Optimal design of multi-former die set by the techniques of horizontal split

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This paper deals with an automated computer-aided process planning and die design system by which designer can determine operation sequences even if they have a little experience in process planning and die design for axisymmetric products. An attempt is made to link programs incorporating a number of expert design rules with the process variables obtained by commercial FEM softwares, DEFORM and ANSYS, to form a useful package. The system can provide a flexible process based on either the reduction in the number of forming sequences by combining the possible two processes in sequence, or the reduction of deviation of the distribution on the level of the required forming loads by controlling the forming ratios. Especially in die design module optimal design technique and horizontal split of die insert were investigated for determining appropriate dimensions of components of multi-former die set. Results obtained, using the modules, enable the design and manufacture of a die set for a multi-former to be more efficiently performed.

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1. Introduction

Cold forging has its major advantages for making axisymmetric parts of small or medium sizes in multistage automatic forging machines or on conventional presses in several steps. It can produce parts with good surface finish and dimensional accuracy, improve mechanical properties, and also eliminate extra post-processing such as trimming and machining.[1]

But it has a weak point that needs much more time and cost to carry out a process and die design when compared with other processes. Using computer in performing repeated job such as calculation of process variables and generation of process planning drawings will help the design engineers. In this study, a cold forging expert system is developed by various processes and die design through expert system's module, which contains production feasibility check, and process and die design modules. The production feasibility check module generates process planning drawings which are feasible according to the design rules.[2] The process planning module chooses the process planning drawing best suited to the product through redesign function. And it carries out a flexible process based on either the reduction in the number of forming sequences by combining the possible two operations in sequence, or the reduction of deviation of the distribution on the level of the required forming loads by controlling the forming ratios. The die design module calculates stress with the thick-walled cylindrical theory after carrying out elastic finite element analysis.[3] After calculating optimal diameter ratio, permissible inner pressure, absolute interference, contact pressure and horizontal and vertical split of die insert, the system can help to generate die set drawings automatically.[4] It performs finite element analysis in order to verify the drawing of the die set and the process planning.

2. Structure and working principle of the system

The system is composed of input and shape treatment module, production feasibility check module, process planning module, and die design module. Configuration of the system is shown in Fig. 1

2.1 Production feasibility check module

The production feasibility check module determines the billet diameters which are able to form forged shapes. It generates feasible process planning drawings according to the billet diameters by the design rules.

2.2 Process planning module

The process planning module carries out separation or combination of operations to distribute the forming load relatively evenly at each stage of the process planning drawing that are chosen by the production feasibility check module. It carries out process planning of multi former balanced either as decreasing the forming load, which is beyond the forming load ranges, by separating two processes in sequence, or increasing it, which is lower than them, by combining two processes. When carrying out the combined process, it checks forming feasibility. In case of infeasible forming, it determines the extrusion angle that is able to be formed and makes the operation feasible.

2.3 Die design module

To increase maximum permissible inner pressure of the die set, the die design module automatically generates a die set drawing with the most effective design variables in Fig. 2 according to the drawing of process planning.

