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Development of Automative Program for Designing Involute Spur Gear

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ABSTRACT

This study develops an automation system for metallic mold design that is applicable in forging non-axial symmetric parts. The metallic mold design program is used to design the metallic mold using two-dimensional axial symmetric metallic molds and to predict the stress concentration using finite element analyses. Then, the program redesigns the metallic mold using variables such as the optimal split diameter, maximum allowable inner pressure, fit tolerance, and stress distribution, which are calculated using the metallic mold design program. When the involute spur gear is forged, stress concentration occurs on the tooth root bounded at the symmetric surface. The SCM4 material is suitable for metallic molds because the stress is less than the yield strength of the insert and it acts on the tooth root regardless of the inner pressure. The metallic mold for forging non-axial symmetric parts can be designed through adjusting the magnitude of the contact pressure. The program developed in this study can be applied to metallic mold designs in involute spur gears of forging, which is an ordinary non-axial symmetric part.

Key Words : Non-Axisymmetric Three-Dimensional Parts, Stress Concentration, Computer Aided Die Design

1. Introduction

A metallic mold, which is employed for an involutes spur gear, is easily damaged and has a short lifspan due to its severe working condition. The short lifspan causes increasing of an expense of metallic mold and quality control, and eventually resulting to increased costs on the parts. Thus, the metallic mold should be designed considering structure, material, and strength.

Especially, when manufacturing precision part of metallic molds, elastic expansion of the metallic mold and elastic restoration of a product need to be

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considered. The reason is that precision of forging was affected dominantly by precision of metallic mold[5-8]. Designing of a metallic mold in industry sites depended on accumulated technology and experience. Applying an automatic system employing computer is essential to determine an optimal design variables and metallic mold variables in metallic mold design.

For development of a metallic mold design system using a computer, Choi[3] et al. developed an automatic system to design an axial symmetric forging using GWBASIC computer language, which is easily accessible to novice designers. However, this system had limits for designing targets and modifying the metallic mold or redesigning due to the restrictions of shape expression.

For metallic mold designing of nonaxial symmetric shape forging, Cho[2]designed a helical gear extrusion considering over discharge magnitude of electrode and post processing of extruding gear, and finite element analysis and experiment with an alloy steel were carried out.

Choi[4]et al. determined loads on metallic molds using upper bound method, designed metallic molds, and experimented the metallic molds applying stiffening rings based on loads data. However, this model was for aluminum not alloy steel. Automation of metallic mold design was mostly realized with CAD program for CAM, and the developed systems were only applicable to extrusion, two dimensional axial symmetric parts, and aluminum model material[1]. In addition, the computer-aided engineering (CAE) analysis was applied to the design of nonsymmetric plastic mold[9].

This study developed a metallic mold design system of cold forged part using computer. In doing so, it would be capable of automation on metallic mold design, output of drawing, accessibility for novice designers. This study designed a metallic mold of axial symmetric shape using two dimensional axial symmetric metallic mold design rules and empirical formulas from various literatures. Then, finite element analysis using the designed metallic mold was carried out to check the stress concentration occurred on nonaxial symmetric shape. The stability of the metallic mold was estimated using the finite element analysis, and the metallic mold variables were modified to protect the damage of the metallic mold during forging process. The metallic mold design program developed for this study could be applicable on forging of nonaxial symmetric parts. Also, the program could be applied to a metallic mold design of involute spur gear of forging, which is one of ordinary nonaxial symmetric parts.

2. Design rule base

Rule base of the metallic mold design system for cold forged part was constructed from generous and theoretically well balanced contents, which were obtained from theory of plastic deformation, various handbooks, related literature, and empirical knowledge of experts.

The system, constructed for the metallic mold design, used a production rule of “IF [condition] THEN [actions]” type based on a determine tree. Information of result part was calculated from the condition part, and then output information of result part would be next condition part. The rule base presented below was quantized by systemized the empirical design guides and know-how:

Rule 1) Total external diameter of the metallic mold set was determined by specification of a press.

Rule 2) Tresca yield condition was applied to yield condition of insert and stiffening ring.

