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<table>
<thead>
<tr>
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<tbody>
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Die Stress Analysis and Improvement of Welding Valve Fastener in Multi-Stage Forging

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ABSTRACT
This study explores the multi-stage cold forming die of welding valve fastener by applying the simulation software. There is a possibility of understanding that the various stress intensities the die core bore and corresponding distributions during each forging stage of formation meanwhile so as to improve die’s service life. These stresses include the radial stress, axial stress, hoop stress and maximum principal stress, and different types of stresses which could yield different fractures for die core. Therefore it is needed to use different die design methods to improve the fracture issues for different die cores. For example, the shrink fit is used between the die core and die case. Adjusting the size of shrink fit to convert the tensile stress into the compressive stress for the hoop stress; it could avoid generating the axial crack for dies during the forging formation. In addition, for the drastic changes in the axial stress caused by the stress concentration on the die core, it would yield the transverse crack for the die core. Thus it adopts the preventative measures to split such a stress concentration into two sections in order to reduce the drastic changes in the axial stress on that section.

Keywords: multi-stage cold forging; hoop stress; axial stress; maximum principal stress.

1 INTRODUCTION
In general, the simulation software analysis can be used to easily understand the material flow during the forging process, whether the material can be filled completely on the corner of the die, and avoid occurring defect and abnormality. Also, the design of die can be changed to reduce the forging load and the die wear, and increase the service life of the die. However, this information is difficult to be obtained from the traditional trial and error method. Therefore, the simulation software analysis has become one of the necessary tools for designing the forming methods. Biba et al. (2001) applied the QForm software to simulate the forging process to ensure that can be accurately displayed the overlapping phenomenon yielded during the material flow. Besides it can avoid transferring this overlapping phenomenon to the next stage and continue the forging process unknowingly. Liu et al. (2004) also applied the deform simulation software and discovered that when forging the wheel nut that the tensile axial stress occurred on the outer diameter of the punch during the forming process of internal hole and flange to cause the crack while the punch is withdrawing. Lee et al. (2003) though that the overlapping phenomenon occurred in the complex extrusion forming process of the piston-pin, and the defect was caused because the dead metal region was appeared during the material flow, and the main reason was saving the material cost and reduced the scrap thickness as much as possible after forming.
However, yielded defect not only occurred damage to the accuracy of the workpiece, but also reduced the strength and endurance life of the workpiece accordingly. Lee et al. (2009) applied the AFDEX software analysis and thought that the overlapping phenomenon is an unallowable defect in most cases. However, for these defective phenomena, if it could use the trimming and piercing process to cut off the defect area before the end of forging process, then the overlapping defect phenomenon could exist temporarily. Park et al. (2007) aimed at choosing the optimal preform shapes and sizes from the middle stages as the final near-net-shape product in the multi-stage forming. Giuliano (2007) used the MSC.MARC software analysis. His purpose was to use the forward extrusion and backward extrusion to complete the multi-stage forming, and used the simulation result analysis to avoid the defect. The suitable forming design was chosen for the previous stage in order to understand the strain distribution and forming load inside the workpiece. Lee et al. [7] aimed at the axisymmetric flange components to carry out the study; the overlapping phenomenon was easily yielded in the forming process. This was a defect issue that derived from the material flow, and would yield the material discontinuity on such an area. This area was frequently having the stress concentration, and led to elements’ failure not be used. Chan et al. (2009) tended to use a single die to make an overlapping phenomenon free die structure of the axisymmetric flange components. Among which, modifying the shapes and sizes of die based on the FEM in order to study the process of occurring overlapping. Furthermore, the overlapping-free dies structure was obtained. Shih et al. (2014) used the Deform 2D/3D software analysis to simulate the fastener forming feasibility, as well as chose the optimal combination of forging stages to provide the practical trial.