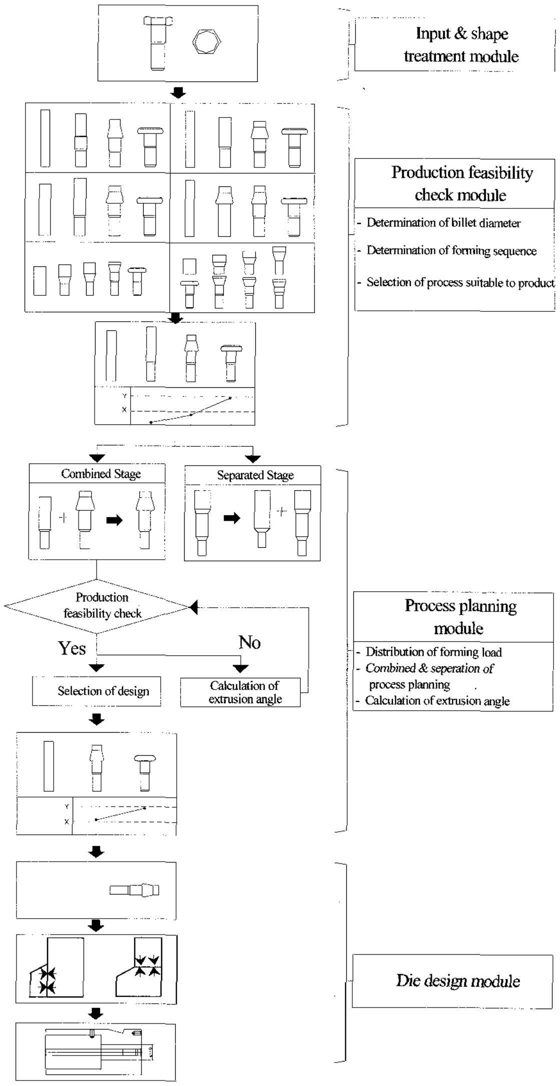


Fig. 1 Configuration of the system

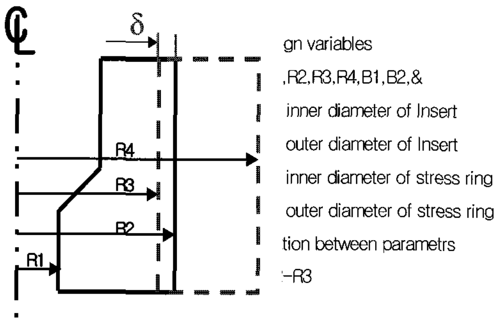


Fig. 2 Geometrical variables for the optimization model

2.3.1 Die design rules

Rule 1. Calculation of the pre-stressed die inserts where no tensile stress is permitted in the die is as follows:

① When yield stress is permitted in die insert.

$$\sigma_{sk} \cdot Q_k^2 = \sigma_{s1} \cdot Q_1^2$$

$$Q_1 = \frac{Q}{\sqrt[n]{\sum_{k=2}^{n} x_k - 1}}$$

where

σ_{sk} : Yield stress of stress ring

Q_1 : Optimum diameter ratio

② When tensile stress is permitted in die insert.

$$\sigma_{sk} \cdot Q_k^2 = P \cdot Q_1^2$$

$$Q_1 = \sqrt[n]{Q\sqrt{\frac{\sum_{k=2}^{n} \sigma_{sk}}{P^{n-1}}}}$$

▶ In case of steel tool in die insert :

$$r_m = \sqrt{(r_i \times r_o)}$$

$$P_2 = \frac{\sigma_{y2}}{2}\left[1 - \frac{r_m^2}{r_o^2}\right]$$

where

r_m : Outer radius of the die insert

P_0 : Contact pressure

▶ In case of W.C. alloy in die insert :

$$r_m^4 = \frac{\sigma_{y1}}{\sigma_{y2}}\left[r_i^2 \times r_o^2\right]$$

$$P_2 = \frac{\sigma_{y2}}{2}\left[1 - \frac{r_m^2}{r_o^2}\right]$$

$$\delta = \frac{2 \times r_m \times p_2}{E_{insert}}$$

where

δ : Interference

σ y1 : Yield stress of die insert

σ y2 : Yield stress of stress ring

Rule 2. Calculation of radial and tangential stresses on symmetric cylindrical material is as follows.

$$\sigma_r = \frac{r_1^2 P_i - r_2^2 P_o}{r_2^2 - r_1^2} - \frac{(P_i - P_o) r_1^2 r_2^2}{(r_2^2 - r_1^2) r^2}$$

$$\sigma_\theta = \frac{r_1^2 P_i - r_2^2 P_o}{r_2^2 - r_1^2} + \frac{(P_i - P_o) r_1^2 r_2^2}{(r_2^2 - r_1^2) r^2}$$

where

r1 : Inner diameter of die

r2 : Outer diameter of die

σ_r : Radial stress

σ_θ : Tangential stress

Rule 3. The number of stress rings is determined as follows:

- $P_{act} \le 100 kgf/mm^2$: 0 Die insert ring
- $100 kgf/mm^2 \le P_{act} \le 160 kgf/mm^2$: 1 Die insert ring
- $160 kgf/mm^2 \le P_{act} \le 200 kgf/mm^2$: 2 Die insert rings

Rule 4. When the material of the die insert, a WC alloy, is not same as that of the die stress ring, the die insert doesn't permit tensile stress.