Rule 3) Diameter was divided for generating the maximum allowable internal pressure in designing of insert and stiffening ring. Equation of the maximum allowable internal pressure is as follows:

$$P_{i\,opt} = S_{y1} \cdot \left(\frac{1}{2} \cdot \left[1 + \frac{1}{K_1} \right] - Q \cdot \sqrt{\frac{1}{K_1}} \right) \qquad (1)$$

Rule 4) When the maximum allowable internal pressure acted, the fit tolerance was allowed to yield insert steel ring simultaneously. Equation of the fit tolerance is as follows:

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

Rule 5) In designing insert and stiffen ring, relationships among the internal pressure of the die P_d, P_{iopt} in the optimal split ratio, and the limit internal pressure, P_{ilimit}, for protecting yield of the insert associated with fit were $P_d \le P_{iopt} \le P_{ilimit}$. The limit internal pressure is as follows:

$$P_{i\,limit} = S_{y1} \cdot (1 - Q^2) \quad \left\{ \begin{array}{c} Q = 0 \\ \dfrac{P_{i\,opt}}{S_{y1}} = 1 \end{array} \right. \qquad (3)$$

3. Program structure

There is a need to develop computer-aided design and manufacturing technique to reduce the design periods and to improve quality. This study constituted the overall system (Figure 1) and constructed an integrated design system to design metallic molds employing computer. The integrated design system consisted of an initial value input module, a metallic mold design module, an analysis and modification module, and a management module which manage and control modules.

All modules, except the analysis and modification module which carry out finite element analysis, of the integrated design system were performed under one environment, and each module carried out all procedure without suspension of the integrated design system. The finite element analysis of the metallic mold predicted the stress distribution and stress concentrated portion applied onto the metallic mold by an elasticity simulation. The elasticity simulation of the designed metallic mold was carried out by the integrated design system, which was programmed with AutoLISP operated under AutoCAD environment, using the commercial finite element analysis program NISA II. Interface between the integrated design system and NISA II was carried out by IGES file.

3.1 Management module

In general, the metallic mold was designed to

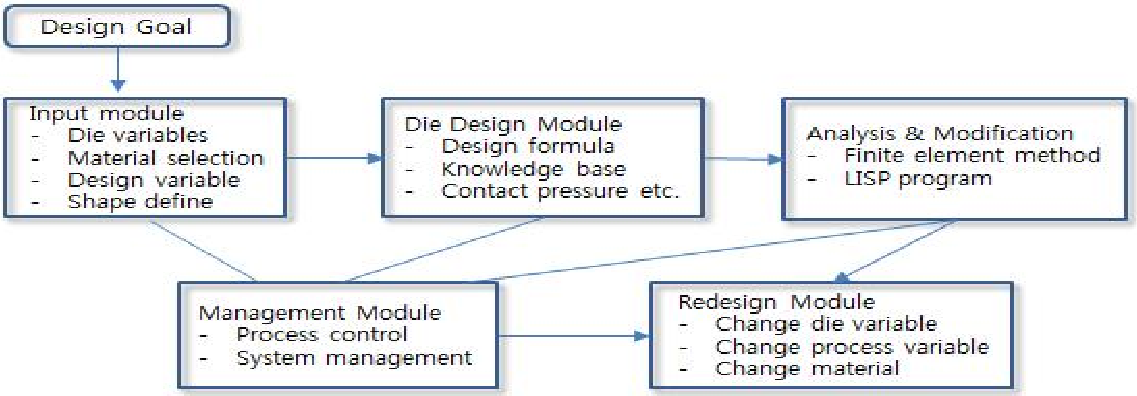


Fig. 1 Structural diagram of the developed system

satisfy intensity reliability and demanded lifetime depending on the purpose and conditions of use. Various design knowledge exists in design procedure, and each module cooperates mutually in the process.

3.2 Initial value input module

The initial value input module allowed inputting initial values of the metallic mold design. This module consisted of a die variable input part, a metallic mold material selection part, a design variable input part, and forging part shape input part. The die variables for the metallic mold design included the total external diameter, thickness of the metallic mold, and the number of stiffen rings. Variables of the forging part shape input part in a gear forging metallic mold were the number of teeth, module, and pressure angle. These variables were defined by users.