Although, the simulation software can be analyzed the data, then the optimal forming combination is obtained to get the minimum forging load. However, with the practical massive forging production, the service life of the die is also of great important issue. Walters et al. (1997) thought that in the cold forging process, the forging pressure was high frequently, and then the die would have a high stress accordingly. Therefore, the cold-forging die not only needs to have the high-strength property but also has the toughness; however, the die receives more tensile stress than compressive stress. Vazquez et al. (2000) and Dehghani et al. (2010) all thought the transverse crack on die that caused by the maximum principal stress and tensile yielded at corners inside the cavity during the forming process in general; in addition, such a maximum principal stress had exceeded the die’s yield strength, and caused an initial crack and extended slowly. To solve this problem, it needs to use the die case to make the compressive assembly for the die core to generate the pre-compressive stress to offset or reduce the tensile maximum principal stress generated. Even horizontally cut the die core into the...
upper and lower sections, and the cutting position is at the internal corner of the cavity. As a result, it will make the die core to offset the positive maximum principal stress in the forging process, or remain the negative compressive stress. Due to the cold forging products which need higher accuracy for sizes, and it will strongly depend on the elastic property of die materials.

Thus Hur et al. (2003) adopted the sintering tungsten steel, its high stiffness can reduce the elastic deformation during the forging process; however, the tungsten steel is hard to resist the tensile maximum principal stress generated in the forging process. Thus, it should use the stress ring and shrink fit to the tungsten steel die in order to reduce its elastic deformation in the cold forging process. Therefore, Yokoyama et al. (2000) and Walters et al. (2000) also used the shrink fit of stress ring, and cooperated with the FEM to understand the stress distribution for the die, as well as how to affect the changes in the die’s axial stress and hoop stress during the forging process so as to let the die obtain the maximum service life in such process. Chang et al. (2015) applied the Deform 2D software to simulate the damage factors for the die’s transverse horizontal crack during the extruding process of the axisymmetric tube-shape die in order to improve and increase its service life. Thus, in addition to the choice of forming methods, this study also applied the assistance of the simulation software, as well as inspected the possible influences of stress changes that bore by the die core before and after the forging process.

2 WELDING VALVE FASTENER FORMING METHODS

The finished product is a welding valve fastener, and its sizes are as shown in Figure 1. 10B21 is the carbon steel including boron element to be as workepiece, the feeding volume is 725.9mm³, and the wire diameter is 9.2mm and the length of about 11.23mm. The key to the formation is the welding ring with a height of 0.45mm, and the outer diameter of 9.7mm for its connecting accessory.

After analysis by using the Deform 2D/3D software simulation, the optimal forming method is obtained as shown in Figure 2 which had been completed in 6 stages. The simulation conditions are shown in Table 1.

The stages are elaborated in the following:

First, cut off the wire into the required lengths and feed it horizontally into the 1st stage cavity. Modify the lower surface to trim off the burr that yielded by cutting off the wire, and implement the upsetting process inside the die to make the workpiece’s outer diameter achieve the preset size.
Flip the workpiece completed in the 1st stage to enter the 2nd stage cavity. Re-modify another lower surface of the workpiece and use the 2nd front punch to upset the die and complete the preformation and the inner hole positioning process.

Next, flip the workpiece completed in the 2nd stage into the 3rd stage cavity. Implement the main body upsetting process till achieves the preset size of outer diameter, then use the 3rd back punch to maintain the center tube sizes, which is the follow-up of the preformation process for the 2nd front punch, and conduct the preformation process of the welding ring outside the main body. Meanwhile, the welding ring size outside the main body is only a process of preformation, which is not able to achieve the requirement for the fastener products. Therefore, the sizes of welding ring need to be completed by using multiple stages.

The next step is to horizontally feed the workpiece completed in the 3rd stage into the 4th stage cavity. Use the 4th front punch to make the extrusion reduce the volume and thickness of the iron scrap, which can not only reduce the use of materials, but also the thinner iron scrap can easily complete the feed through the process. In addition, it can increase the tube sizes at the center, and complete the sizes of the welding ring outside the main body.

