Die design for the cold forging spur gears

Hyuk-Hong Kwon*

Abstract

The near net shape forging of gears offers significant technical and economic advantages over other forms of manufacture. These potential benefits can however only be realized by careful die design. This paper describes a computer-based methodology for achieving this. A Visual-BASIC program has been developed on a rule based system that enables optimal design of the dies taking into account the elastic deflections generated in shrink-fitting the die inserts and that caused by the stresses generated in the forging process. The method also enables the profile of the spark erosion electrode to be determined. An example of the application to forging spur gears is given.

Key Words : Die Design, Cold Forging, Die Insert, Stress Ring

1. Introduction

Currently rapid developments are taking place in the research and manufacture of geared parts by cold metal forming processes. This is because cold forming of gears often offers technical and economical advantages when compared with the conventional methods for gear manufacture. To be successful in this regard it is however necessary to forge gears with near net-shape gear tooth profiles. The process of precision gear forging has been developed recently because of its advantages of giving high production rates, improved strength and surface finish. This is due to their inherent advantages compared with conventional cutting methods. Investigation of gear manufacturing of cold forming operations has been the subject of numerous numerical and experimental investigations. In some of the recent achievements in this field are presented. Takahashi and Brebbia [1] proposed the boundary element flexibility approach for solving two dimensional elastic contact problems involving friction, Sadeghi and Dean [2] analyzed the die correction factors including die expansion due to heating and forming stresses as well as thermal shrinkage for cylindrical shaped forgings. Experience from industrial applications shows that important die life increases can be obtained [3] if the design and the abilities of the prestressed container are corresponding.

To enhance their competitiveness, forging companies

* Dept. of Mechanical Design Engineering, Daejin University
(hhkwon@daejin.ac.kr)

always have to increase the quality of both the forging process and the finished parts. For the case of axisymmetric parts, one well-known solution is to use pre-stressed die inserts. Kim et al [4] showed that this solution enables the control of the stress state in the dies, as well as the final shape of the product. Due to the complexity of the system, it is very difficult to design the process, and especially to find the optimum value of the interference. Generally the design of the process is based on the designers knowledge and the application of simple numerical tools based on Lamés equations. Choi et al. [5] proposed a new extrusion process for helical gears. They analyzed the new process by using the upper bound method.

Various kinds of techniques, such as surface treatment, lubrication and the use of replacement die parts, are employed to prolong die life. One of the most important methods for reinforcing forging dies is pre-stressing. In forging die design, pre-stressing is useful in preventing excessive tensile circumferential stresses which may cause die failure during metal forming. It is therefore necessary to determine accurately the interference value for pre-stressing. Since the applicability of analytical solutions is rather limited, numerical techniques are applied to solve most industrial problems. For applying the method for reinforcing forging die, two main parameters have to be determined, i.e., (1) the interference value and (2) the position of the parting line between the die insert and the stress ring. In general, empirical methods have been used to provide these parameters, though it is difficult to obtain optimum values.

In this study, to determine the optimal design, die variable and etc., an automated program constructed with Visual-BASIC based on a rule-based system has been developed. The design rules are extracted from the plasticity theories, handbook, relevant references and empirical knowledge of field experts in cold forging company. After calculating interfacial pressure between the die insert and stress ring using this system, the safety of the die can be evaluated by determining the magnitude of the die stresses using the finite element method. The method is applied to the design of a spur gear die thus enabling the avoidance of die failure.

2. Rules of die design

Quantitative and empirical rules, presented in the paper, are formulated by using Lamés equations [6] which are applied to a thick cylinder with constant pressure along its whole length. Thermal effects are not considered. Fig. 1 shows Die schematic assembly for the gear forging. It consists mainly of a gear shaped die-insert, inner and outer stress ring, ejector, punch, punch holder, mandrel, upper die and lower die. Fig. 2 shows a block diagram of a CAD system for a forging die design module.

