ABSTRACT
This study aims at analyzing the influence of the maximum principal stress on Tungsten Carbide Steel die core in an extrusion die which caused the crack of die core, and then adjusts the dies assembly method in order to improve the service life of die. In this study, we combine FEM simulation software with the Taguchi Method L$_9$($3^4$) to choose the cobalt content for die core materials, and the quantity of shrink fit while assembling the die core and die case as the reference parameters. When carrying out the simulation process, we compared the changes of the maximum principal stress of the die core caused by the plastic deformation of die materials to achieve the minimum expected value as the goal for the most optimal die combination. Then, the results obtained are to make dies in trial and mass-production practically; as a result, the die life is improved from the original 1000 to 150,000 pcs, which is more than 150 times better than before.

Keywords: tungsten carbide steel; maximum principal stress; shrink fit; Taguchi method.

ÉTUDE POUR L'AMÉLIORATION DES DÉFAUTS DES MATRICES D'EXTRUSION UTILISANT LA MÉTHODE DES ÉLÉMENTS FINIS (FEM) AVEC LA MÉTHODOLOGIE TAGUCHI

RÉSUMÉ
Cette étude a pour but d’analyser l’influence des contraintes principales maximales sur un noyau de matrice en carbure de tungstène dans une matrice d’extrusion causant la fissure du noyau de la matrice, et par la suite, ajuster la méthode d’assemblage des matrices afin d’améliorer la durée de service de la matrice. Dans cette étude, la combinaison du logiciel de simulation FEM avec la méthodologie Taguchi est de choisir l’alliage de cobalt pour la matrice d’extrusion et l’ajustement fretté pendant l’assemblage du noyau et du corps de la matrice. Au cours du processus de simulation, on fait la comparaison des changements des contraintes principales maximales de la matrice d’extrusion, causées par la déformation du plastique du matériel de la matrice, comme l’objectif à atteindre pour la combinaison optimale. Les résultats obtenus permettent de mettre la matrice à l’essai, et éventuellement d’en faire une production de masse. Il est prévu que la durée de vie de la matrice s’améliore de 1000 ps à 150,000 ps, ce qui représente 150 fois plus qu’avant.

Mots-clés : carbure de tungstène; contrainte principale maximale; ajustement fretté; méthodologie Taguchi.
1. INTRODUCTION

In the forging process, the die failure is usually caused by die wears, fatigue failure, plastic deformation, etc., and 70% failure in hot forging came from wearing; moreover, in cold forging process, the die failure was almost caused by the endurance failure. This study can be considered as an actual example in the cold forging process, thus it mainly explores isotropic fatigue failure. Its failure mechanism almost results from the mechanical load on the die, and the effective stress acting on some local areas exceeds the yield strength of tools and materials that caused stress concentration and formed a plastic deformation area; such a stress concentration phenomenon could easily cause dies failure.