Rule 5. The optimum diameter ratio is required to be able to apply the maximum permissible inner pressure and if it is applied to the inner diameter of the die insert, the inner diameter of the stress ring would be yielded by the press fitting interferences.

Rule 6. Assembling of the stress ring is successively done from the outer ring.

Rule 7. The heating temperature suitable to press fitting is lower than the annealing temperature.

Rule 8. Horizontal split of die insert is needed when the trap extrusion as extrusion ratio is over 50%.

3. Application and results of the system

When M24 hexagon head bolts, made from S45C as shown in Fig. 3, are used as examples in the developed system, the results obtained in each module are as follows.[6]

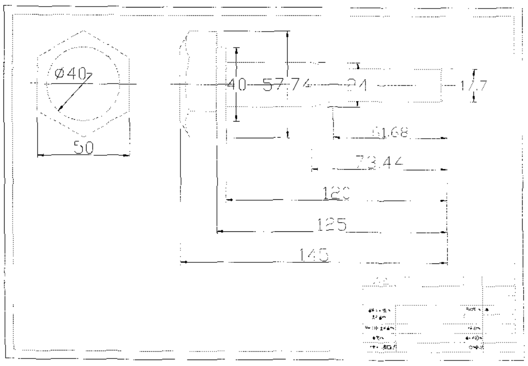
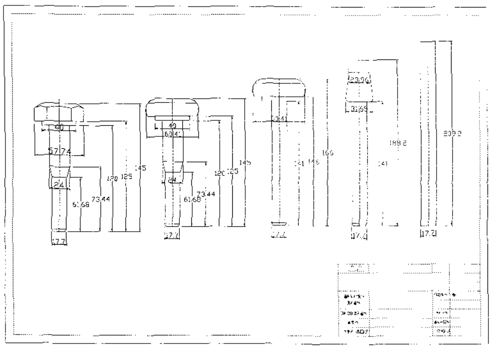
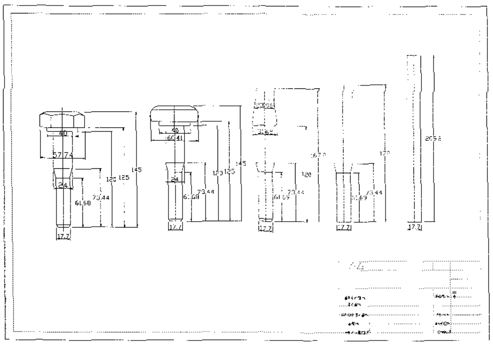


Fig. 3 A sample drawing of hex bolt, M24

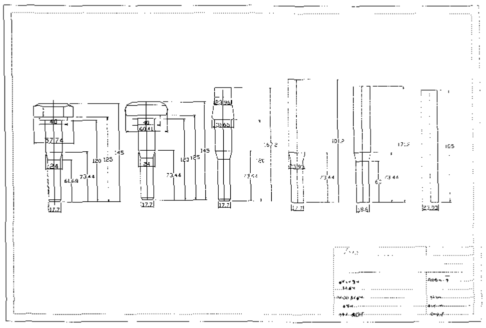
3.1 Production feasibility check module example



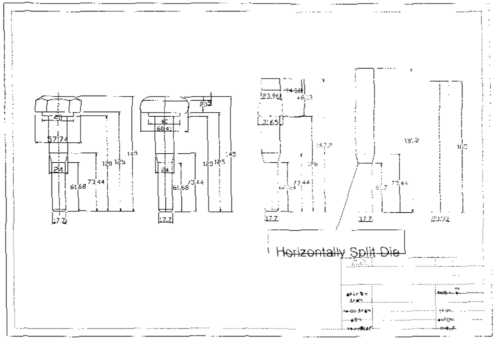
(a) In case of the billet diameter, 17.7mm