3.3 Metallic mold design module

The metallic mold design module calculated metallic mold variables such as an optimal split diameter, a limit internal pressure, a contact stress, and a fit tolerance based on input items using data base of material for the metallic mold. Results from the design of the system were displayed on the monitor. After the results were accepted by the user, the system was switched to input conditions of the analysis and modification module.

3.4 Metallic mold analysis and modification module

The metallic mold analysis and modification module performed the stress analysis of the designed metallic mold using the finite element analysis, and it also modified the metallic mold to extend the life span based on the stress analysis. Boundary conditions imposed on the metallic mold for the finite element analysis were: the contact pressure occurred by the fit tolerance between stiffen rings and between the insert and stiffen ring, and the forming pressure applied to the die at the final forming procedure. The contact pressure values and the internal pressure values, applied onto the metallic mold at the final forging state, used the values that were calculated by the upper bound method using a velocity field suggested by LISP program.

When forging the outer gear parts using a tooth form which is manufactured at inner side of the metallic mold, the metallic mold could be destroyed due to excessive stress concentration at the root. When metallic mold breakage was predicted, the metallic mold was redesigned following suggested method from the system to reduce the stress. The first method to modify the metallic mold was increasing total outer diameter of the metallic mold set. The second method was increasing the maximum allowable inner pressure of the metallic mold set by adding the stiffening rings even though the total external diameter of the metallic mold set was determined. However, this method required more time and money to manufacture the die. The third method was controlling the stress on the metallic mold, which was possible by adjusting the amount of tolerance calculated by the metallic mold design module. This eventually decreased the magnitude of the stress concentration applied onto the tooth root of the metallic mold.

4. Results and discussion

4.1 Initial value input module

This study designed the forging metallic mold of involute spur gear, one of the nonaxial symmetric parts, based on the metallic mold design rules. General metallic mold for axial symmetric shape was designed first, and then the metallic mold for nonaxial symmetric shape of the gear was designed using the metallic mold analysis and modification module. One stiffening ring was shrink fitted, and

Table 1 Specifications of gear and design variables

Involute spur gear			Dieset			
No. of teeth	Module	Pressure angle	Diameter	Material		Height
				Insert	Stress ring	
10	2.0	20˚	225.0 mm	SKD 11, HRC62	SKD 61, HRC50	30.0 mm

tool steel was selected for the material of die and punch. The design target was a standard involute spur gear with 10 teeth of an outer gear, the module ratio of 2.0, and the pressure angle of 20°. Table 1 shows input values determined by the user for initial value input module.

4.2 Metallic mold design module

To design a forging metallic mold of a gear part, which was set the inner diameter of the die as an addendum circle diameter, a forging metallic mold for axial symmetric part was designed in advance following design rules of metallic mold for axial symmetric circular inner surface. Table 2 shows the metallic mold variables calculated according to input conditions of Table 1, and Figure 2 shows the metallic mold designed with the values of Table 2.

4.3 Metallic mold analysis and modification module

Figure 3 shows the results of finite element analysis of the stress distribution acting onto the gear forging metallic mold with involute tooth form. The analysis was based on the results of the axial symmetric forging metallic mold design from the metallic mold design module. When the inner pressure acted, the magnitude of the maximum stress due to the stress concentration of the tooth root was not exceeded the yield strength of the insert. When the inner pressure did not act, the stress, which exceeded the yield strength, occurred. When the maximum stress exceeded the yield strength of the material quality of metallic mold, deformation or damage of metallic mold could happen. In this case, the metallic mold designed was modified to reduce the magnitude of the maximum stress using suggested metallic mold modification method.