In an ideal situation, the effective stress die bore should be less than the yield strength; however, since the forging frequency, the dies would bear and release load continuously and reciprocally, which would cause failure in die at the end [1, 2]. Therefore, this component of stress–maximum principal stress is commonly used as an indicator of predicting fatigue failure. Along with the macroscopic scale, fracture surface (crack) is often perpendicular to the direction of the maximum principal stress. Walters et al. [3] think that in the cold forging process, the forging pressure is usually very high, thus its die will yield along with higher stress. As a result, the cold forging die must have a high-strength characteristic, however, it will show some brittle characteristics meanwhile, thus the fragility caused by tensile stress will be much more than the compressive stress. At the position of the failed die core, it always discovers that the maximum principal stress would be the stretching situation, and most carbide alloy materials dies are subjected to the maximum principal stress; in fact, there would be smaller tensile stress, around 200 MPa ∼ 350 MPa, but it would have higher compressive stress around 2800 ∼ 3500 MPa at such position normally. Vazquez et al. [4] also think the horizontal crack of die that would be caused by the maximum principal stress of stretching yielded at the round turn of inside cavity while forming; in addition, the maximum principal stress exceeds the die’s yielding strength and causes initial crack and then gradually stretches out. In order to solve this problem, it has to make use of the compression assembly for the die case to die core to produce compressive pre-stress to make up or reduce the tensile stress occurring from forming, or even horizontally cut the die core into upper and bottom parts at the round turn of inside the cavity. As a result, it would make die core to cause positive maximum principal stress to compensate in the forging process, or even negative compressive stress would be left as well. Liu et al. [5] apply Deform software to analyze the forging process for nuts of truck tires which discover the stretching axial stress yielded on the punch while forming, thus it results in crack of punch while exiting from die. Dehghani et al. [6] use FEM to analyze the stress occurring from the die of bolt forging; there are many methods to increase the die’s service life, such as properly cut at the position where the die core bearing the stress concentration to reduce the stress value, and use stress ring to generate the compressive pre-stress on the die core, which could use to make up the tensile stress occurring from the forging process, and increase die core’s service life. Since the cold forging products need higher dimensional accuracy and strongly depend on elastic characteristics of die materials, Hur et al. [7] therefore adopt the sintered tungsten steel material, in which its high stiffness is able to reduce elastic deformation in the forging process, but the tungsten steel material is hard to resist tensile stress occurring from forging process. Therefore, the tungsten steel die applies the stress ring and shrink fit to reduce its elastic deformation in the cold forging process, as well as reduce the influential level of the die’s elastic deformation on dimensional accuracy for products. Therefore, Yokoyama et al., Goh et al., and Kim et al. [8–10] also use the shrink fit of stress ring and FEM to understand how the stress distribution on the die would influence the changes in the die’s vertical and circumferential stresses yielded while forging which could make the die to obtain the maximum service life in the forging process. Biba et al. [11] use the QForm simulation software and the point-tracking mode to investigate the growing trend of crack value which is obtained from the forming in each stage, and then make improvement in the part or stage exceeding the critical limit value. Walters et al. and Li et al. [12, 13] analyze the shrink fit that initially changed between
die case and core for improving the crack of die core, and they discover that within a smaller shrink fit, the die core’s effective stress is lower than the yielding strength, but it couldn’t reduce the maximum principal stress of stretching. However, within a higher shrink fit, the die core’s effective stress is already higher than material’s yielding strength. Therefore, under certain situations, it could not reach the reduction of tensile stress with only changing the shrink fit between the die case and the core. Thus, it needs to be aided by increasing stress ring to achieve the requirement.

In this study, it applies the FEM simulation software, and chooses the cobalt content of die core materials, the shrink fit of assembling die core and die case, the usage of stress ring and various designs with different assembly angles altogether as the reference parameters. When carrying out simulation along with the Taguchi Method $L_9(3^4)$, we compare the changes of die in the plastic deformation process, which causes the die core to bear the maximum principal stress, adopt the optimization of the maximum principal stress to be minimal expected value as the target, choose the most optimal die combination, and then carry out the trial for practical application with such optimal combination, and conduct the relevant comparison with confirming its feasibility.

2. PROBLEM STATEMENT

This study adopts one of extrusion molding stages in the multi-stage cold forging process as the research object, when the billet enters a die with diameter 15.46 mm; then reduces its diameter to 12.88 mm by the forward extrusion method, and the relative position between billet and die is shown in Fig. 1. Its percentage of area reduction is about 30%. In terms of die, the die core is made of the tungsten steel containing 24% Co, the die case material is made of the hot work tool steel SKD61, and the shrink fit is 0.4% with using the cylinder compression fit.

For the hypothesis of this study, it designs a process with 30% percentage of area reduction and 7.5° semi-die angle to carry out the forward extrusion. In general, it could be considered as a convenient process; however, the horizontal crack yielded from the actual forging die and its service life was very short with 1000 pcs only. The horizontal crack in Fig. 1 appeared along the direction of view A, and such photo is shown in Fig. 2, it shows that the die’s crack point at the inlet of semi-die angle was at B in Fig. 1, and it is the starting point of billet to start conducting the extrusion process.

In general, the tungsten steel die has 2 types of crack. One is the vertical crack in which its crack line will be developed along the axial line, and it is because the powder-sintered tungsten steel could not bear...
the exceeding stretching circumferential stress. Another one is the horizontal crack as the same crack in this study, which is caused by the exceeding stress concentration on die in the forming process, or the stress is less at such position, but it makes the fatigue failure from the repeated actions with die bore in the forming process.