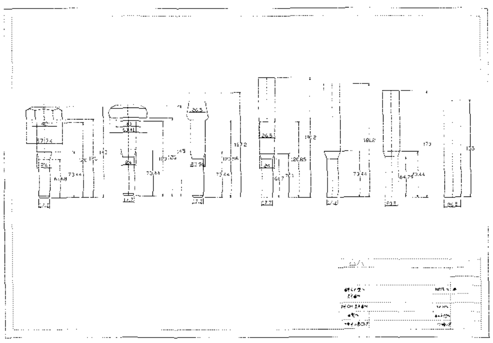
(b) In case of the billet diameter, 17.7mm (all upsetting)



(c) In case of the billet diameter, 23.93mm



(d) Combined process of the billet diameter, 23.93mm



(e) In case of the billet diameter, 26.5mm

Fig. 4 Automated process planning drawings generated according to the design rules

Figs. 4(a)~(e) show the processes for the billet diameters, 17.7mm, 23.93mm, and 26.5mm by process planning design rules. Fig. 4(a) shows the process for the billet diameter of the lower part of the bolt(screw part), (17.7mm) and all processes are composed of upsetting operations. The screw part formed in the above mentioned processes can obtain the effect of work hardening in the upper part but can't obtain it in the lower part of the product. Fig. 4(b) is made of all upsetting processes as Fig. 4(a) and the middle part of the bolt is formed after forming the upper part of it. Fig. 4(c) shows the process as the billet diameter of the middle part of the bolt, (23.93mm) and the upper parts of the bolt is formed by upsetting operations after trap extrusion as the extrusion ratio of 50% and open extrusion is carried out in the screw part of the bolt. Fig. 4(d) shows the process as the billet diameter of middle part of the product and reduces the stages by increasing maximum permissible inner pressure of the die through horizontal split of the die insert. Fig. 4(e) shows the process as the billet diameter(26.5mm), which is calculated to be able to operate most balanced process condition. It can take a uniform load condition by controlling the extrusion ratios, but has a demerit to increase the number of processes.

3.2 Process planning module example

Considering intermediate geometric shape and strength of screw thread's part by the production feasibility check module in Fig. 4(a)~(e), the best process suitable to the product is shown as in Fig. 4(c) and (d). The system may select the process planning of Fig. 4(d) which is reducing the number of forming sequences and deviation of the distribution on the level of the required forming load. Fig. 5 shows the simulation results to check production feasibility regarding process of Fig. 4(d).

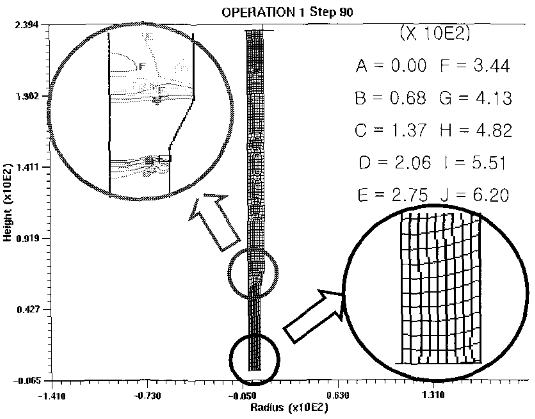


Fig. 5 Effective stresses for the trap extrusion with the ratio, 60%

According to the simulation there is no defects occurred in forming operation because maximum effective stress, 62kgf/mm^2, is smaller than tensile strength of the material. Load region of the process in Fig. 4(d), 8 ~ 24kgf/mm^2, is more uniform load distribution when comparing to that of the process in Fig. 4(c) shown as in Fig. 6.