Table 2 Calculated results of die variables

Variables	Values
Optimum division diameter	81.32 [mm]
Contact pressure	453.638 [N/mm^2]
Theoretical interference fit tolerance	0.4365 [mm]

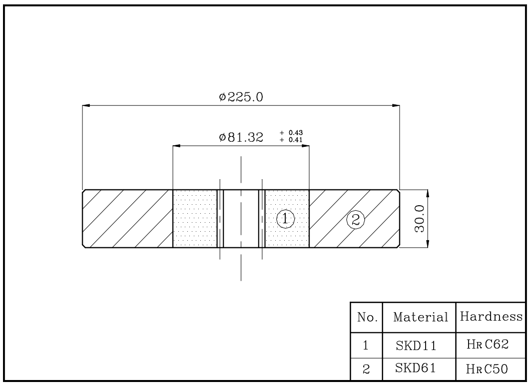
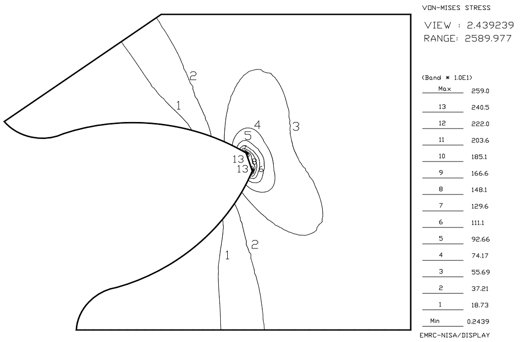
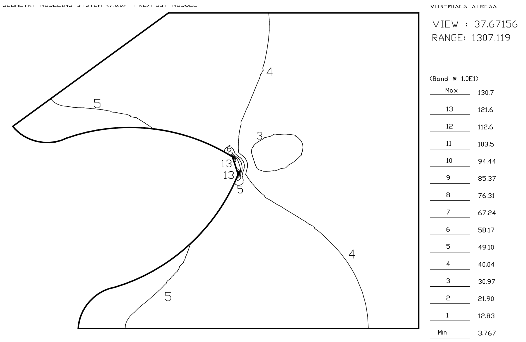


Fig. 2 Schematic drawing of designed die with input die variables

The first method to modify metallic mold was changing the total external diameter of the metallic mold set. Figure 4 shows stress distribution when the total external diameter of the metallic mold set was changed from 225.0 to 250.0 mm. When the inner pressure acted, the fit tolerance increased as the external diameter of the metallic mold set increased. As a result, the contact pressure acting onto the insert increased, which decreased tensile stress occurred at the insert during the forging manufacturing. Thus, the stress distribution acting on



(a) Without inner pressure

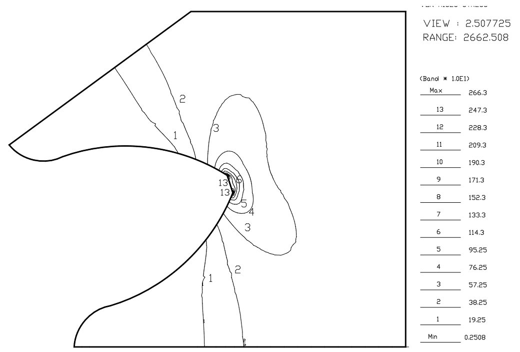


(b) with inner pressure

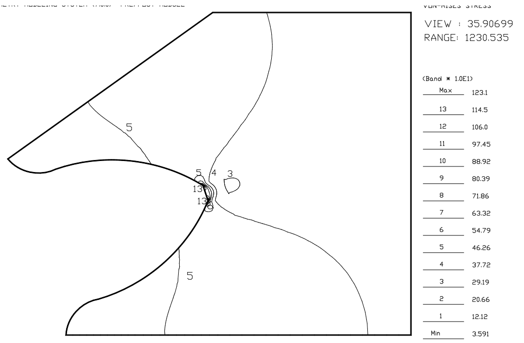
Fig. 3 Stress distribution on the modified die

the overall metallic mold and the maximum stress of the tooth root decreased at the final status of the forging. Meanwhile, without inner pressure, the stress of the tooth root increased as the contact pressure increased. And this caused damage to the metallic mold. Thus, the method of increasing external diameter increased the maximum stress which caused to decrease the stability of the metallic mold when inner pressure did not act. In addition, the external diameter of the metallic mold was set by press specification, so the method was not proper to modify the metallic mold.

The second method to modify the metallic mold was changing the number of stiffening ring. The finite element analysis of the stress distribution on metallic mold was carried out by changing the number of the stiffening ring from 1 to 2 while the external diameter of the metallic mold set was fixed. Table 3 shows input conditions with two stiffening rings, and Table 4 shows variables of the metallic mold calculated by metallic mold design system.