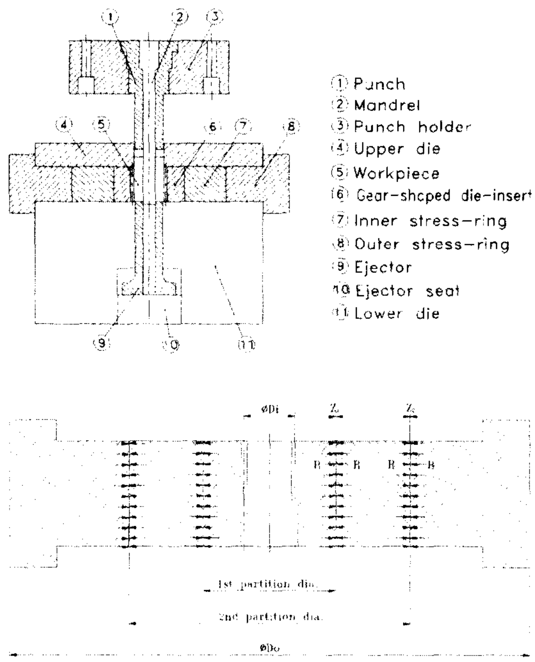


Fig. 1 Die schematic assembly for the gear forging

One stress ring

- Partition diameter ratio

$$Q_{1opt} = \sqrt{\frac{Q}{\sqrt{K_1}}}$$

- Maximum allowable internal pressure

$$P_{iopt} = S_{y1}\left\{\frac{1}{2}\left(1+\frac{1}{K_1}\right) - Q\sqrt{\frac{1}{\sqrt{K_1}}}\right\}$$

- Limit internal pressure

$$P_{i\lim it} = S_{y1}\left(1-Q^2\right)\left\{Q = 0, \frac{P_{iopt}}{S_{y1}} = 1\right\}$$

- Interfacial pressure

$$P_1 = \frac{1}{2}\frac{1-Q_{1opt}^2}{1-Q^2}\left\{S_{y2}\left(1-Q_{2opt}^2\right) - S_{y1}\left(Q_{1opt}^2 - Q^2\right)\right\}$$

: in the case of one stress ring

- Interference value

$$Z_1 = \left(\frac{1}{E_2}\frac{1+Q_{2opt}^2}{1-Q_{2opt}^2} + \frac{1}{E_1}\frac{1+Q_{1opt}^2}{1-Q_{1opt}^2}\right)P_1 d_1$$

Two stress rings

- Partition diameter ratio

$$Q_{1opt} = \sqrt[3]{\frac{Q}{\sqrt{K_1 K_2}}}, Q_{2opt} = Q_{1opt}\sqrt{K_1} = \sqrt[3]{\frac{QK_1}{\sqrt{K_2}}}$$

- Maximum allowable internal pressure

$$P_{iopt} = \frac{1}{2}\left(S_{y1} + S_{y2} + S_{y3}\right) - 1.5 S_{y1} Q_{1opt}^2$$

- Limit internal pressure

$$P_{i\lim it} = S_{y1}\left(1-Q^2\right)\left\{Q = 0.22, \frac{P_{iopt}}{S_{yi}} = 0.95\right\}$$

- Interfacial pressure

$$P_1 = \frac{1}{2}\frac{1-Q_{1opt}^2}{1-Q^2}\left\{S_{y2}\left(1-Q_{2opt}^2\right) + S_{y3}\left(1-Q_{3opt}^2\right) - S_{y1}\left(Q_{1opt}^2 - Q^2\right)\right\}$$

$$P_2 = \frac{1}{2}\frac{1-Q_{1opt}^2}{1-Q_{2opt}^2 Q_{3opt}^2}\left\{S_{y3}\left(1-Q_{3opt}^2\right) - S_{y2}\left(Q_{2opt}^2 - Q_{1opt}^2 Q_{3opt}^2\right)\right\}$$

: in the case of two stress rings

- Interference value

$$Z_1 = \left(\frac{1}{E_2}\frac{1+Q_{2opt}^2 Q_{3opt}^2}{1-Q_{2opt}^2 Q_{3opt}^2} + \frac{1}{E_1}\frac{1+Q_{1opt}^2}{1-Q_{1opt}^2}\right)P_1 d_1$$

$$Z_2 = \left(\frac{1}{E_3}\frac{1+Q_{3opt}^2}{1-Q_{2opt}^2} + \frac{1}{E_1}\frac{1+Q_{2opt}^2}{1-Q_{2opt}^2}\right)P_2 d_2$$