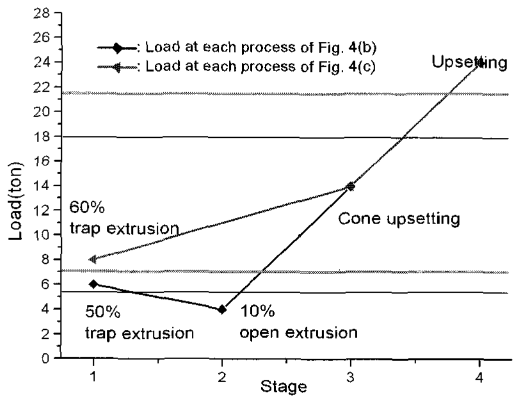


Fig. 6 The comparison of the deviation of the forming load distributions from the forming loads ranges

3.3 Die design module example

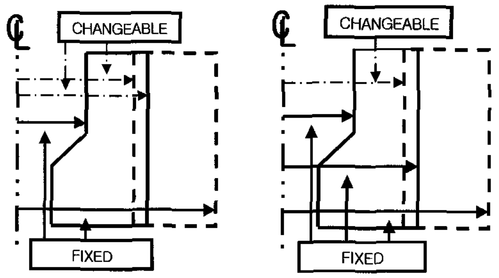
Die insert and stress ring drawings were generated automatically according to the process planning drawing after calculating optimal diameter ratio, permissible inner pressure, absolute interference, contact pressure, and radial and tangential stresses of the die insert. Table 1 shows the mechanical properties of the materials of die insert and workpiece.

Table 1 Mechanical properties of the workpiece, die and stress ring

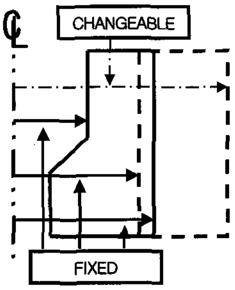
	AISI 1045 (Workpiece)	W.C. (Insert)	SKD 61 (Ring)
Modulus of Elasticity (Kgf/mm^2)	20,000	465,000	212,000
Poisson Ratio	0.3	0.24	0.3
Hardness (HRA)	-	92.0	77.0
Yield Stress (Kgf/mm^2)	54.08	273.7	117.2

To increase the die life, there are lots of factors such as elastic deformation, wear, repeated stress, thermal stress, the change of elastic modules and plastic deformation. In this study, however, we consider a circumferential stress of the die insert as starting point of fatigue fracture among many factors. Three cases for optimizing stresses of the die set with single stress ring are shown in Fig. 7.

Because the outer diameter of the die set is limited and the shape of the die set is determined by dimensions of products, it is possible to change three cases as follows. The changes of outer diameter in die insert and the changes of the inner diameter in stress ring are shown in Fig. 7(a). The changes of the amount of interference between die insert and stress ring are shown in Fig. 7(b), and the amount of extension of the outer diameter of stress ring is shown in Fig. 7(c). Stress distributions in the inner diameters of die insert and stress ring according to the conditions of Table 2 are shown in Fig. 8 and Fig. 9.



(a) (b)



(c)

Fig. 7 Three cases for optimizing stresses of the die set with a single stress ring

Table 2 Dimensions of outer diameters of insert and stress ring

	outer diameter of insert(mm)	outer diameter of stress ring(mm)	clearance(mm)
case1	56	110	0.14
case2	58	110	0.14
case3	60	110	0.14
case4	62	110	0.14
case5	64	110	0.14
case6	66	110	0.14
case7	68	110	0.14
case8	70	110	0.14

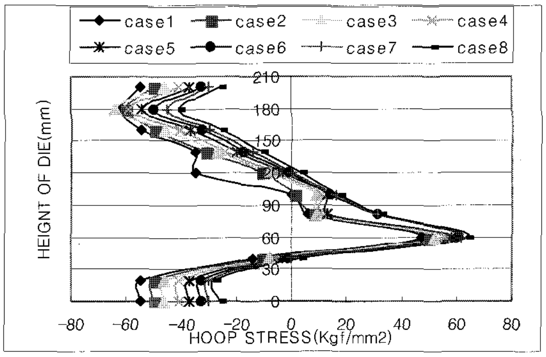


Fig. 8 Hoop stress in the inner diameter of insert according to the diameter ratios

Stress distributions of die insert and stress ring according to the changes of the amount of interferences at the optimum diameter ratio of die set are shown in Fig. 10 and Fig. 11.