(a) Without inner pressure



(b) With inner pressure

Fig. 4 Stress distribution on the modified die (Do = 250.0 mm)

Table 3 Design variables for two stress rings

Diameter	Die material			Height
	Insert	1st stress ring	2nd stress ring	
225.0 mm	SKD11, HRC 62	SKD61, HRC 50	SCM4, HRC 35	30.0 mm

Table 4 Calculated results of die variables for two stress rings

Variables	Values
Optimum division diameter	77.69, 144.94 [mm]
Contact pressure	572.195, 169.14 [N/mm^2]
Theoretical interference fit tolerance	0.42216, 0.3756 [mm]

Figure 5 shows the metallic mold with two stiffening rings using calculated variables as shown in Table 4. The contact pressure and forging pressure at the final condition were set as boundary conditions, and the finite element analysis for two cases (having pressure of final forging condition on the metallic mold vs. having no pressure) was carried out. The stress distribution of one tooth form is shown on Figure 6. With inner pressure, the stress acting on tooth root reduced considerably compared with the one having one stiffening ring. However, without inner pressure, the stress concentration at the tooth root caused damage to metallic mold. Furthermore, increasing the number of the stiffening rings was not desirable in that it requires more money and time to manufacture it.

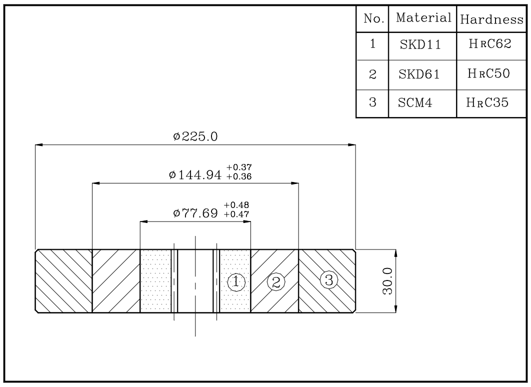
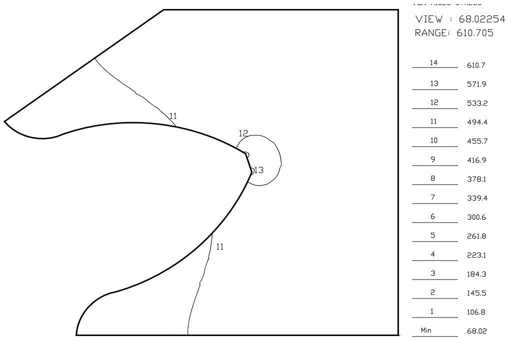
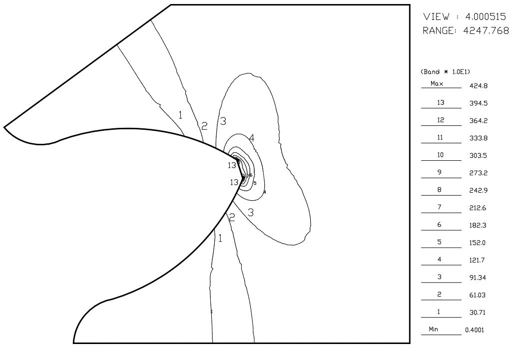


Fig. 5 Schematic drawing of two stresses



(a) Without inner pressure



(b) With inner pressure

Fig. 6 Stress distribution on the die with two stress rings

Table 5 Calculated results of die variables for stress ring material SKD11

Variables	Values
Optimum division diameter	81.6 [mm]
Contact pressure	576.368 [N/mm^2]
Theoretical interference fit tolerance	0.5438 [mm]

Tables 5 and 6 show the calculated design variables; it was calculated with high speed tool steel, SKH9 for the insert material and SKD11 & SCM4 for stiffening ring material. Figures 7 and 8 depict the metallic mold designed with the variables from the Tables 5 and 6.