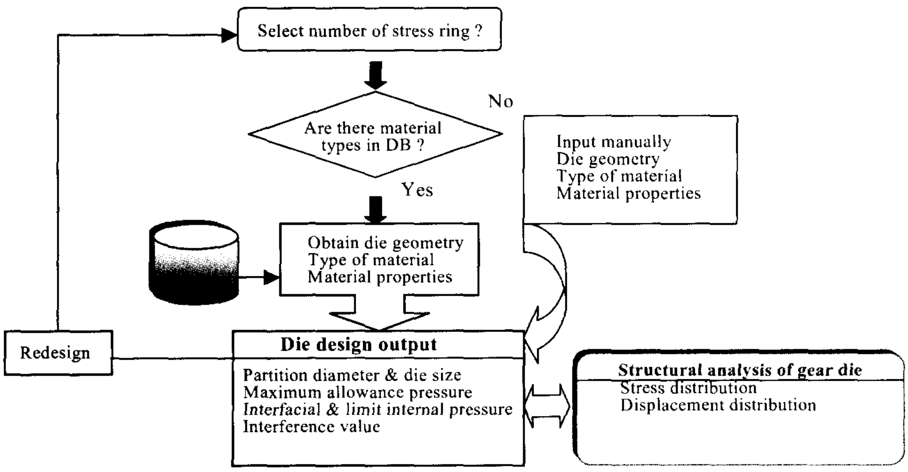
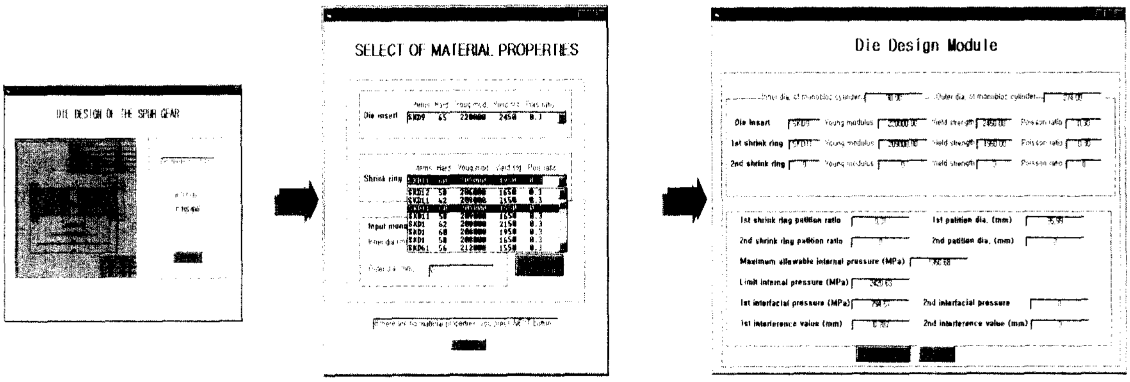
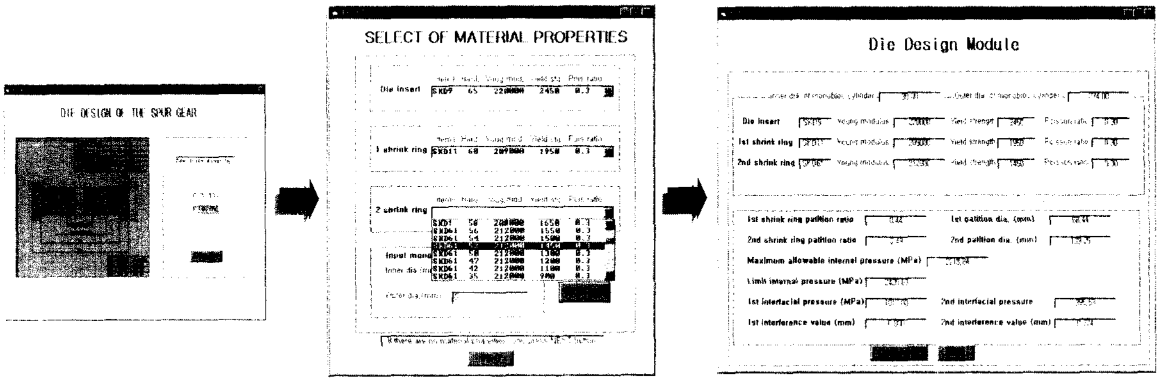


Fig. 2 Block diagram of CAD system for forging die design module



(a) in a case of one stress ring



(b) in a case of two stress rings

Fig. 3 Forging die design module for spur gear [7]

where Q s the inner to outer diameter ratio (D_i/D_o) of a monobloc cylinder, K_1 represents yield stress ratio, S_{y1}/S_{y2}, between the die insert and the first stress ring. The design is based on the criterion of selecting die insert and stress ring diameters such that both components experience critical stress levels simultaneously. This then determines the necessary interference values. This system requires the user to input the variables which are necessary to design the die. Die materials are selected from a database.

3. Structural analysis of spur gear die

The procedure applied to a spur gear forging with a commercial aluminum is illustrated in Fig. 3. The specification of the spur gear is shown in Table 1.