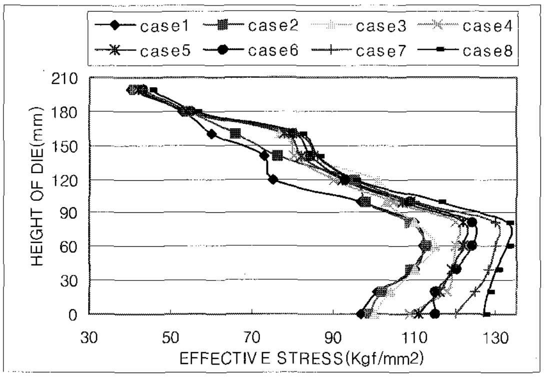


Fig. 9 Effective stress in the inner diameter of stress ring according to the diameter ratios

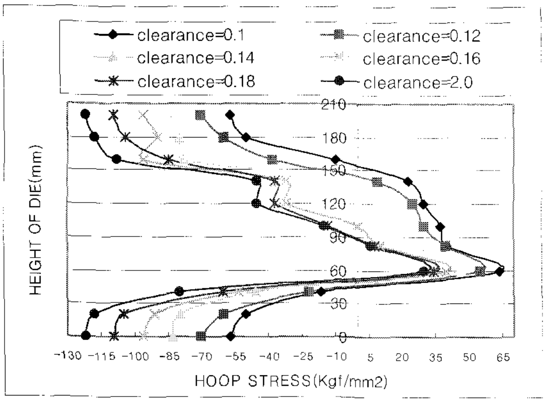


Fig. 10 Hoop stress in the inner diameter of die insert according to interferences

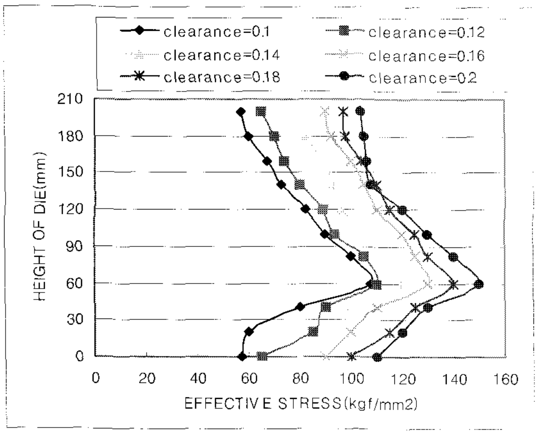


Fig. 11 Effective stress in the inner diameter of stress ring according to interference

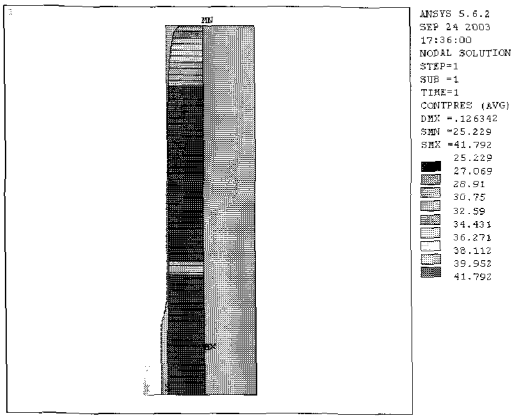


Fig. 12 Contact pressure between the insert and the stress ring as the interference, 0.14mm in the case3

The optimal outer diameters of die insert and stress ring, and the optimal interference are obtained from the case3 where the amount of interference is 0.14mm. The analysis of the case3 shows the optimal compressive residual stress in the die insert and the optimal tensile stress in the stress ring and the simulation results of the case3 are shown in Fig. 12. Stress analysis by ANSYS, the FE analysis software, is performed in order to verify strength of the die set. First of all, loads of the billet to be applied to the die set are extracted by use of interpolate forces function with the simulation results of DEFORM, and then translated coordinates/loads values of ANSYS. Fig. 12 shows the stress analysis results by modeling contact problem between the stress ring and the die insert on contact element(contact 172 element, target 169 element). Fig. 13 shows radial and tangential stresses in the die insert. The stresses are; $\sigma_r = -98.51$kgf/mm^2 and $\sigma_\theta = 47.2$kgf/mm^2 on the inner diameter of the insert, $\sigma_r = 37$kgf/mm^2 and $\sigma_\theta = -9$kgf/mm^2 on the outer diameter of the insert.