This study applies the Deform simulation software to carry out the simulation on the forming material 1035SAK. After the actual compression experiment, it obtains its flow stress as $\sigma = 824\varepsilon^{0.229}$ MPa, and sets the die core material to be the 24% Co tungsten steel, in which the main purpose is to get the simulation result and compare to the die with actual crack. Therefore, after carrying out the simulation, the distribution of the die’s maximum principal stress in forging process is shown in Fig. 3, and compares with the die with actual crack (B spot as shown in Fig. 1); as a result, the maximum principal stress on elements above the crack line is stretching and upward; however, the maximum principal stress on elements under the crack line is compressive and downward, thus these two stresses in opposite direction are pulled and dragged toward each other, as well as the fatigue failure is yielded from the repeated forging process. Accordingly, the contact point of these two opposite maximum principal stresses become the point of die where they would be cracked very easily. The tensile stress obtained from the cracking point is just only 300 MPa, not large. Generally, the crack line is caused by the fatigue failure, not caused by the exceeding yield stress.

3. TAGUCHI METHOD

The Taguchi Method was invented by Taguchi Genichi Ph.D., who combined the statistic methods with engineering techniques to make the process and product design consider quality but also improve cost. We set control factors that would influence quality characteristics and their change levels; we then apply the
A statistic technique to design the Orthogonal Array and simplify the data analysis to make its results to be more reliable [14].

According to previous experiences, if it intends to increase the die’s capability of bearing stress, then each method and data of die assembly are adjusted that will be helpful to the service life of the die. The following describe the parameter of control factors and the division of change levels as shown in Fig. 4.

A: The content of adhesive [cobalt (Co)]: For the choice of die core materials, the content of adhesive [cobalt (Co)] that was used before sintering for the chose tungsten steel materials will influence the hardness of the sintered materials, and further influence its wear and impact resistance; that is, materials with higher cobalt content will have less hardness; and higher impact resistance will reduce the wear resistance. Tungsten steel material used for the die core is limited by specification prescribed by manufacturers, where more or less Co was the standard of differentiation, that is, a total of four types including 10, 15, 19 and 24% under general situation; the latter three of them were used in this study.

B: Compression fit of die: Because this die is composed of three sections, it will have two contact surfaces that need to choose the compression fit methods: the first contact surface is between die core and inner stress ring, another one is between inner stress ring and outer die case. Since the first contact surface is including die core, and it also is the core for the entire forming process, thus the fitting method and angle selection of the first contact surface include 0° cylinder fit and 2° and 4° incline fit; the second contact surface can only be used with 0° cylinder fit then. Practically speaking, inclined fit would be more stable, but the quantity of angle would be the most optimal condition, especially when it still needs to be fitted with other factors, and there will various changes in such result.

C: Shrink fit for inner stress ring: Based on previous experiences, it will choose three types of shrink fit for inner stress ring: 0.4, 0.6 and 0.8%, because shrink fit less than 0.4% is only able to yield small compressed stress, with smaller effects to improve life of use of die. On the contrary, shrink fit more than 0.8% is able to yield larger compressed stress, leading to crack of die core generated in the assembly. Its main purpose is to use the shrink fit to make die to pre-set the compressive stress, while assembling die, to resist and reduce the tensile stress that is yielded from the forming process, thus increase the die’s service life.
Table 1. Control factors and levels for the Taguchi Method L$_9$(3$^4$).

<table>
<thead>
<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Material(WC-Co)</td>
<td>15% Co</td>
<td>19% Co</td>
</tr>
<tr>
<td>B</td>
<td>Assembly degree</td>
<td>0°</td>
<td>2°</td>
</tr>
<tr>
<td>C</td>
<td>Inner shrink fit</td>
<td>0.4%</td>
<td>0.6%</td>
</tr>
<tr>
<td>D</td>
<td>Outer shrink fit</td>
<td>0.4%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Table 2. L$_9$(3$^4$) parameters layout and simulation result.

<table>
<thead>
<tr>
<th>EXP</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Result ($\sigma_p$)$_{\text{max}}$ (MPa)</th>
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<td>1</td>
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<td>1</td>
<td>1</td>
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<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
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<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>301.24</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>315.81</td>
</tr>
<tr>
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<td>2</td>
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<td>3</td>
<td>1</td>
<td>74.91</td>
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<tr>
<td>6</td>
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<td>3</td>
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<td>2</td>
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<td>3</td>
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<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
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<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>205.90</td>
</tr>
</tbody>
</table>

D: The shrink fit of outer die case: The shrink fit between inner and outer rings is set to be 0.4, 0.5 and 0.6%, which is aimed at supplementing deficiency between inner ring and die core; the selection of shrink fit of outer ring is usually smaller than that of inner ring. As larger shrink fit of outer ring will intervene with that of inner ring, it would reduce effects as expected in turn.