Table 1 Adopted standard external spur gear

Items	Dimensions
Number of teeth	18
Module	1.5
Pressure angle	20°
Pitch circle	27.0 *mm*
Base circle diameter	25.3667 *mm*

The stresses and the elastic deformations of the gear dies are calculated with the finite element code, ANSYS.

Table 2 Material properties which used for die insert and stress rings

Material properties	Die insert	stress ring	
		1st	2nd
Kind of die steel	STD9, H_RC62	STD11, H_RC50	STD61, H_RC50
Young modulus[MPa]	220000	209000	212000
Yielding stress[MPa]	2450	1950	1450
Poisson ratio	0.3	0.3	0.3

In the finite element analysis for the spur die stress analysis, the given internal pressures of the die were determined by an upper bound method was proposed by Choi et al. [8]. The final forging load is 85.5 tons, and the working pressure is 1800 [MPa] in this forging. The interfacial pressure due to interference values between die insert and stress ring calculated in the Fig. 2 is input as body load for the structural analysis in order to calculate the stress and elastic deformation. The distribution of the von-Mises equivalent stress and the elastic deformation of the die analyzed by ANSYS are shown in Fig. 4 and 5.

The equivalent stress of the spur die with one stress ring is seen to be around the root circle of the die teeth. The magnitude of this stress exceeds the yield stress of the die insert material (Table 2), which means that fracture of the die will probably occur during the cold forging. But in the case of the spur die with two stress ring, the maximum stress is lower than the yield strength (2450 [MPa]) [9,10] of the die insert material, which means that fracture does not occur during forging. The maximum radial elastic deformation is seen to be around the tip circle of the die teeth. However the magnitude of this deformation is very small, so it cannot affect the accuracy of the finished gear as this can be overcome by controlling the amount of shaving on the product profile in Fig. 5.

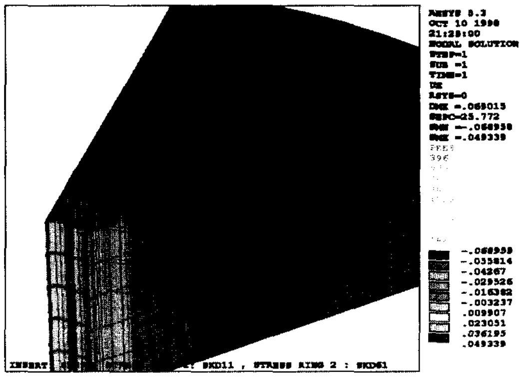
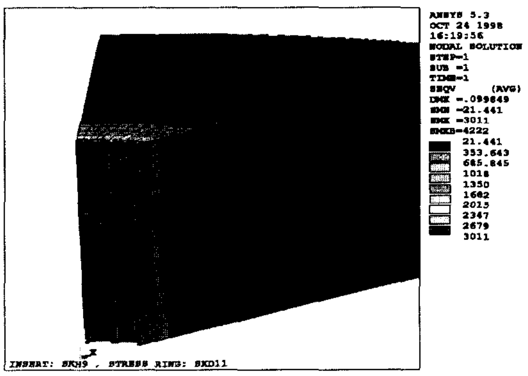
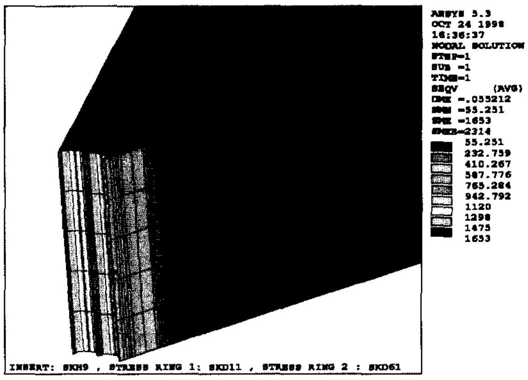