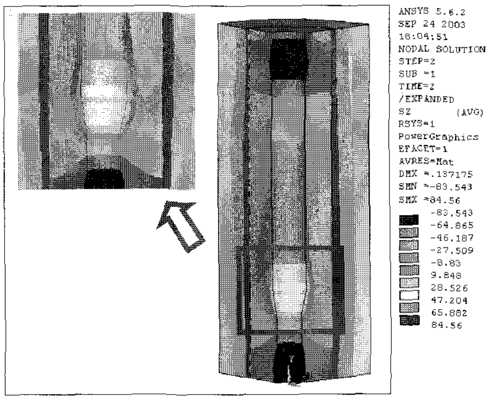


Fig. 13 Tangential stresses of the die insert for the trap extrusion with the extrusion ratio, 60%

The tangential stress of the die insert obtained from the simulation results does not comply with the die design rule 2. This module carried out stress analysis of horizontal split of the die insert as shown in Fig. 14.

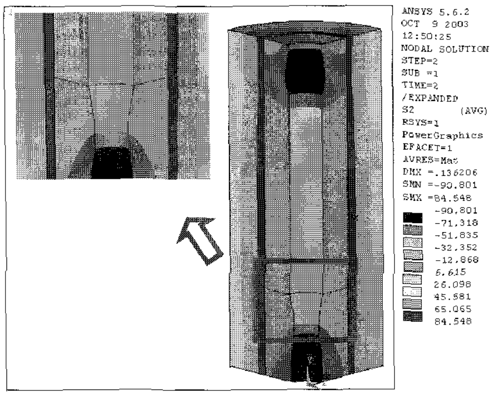


Fig. 14 Tangential stresses of the die insert for the 60% trap extrusion with the horizontal split die

When contact length of the horizontal split die is over 9mm, compressible stress is applied in tangential directions as shown in Fig. 15. When contact length is 18mm, the results of F.E. analysis are as follows. The stresses are $\sigma_r = -77$Kgf/mm^2 and, $\sigma_\theta = -12$Kgf/mm^2 in the inner diameter of the die insert. According to the Tresca yield criterion, each nodal stress of the die insert should be smaller than the yield stress of the die insert material. Therefore, the strength of the die set generated by the design model is safe. We notice that it is possible to carry out the trap extrusion as the extrusion ratio of 60%, only in one process through horizontal split of the die insert.

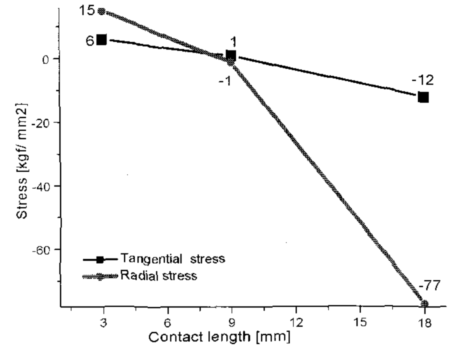


Fig. 15 Stress distribution according to the contact length between upper and lower parts of split die

4. Conclusions

In this study, an automated process planning and die insert design system for multi former-bolt product is developed based on process variables extracted from plasticity theories, F.E. simulation, relevant references and the empirical knowledge of field experts in the forging industries. The process planning module in the developed system chooses the process planning drawing best suited to the product, and carries out a flexible process based on either the reduction in the number of forming sequences, or the reductions of deviation of the distribution and the level of the required forming loads. The die design module can calculate contact pressure, die distribution of stress and strain by press fitting with the interference between die inset and stress ring and carry out the trap extrusion as the ratio of 60% by horizontal split of the die insert. The results carried out in each module will be applied to optimal design of multi-former die set. The development system which could serve as a valuable system for experts will minimize trial and error and reduce the period for developing new die sets due to the drawings generated automatically as a graphic form.

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