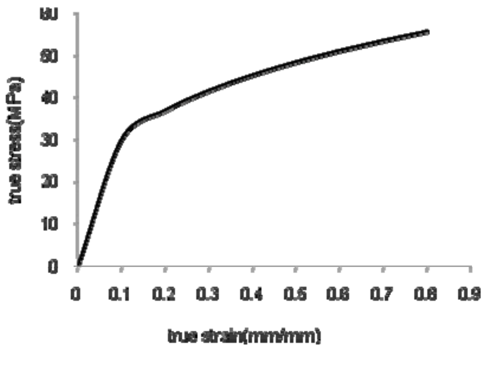


Fig. 2. True Stress-strain curve of Lead

The stress-strain equation of the curve fitted is:

$$\bar{\sigma} = 59.8\varepsilon^{-0.296}(MPa) \qquad (1)$$

B. Die design procedure

Specific tool parts are presented in fig.3, showing the container, the die insert (pre stressed container) and the forging gear shaped punch. In flashless precision forging of gears the container is fixed to the machine bed and a penetration punch is attached to the slide of the machine.

Material type of the die insert and punch contacting with the workpiece was commonly decided to be AISI, H-13 and in order to endure higher forming pressures and minimize elastic deformation, they were hardened up to 50 HRC.

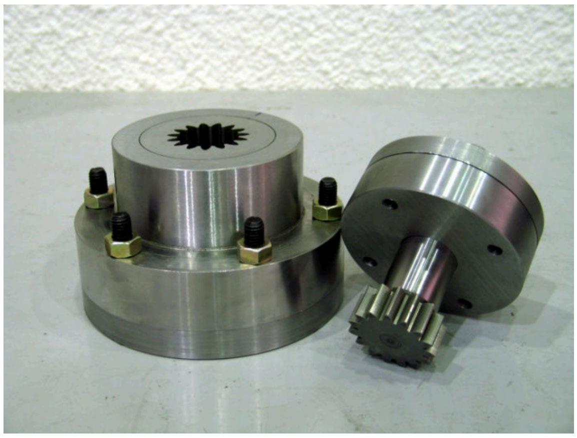


Fig. 3. Die insert in container and punch

The die insert was shaped by wire-cut EDM machine and was shrink-fitted before being wire-cutted to prevent deformation that could cause gear errors and wrong shrink-fit interference. The shrink-fit interference was set to 0.05 mm in order to reduce the level of the tensile circumferential stress generated by the forging process. The forging gear shaped punch was also machined by wire-cut EDM. In this stage, the spur gear used as a component of the tractor was determined for close die forming process design. Table 1 shows the specifications and dimension of the spur gear selected, of which teeth number, module and pressure angle are 15, 3, 24°, respectively. The billets for the forging experiments were machined from Lead. The initial diameter of the billets was equal to that of the root circle of the gear i.e. 38.85 mm.

TABLE I
SPECIFICATIONS AND DIMENSION OF THE SELECTED SPUR GEAR

No. Of TEETH	15
NORMAL MODULE	3
NORMAL PRESSURE ANGLE	24
REFRENCE PITCH DIAMETER	45
THEOR TOOTH THICKNESS	5.3268

Fig.3 shows an example of a spur gear part forged by precision heading process that was described above.

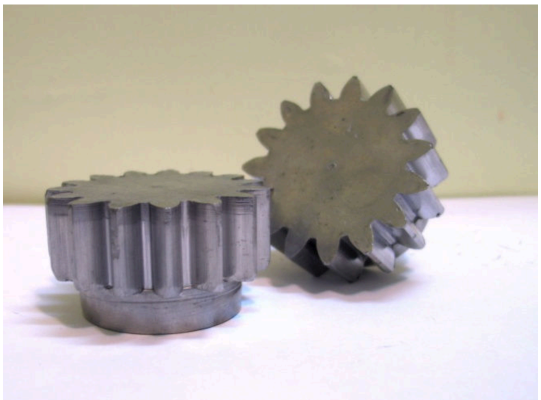


Fig. 4. Precision forged spur gear
(N=15, M=3, Teeth Height=20 mm, constrained length=10 mm), material: Lead

The experiments were performed on a 500 KN AMSLER hydraulic press as shown in fig. 4, and carried out at the constant punch velocity at room temperature.

Fig. 5. gear forging die set.

In precision forging it is difficult, but very important, to determine the punch stroke that is necessary for obtaining a finished product. In this study the stroke of the punch has measured by means of a gage with a precise of 0.01 in.

IV. Results and Discussion

A. Results of numerical analysis

The precision heading of spur gears using cylindrical billets and commercial lead as a model material has been investigated by means of numerical analysis. Fig.6 shows the variation of forging load with the punch stroke. The results are determined for gears of module 3 with pressure angle of 20°. The number of teeth is varied from 10 to 35, the height of gear is 10 mm, constrained length is 10 mm, the height of tooth is 2.25M and constant friction factor is 0.1.