Table 6 Calculated results of die variables for stress ring material SCM4

Variables	Values
Optimum division diameter	94.7 [mm]
Contact pressure	289.081 [N/mm^2]
Theoretical interference fit tolerance	0.3321 [mm]

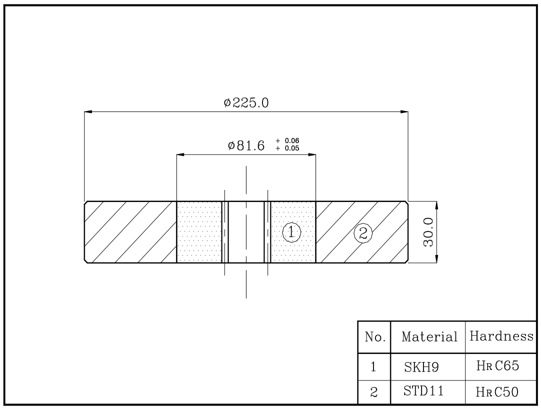


Fig. 7 Schematic drawing of designed die with modified die materials (Insetrt: SKH9, stress ring: SKD11)

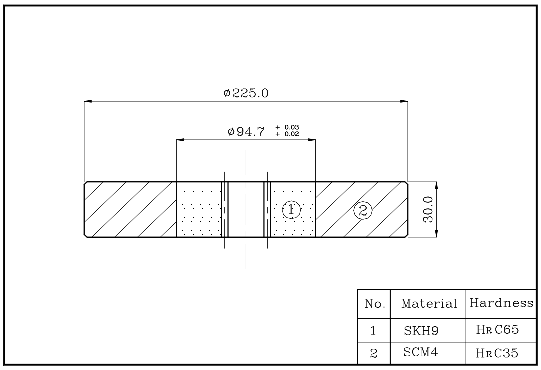
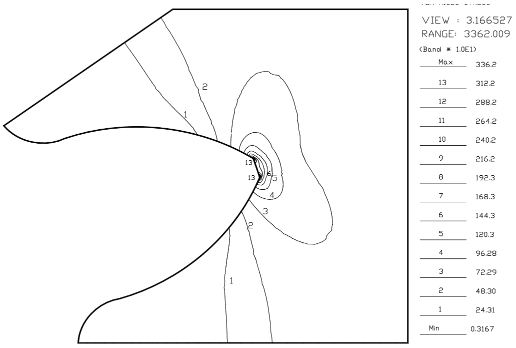
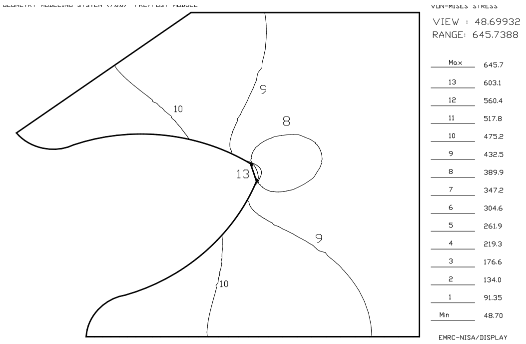


Fig. 8 Schematic drawing of designed die with modified die materials (Insert: SKH9, stress ring: SKD11)



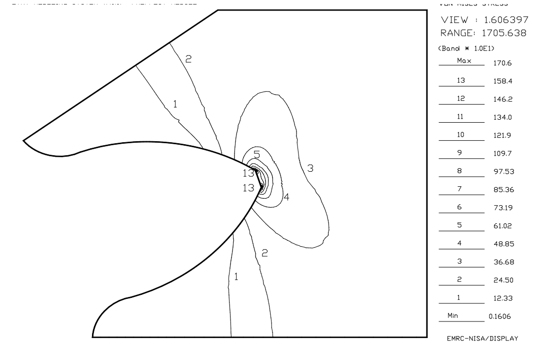
(a) Without inner pressure



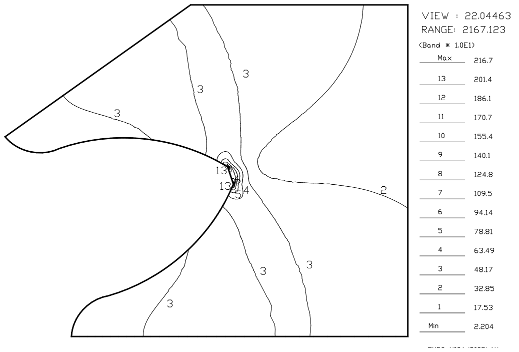
(b) With inner pressure

Fig. 9 Stress distribution on the die with modified die materials (Insert: SKH9, stress ring: SKD11)