We listed four control factors in Table 1 with three levels respectively. Applying the Taguchi Method to choose the L$_9$(3$^4$) statistic methods as shown in Table 2, we obtain the parameter setting for nine experiments. It adopts the smaller-the-better characteristics; that is, the smaller maximum principal stress on the die in the forming process will have better result.

4. SIMULATION ANALYSIS

This study uses simulation software DEFORM-3D [15], wherein the simulation process is divided into two parts; first, it simulates the billet’s being squeezed in the die; the billet is set as a plastic object configured with node and element and die is set as a rigid body; constant shear friction factor ($m$) is used between them. After simulation, billet is squeezed under its own condition of flow stress, its plastic material has been deformed, and information of strain is retained in the element and node. The second part is to simulate the die with stress analysis; the die contains die core, inner ring and outer ring; these three objects are set as elastic body, configuration node and element; then the materials used, shrink fit among them and constant shear friction factor ($m$) are set. After that, we insert the force of every node which the billet acquired during the first part of squeezing into the node of die core. These forces are delivered among nodes of die core, inner ring and outer ring until the balance is maintained.

In the simulation results, the die is fixed at the same position, thus in actual extrusion such die’s crack positions are shown in Fig. 5, we circularly and averagely collect the maximum principal stress from 20 points to make comparison.

Figure 6 shows the entire quantity of maximum principal stress distribution for each element in the simulation results. Thus, in Fig. 6, it discovers that almost every experiment’s line shape is very similar to each other; in addition, among these nine experiments, Exp5 shows the lowest value of maximum principal stress,
Fig. 5. Schematic diagram of crack position of maximum principal stress.

Fig. 6. Sets of maximum principal stress results for L₀(3⁴).

and Exp6 has the highest data of principal stress. Then, we take the highest value of principal stress from each experiment, and place in Table 2 for further analysis. After computing the maximum principal stress in Table 2, the parameters of quality characteristics obtained within various levels and their influences on these nine simulation results are shown in Table 3 and Fig. 7.

5. RESULTS AND DISCUSSIONS

Table 3 is quality characteristics factor response table, it shows that among these four parameters of quality characteristics, the changes in three levels of shrink fit for inner ring in Item C have the biggest influence on all experiment results; that is, since the shrink fit changes from 0.4, 0.6 and 0.8% for inner ring, the experiment obtained the results of the maximum principal stress to be changed from 326.68 to 165.66 MPa, the difference would be up to 161.02 MPa. Figure 7 is quality characteristics factor response diagram, it shows a bigger inner ring shrink fit in Item C, its maximum principal stress is smaller then, thus for the inner ring shrink fit, its yield of maximum principal stress would be an inverse ratio to the shrink fit. This means that the inner ring shrink fit would choose the biggest value from 0.4, 0.6 and 0.8% to make the die core to obtain more compressive pre-stress before forming, so as to offset stress yielded from the forming process and also to make smaller yield of the maximum principal stress finally.

Next in Item D, the outer ring shrink fit’s influential level is ranked in 2nd place. Changes of 0.4, 0.5 and 0.6% make the maximum principal stress of such experiment to be changed from 196.46 to 313.44 MPa, with a significant difference of 116.98 MPa. In addition, changes in Item D’s three levels of outer ring shrink fit
Table 3. Quality characteristics factor response table.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>275.99</td>
<td>248.40</td>
<td>326.68</td>
<td>196.46</td>
</tr>
<tr>
<td>Level 2</td>
<td>246.32</td>
<td>205.44</td>
<td>246.63</td>
<td>229.07</td>
</tr>
<tr>
<td>Level 3</td>
<td>216.66</td>
<td>285.13</td>
<td>165.66</td>
<td>313.44</td>
</tr>
<tr>
<td>Range</td>
<td>59.33</td>
<td>79.69</td>
<td>161.02</td>
<td>116.98</td>
</tr>
<tr>
<td>Rank</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 7. Quality characteristics factor response diagram.