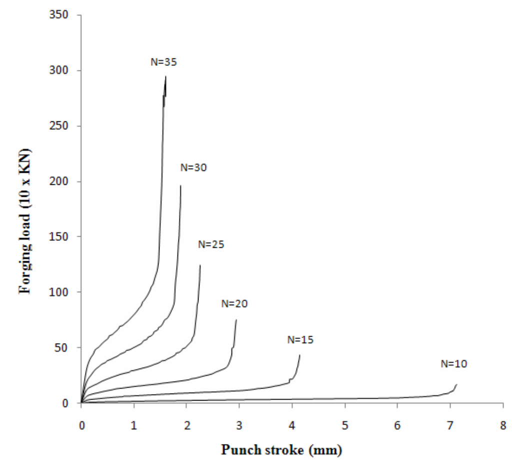


Fig. 6. Variation of the forging load with punch stroke

As it is seen in the fig.6 with increasing of the teeth number in the same module the forging load increases. This is because with increase of the teeth number the size of the gear enlarges and so the required load to forming the gear increases. Therefore, in order to study the effect of teeth number, another parameter should be considered. This non-dimensional parameter is specific pressure and defines with equation (1).

Specific pressure = (1)

The numerical values of the specific pressure are determined for gears of modules from 2 to 4 with pressure angle 20°. For each module, the number of teeth is varied from 10 to 35, the gear height is 10 mm, constrained length 10 mm and the height of tooth is 2.25M.

For the given condition, the calculated results are shown in fig.7 to 9. The figures show the variation of the specific pressure with reduction in height.

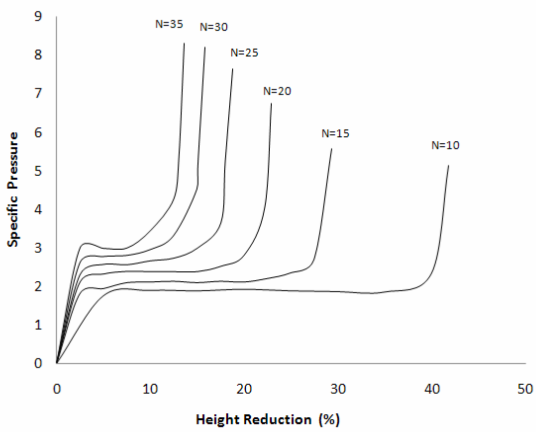


Fig. 7. Variation of the specific pressure with height reduction for module 2

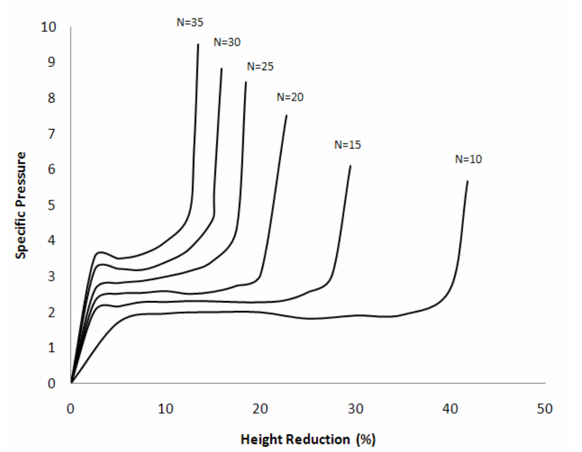


Fig. 8 Variation of the specific pressure with height reduction for module 3

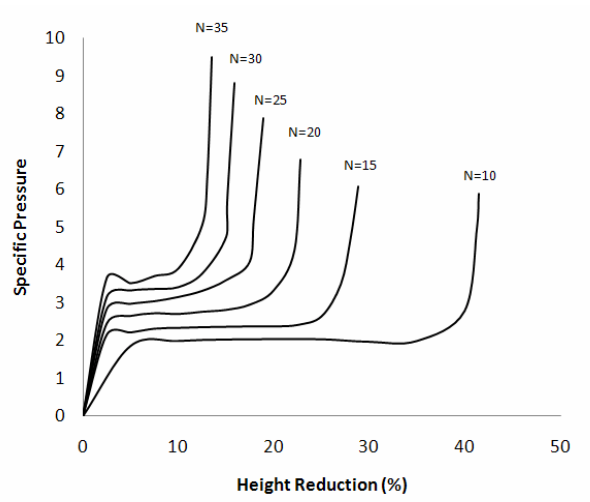


Fig. 9 Variation of the specific pressure with height reduction for module 4

The specific pressures at the final step are minimum around the number of teeth of 10-20 for each module. From these the suitable number of teeth for each module in the precision heading of gears can be found, from which it is concluded that it is not suitable to forge with number of teeth above 20.

B. Comparison of loads between numerical analysis and experiment

Fig.10 shows the comparison of the estimated die load from three-dimensional FE analysis and the experimental one. The estimated load from numerical analysis is in good agreement with the experimental result. In the figure the small difference between numerical and experimental results could be caused by friction condition. In the numerical simulation the friction factor is considered to be constant during the process while in the real condition the friction factor varies during the forming and its value is usually higher than theoretical values.