Figures 9 and 10 show the stress distribution of two cases (having inner pressure vs. having no pressure) with the same insert material. As shown in Figures 9 and 10, without inner pressure, the magnitude of the contact pressure acting onto the metallic mold increased as the strength of the stiffening ring increased. This caused to increase the maximum stress of the tooth root. With inner pressure, the contact pressure increased as the strength of the stiffening ring increased. This countervailed the tensile stress occurred during forging and improved the stability of the metallic mold.

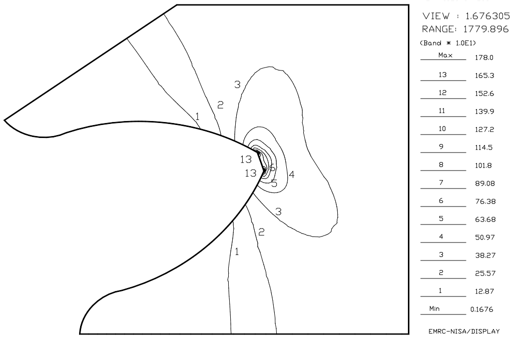


(a) Without inner pressure

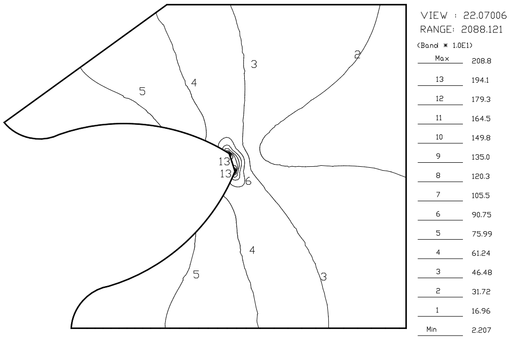


(b) With inner pressure

Fig. 10 Stress distribution on the die with modified die materials (Insert: SKH9, stress ring: SCM4)



(a) Without inner pressure



(b) With inner pressure

Fig. 11 Stress distribution on the die with modified fit tolerance (z=0.3)

The material of SCM4 was suitable for metallic mold because the stress less than yield strength of the insert acted on the tooth root. Therefore, it is applicable to the forging of the axial symmetric part. The third method to modify the metallic mold was varying the magnitude of the contact pressure occurred between the insert and stiffening ring or between the stiffening rings. When strength of the stiffening ring was large and caused damage to the mold without inner pressure, the mold could be designed to lower the magnitude of the contact pressure and to minimize the fit tolerance between stiffening rings.

Figures 11 and 12 show the results of analysis of stress acting on the metallic mold with the fit tolerance of 0.3 and 0.2 as shown in Table 2. Without inner pressure, the maximum stress acting on the tooth root decreased as the contact pressure decreased due to the minimized fit tolerance. When the fit tolerance was less than 0.3 without inner pressure, the maximum stress did not exceed the yield strength of the insert. After all, the metallic mold for nonaxial symmetric part can be designed by adjusting the magnitude of contact pressure.

5. Conclusion

This study developed the automation system for metallic mold design, which was applicable for forging of the nonaxial symmetric parts. The metallic mold design program designed the metallic mold using two dimensional axial symmetric metallic molds and predicted the stress concentration by finite element analysis, and then redesigned the metallic mold using variables such as an optimal split diameter, the maximum allowable inner pressure, fit tolerance, and stress distribution, which were calculated by the metallic mold design program. Results obtained by applying to forging metallic mold for the involute spur gear are as follows:

1. When the involute spur gear was forged, the stress concentration occurred on the tooth root bounded at the symmetric surface.
2. The material of SCM4 was suitable for metallic mold because the stress less than yield strength of the insert acted on the tooth root regardless the inner pressure. In this case, the optimum diameter, the contact pressure, and the fit tolerance were 94.7 mm, 289.081 N/mm^2, and 0.3321 mm, respectively.
3. The metallic mold for forging the nonaxial symmetric part could be designed by adjusting the magnitude of contact pressure.

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