are opposite to Item C, in which a bigger maximum principal stress would be obtained at the biggest shrink fit 0.6%, and the smallest shrink fit 0.4% would then be got smaller than the maximum principal stress; therefore, the quantity of outer ring shrink fit is directly proportional to the yield of maximum principal stress; accordingly, the quantity of outer ring shrink fit is proper and better but bigger. Table 2 shows that the outer ring shrink fit is D3(0.6%), no matter how combining other three items: A, B and C, its maximum principal stress would be greater than 300 MPa, and significantly close to each other. When choosing D1(0.4%) and D2(0.5%), with different combinations of A, B and C, the obtained quantities of maximum principal stress would be very different from each other. Especially, changes in maximum principal stress are discovered that are significantly influenced by Item C which shows a similar tendency. Therefore, in the case of bigger outer ring shrink fit, it apparently would offset the compressive pre-stress effect that was yielded from the inner ring shrink fit.

Item B shows the assembly methods for a die, in Fig. 7. It shows a turning point, in which a proper 2° inclined assembly method is better than cylinder or more inclination, such as 4°. However, it has less and less influence on the experiment results, and thus ranks in the 3rd place.

For the last choice of die core materials, Table 3 and Fig. 7 show that it has the least importance and the difference between the biggest and smallest is only 59.33 MPa. Thus, when choosing materials with higher cobalt contents, such as A3 (24% Co), as the die core materials, it may yield less maximum principal stress; however, with lower cobalt contents, such as Al (15% Co), it may yield bigger maximum principal stress. Even the difference is not significant, it still can determine that, within conditions stated in this study, less hardness of die core materials will have higher cobalt content and obtain smaller maximum principal stress. Thus, the hardness of die core materials is obviously not different in the maximum principal stress that the die core bore in the cold forging process. However, the tungsten steel with higher cobalt content will have less hardness, as well as a small Young’s Modulus, thus it has bigger elastic deformation, which would render the dimension precision of forged products difficult to control in the extrusion process, and then lose the die’s service life.

We recombine the optimal combination, A3, B2, C3 and D1, by using the Taguchi Method L9(3^4) Orthogonal Array, and apply the simulation software Deform 3D to carry out the simulation, and then compare.
Table 4. Simulation result comparison before and after modifying quality characteristics factors.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Result ($\sigma_p)_{\text{max}}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original EXP</td>
<td>A3</td>
<td>B1</td>
<td>C1</td>
<td>D1</td>
</tr>
<tr>
<td>Modified EXP</td>
<td>A3</td>
<td>B2</td>
<td>C3</td>
<td>D1</td>
</tr>
</tbody>
</table>

Fig. 8. Maximum principal stress distribution of original die design (L); Maximum principal stress distribution of modified die design (R).

to the original die design combination, A3, B1, C1 and D1. The results are shown in Table 4, and the distribution of maximum principal stress is shown in Fig. 8.

The optimal combination’s maximum principal stress is 60.23 MPa, however, the original design result is 259.10 MPa. After comparing, the optimal combination’s maximum principal stress is only 1/4 of the original design.

6. CONCLUSIONS

This study has applied the simulation software Deform 3D and the Taguchi Method Orthogonal Array L9(3^4) statistic method to improve the die assembly; among which, it includes the choice of die materials, angle of compression fit and inner and outer ring shrink fit, to choose the optimal combination as an effective basis for improving the die’s service life. In addition, it shows a significant improvement in actual mass-production, and such die’s service life. After modification, the production has increased from the original 1000 up to 150,000 pcs, more than 150 times than before. Thus, the conclusions of these aforesaid results of simulation experiment are as follows:

1. Quantity of inner ring shrink fit has the most influence on the die’s maximum principal stress in the extrusion process, 0.8% shrink fit has a better effect than 0.6 and 0.4% shrink fit.

2. Outer ring shrink fit 0.4% has a better effect, in case of increasing shrink fit to 0.5 or 0.6%, it may obtain a reverse effect.

3. 2° inclination is the optimal compression fit angle for the die core, cylinder (0°) or bigger inclination 4° would have a worse effect reversely.

4. For the choice of die core materials, the tungsten steel with higher cobalt content 24% has less hardness and wear resistance, but has optimal toughness.
REFERENCES