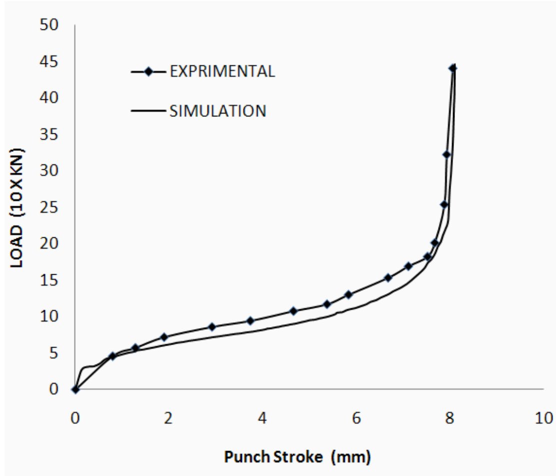
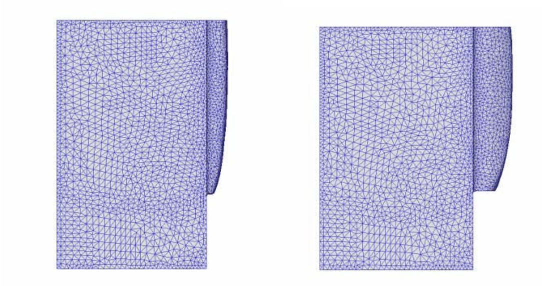


Fig. 10 Comparison of loads between numerical analysis and experiment for the heading of spur gear: (Number of teeth=15, module=3, pressure angle=24°, teeth height=20 mm, constrained length=10 mm)

C. Analysis of material flow

In conventional precision forging of spur gear the basic function of tool is that the workpiece is deformed by relative closure of punch and die. The mode of the flow of the workpiece depends on the relative movement of tool elements and therefore, cavity filling and the positioning of a compensation space will be affected by tool kinematics. The sequence with which a workpiece will fill a cavity can be determined by noting the direction in which friction forces act. In early stage of gear forging, the mode of the metal flow is close to open die upsetting. Thus the material in the middle section flows faster than the material in the top and bottom region because of the friction force. As forging continues, the partly formed tooth is in contact with the tooth die surface. The frictional resistance from the toothed die surface force opposes the metal flow downwards and the top region fills more rapidly [6]. But in the heading of spur gears the product is achieved by constraining one end of the shaft using die which prevents both radial and axial flow of material in that part of the shaft. In the process, the flow of ductile material takes place only within the gear teeth portions thus causing a complete shearing along the surface separating the deforming material from the constrained shaft. Fig.11 shows three stages of teeth forming during heading of spur gear. Fig11.a, b and c shows tooth after 16, 25 and 29% height reduction. Fig12 shows photographic view of deformed specimens. Fig12.a shows a workpiece after 16% height reduction, fig12.b shows a workpiece after 25% height reduction and a full shaped gear is shown in fig12.c

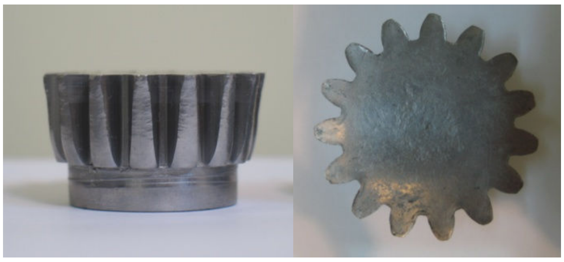


a b

c

Fig. 11 Tooth forming sequence during heading of a spur gear a.16%height reduction b.25% height reduction c.29% height reduction

a



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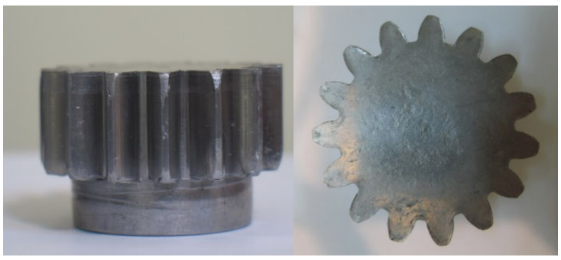

c

Fig.12 photographic views of deformed specimens during heading of a spur gear. a.16%height reduction b.25% height reduction c.29% height reduction

As shown in figure 11 and 12 deformed shape obtained from FE simulation is in good agreement with that obtained from experiments.

V. Conclusion

Heading of spur gears has been investigated by means of numerical analysis. From numerical calculation and experimental testing, the following conclusions are made:

1. The specific pressure increases with the number of teeth and height reduction for a given module. The proper number of teeth for heading of spur gear is 10-20 at modules 2, 3 and 4.
2. The predicted forging load obtained by numerical analysis is in good agreement with the experimental results during process.
3. Because of complete shearing along the surface separating the deforming material from the constrained shaft, bottom corners of gear fill up at the end of process and requires high load to complete forming.

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