Fig. 5 Radial displacement distribution of spur die with two stress rings



(a) one stress ring



(b) two stress ring

Fig. 4 Von mises equivalent stress distribution of the spur die

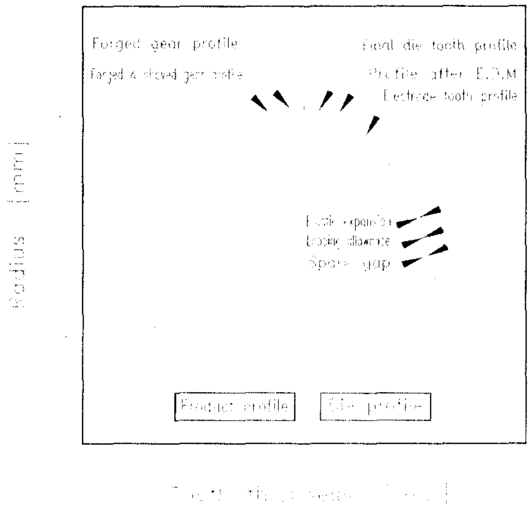


Fig. 6 Schematic illustration of tooth profile

4. Design of the gear die insert

The accuracy of a gear depends fully upon the design and manufacture of the die that is involved with the design and machining of the electrode for electro-discharge machining. Fig. 6 presents schematic illustrations of the tooth profile for the design and manufacture of the insert die. For the manufacturing of the die, the dies were shrink fitted before electro-discharge machining to prevent deformation which could introduce gear errors and to reduce excessive tensile circumferential stresses, which later could cause die fracture during deforming. Production of precise gear forms requires dies to be made with consistent accuracy. Cavity features differ in dimension and geometry from the finished gear form, to compensate for the following process features. A loaded forging die expands elastically and cavity demensions must be made smaller. The dimensions of an electrode should result from consideration of the compensations above, together with a spark gap allowance. A schematic drawing of the designed deformation which could introduce gear errors and to reduce excessive tensile circumferential stresses, which later could cause die fracture during deforming. Production of precise gear forms requires dies to be made with consistent accuracy. Cavity features differ in dimension and geometry from the finished gear form, to compensate for the following process features. A loaded forging die set for spur gears is shown in Fig. 7.

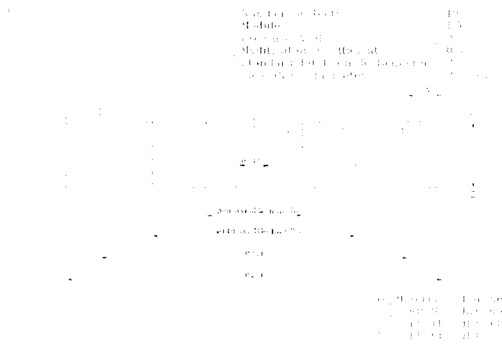


Fig. 7 Schematic drawing of the closed forging die set for spur gears

5. Conclusion

This paper described a computer aided die design for cold forging of non-axisymmetric parts. In order to design the die for cold forging based on a rule base system, commercial FEM codes are used. The designed die is modified to prevent failure in the state of pressurizing and also to take into account the spark gap (½pitch die tooth thickness 0.060421[*mm*]) for electro-discharge machining, lapping stock (0.02[*mm*]) and elastic expansion allowance (0.05[*mm*]). In the end, a schematic drawing of the designed forging die set for spur gears is developed. This method will reduce the amount of trial and error which would otherwise be necessary.

References

(1) S Takahashi, C A Brebbia, Forging die stress analysis using boundary element mehod, *Advanced Technology of Plasticity*, Vol.1, pp. 203~210, 1990.

(2) Sadeghi, T A Dean, Analysis of dimensional accuracy of precision forged axi-symmetric com-

ponents, Journal of Engineering Manufacture, Vol. 205, pp. 171 ~ 178, 1991.

(3) K Lange, L Cser, M Geiger and J A G Kals, Tool life and tool quality in bulk metal forming, *Annals of the CIRP*, Vol. 41, pp. 667 ~ 675, 1992.

(4) Kim, H. and Yagi, T. Estimation of dimensional differences between cold forgings and tool in a backward cup extrusion of steels. In Proceeding of 5th ICTP, pp. 433 ~ 436, 1996.

(5) J C Choi, H Y Cho and H H Kwon, A new extrusion process for helical gears: experimental study, *Journal of Material Processing Technology*, Vol. 44, pp. 35 ~ 53, 1994.

(6) P S Timoshenko, J N Goodier, Theory of eleaticity third edition, *McGraw-Hill*, London, pp. 392, 1982.

(7) H H Kwon, W M Jin, H S Kim, Die design on the precision cold forging of spur gear, '98 Conference Proceeding of KSMTE, pp. 242 ~ 247, 1998. 11.

(8) J C Choi, Y Choi, A study on the forging of external spur gears: upper-bound analyses and experiments, *International Journal of Machine Tools & Manufacture*, Vol. 38, pp. 1193 ~ 1208, 1998

(9) I.C.F.G., Dies for cold extrusion of steel, Data sheet No. 6/72.

(10) I.C.F.G., General aspect of tool design and tool materials for cold forging of steel, No. 4/70, No. 4/82.