Flip the workpiece to enter the 5th stage cavity to adjust and set the final size of the fastener. Then horizontally shift the workpiece to the 6th stage to carry out the feed through the process in the last stage. Figure 3 shows the processing actual forging products of the die adopting the simulated forming method.

3 Die Stress Analysis

After completing the forming simulation of the fastener, it indicated that such product can be possibly achieved for the purpose of such forming method. However, practically speaking, we not only consider the feasibility of the forming method, but also a close attention to the service life of the designed die, due to the cost of the die and the production efficiency. Thus, after simulated the forming method, we also concerned about the size and shape of die core used for the design, the assembly method of the die, and the shrink sizes of assembling the die core and die case. These issues will affect the die core with various stress changes, and further to affect the die’s service life then.

Most die cores used in the multi-stage cold forging process are made of the tungsten steel. This material is made by the powder metal sintering, and the main combination elements are Tungsten and Molybdenum. Thus this material is very hard and has a great wear resistance. However, due to the tungsten steel is made by the powder metal sintering, there are several voids existed inside the whole material block which can make the tungsten steel to be born through a great compressive stress, but could not
withstand the tensile stress. Therefore, the die design for the cold forging process, we have to use every method to reduce the tensile stress for the die, in order to avoid early damage to the die which will reduce its service life accordingly. The main approach is to use the shrink fit to combine the die core and die case together when assembling the die which would generate the pre-compressive stress on the die core before the forging formation, in order to resist the tensile stress generated in the forging formation. In terms of the crack of the tungsten steel die core, normally there are two types of cracks: the horizontal (transverse) crack and axial (longitudinal) crack. The horizontal (transverse) crack is caused by the tensile axial stress, and the axial (longitudinal) crack is caused by the tensile hoop stress. Therefore, regardless of which type of crack the die core generated, most of them are caused by the tensile stress. Figure 4 is the photos of showing that the crack generated from the inappropriate design of the die core. The photo on the left shows the horizontal (transverse) crack on the die core, and the right photo is presented the axial (longitudinal) crack on the die core.

4 DIE STRESS ANALYSIS AND DISCUSSION WITHOUT SHRINK FIT

In this study taking the forming method in the 2nd stage as an example, the relative positions between the blank and the tungsten steel die core is shown in Figure 5. Among which, they include the workpiece, front punch, back punch and die core. On the left side, it is the blank in the 2nd stage before forming, which is the workpiece that flipped after completing the forming process in the 1st stage, and the right side is the blank shape and position in the 2nd stage after forming.

Prior to forming, the assembling condition has to be set first, e.g. the tungsten steel die core and die case without using the shrink fit, in order to understand the original stress and the die core bore, which can be used as a reference for improving the die design. Analysis points are along the inner surface of dies to show the radial stress, the hoop stress, and the axial stress. For measuring the data of various stresses the inner holes of the die core bore before the forging formation, we divided the area along the die core’s inner holes into 55 points from bottom to upper. They are indicated as P1 to P55, to take the data of various stresses respectively, as shown in Figure 6, where they included the effective-stress (Stress Effective), the radial stress (Stress R), the hoop stress (Stress Theta) and the axial stress (Stress Z). After completing the forging process, the forming height of the workpiece was between the P15 to P34, and for the requirement of the forming method, a chamfer is set on the P31 position of the die core which will be shrunk back to the back holes with smaller inner diameter.
Between P15 to P34, the radial stress (Stress R) is a compressive stress, the hoop stress (Stress Theta) is a tensile stress, and the axial stress (Stress Z) is like a compressive stress roughly, but the tensile stress existed upon P15.

Now use the stress data that measured from each point of the die core’s inner diameter, and the final position after the workpiece’s formation would be between P15 to P34, to place each point sequentially from upper to lower positions in Figure 7 to get a better comparison which including the radial stress (Stress R), the hoop stress (Stress Theta) and the axial stress (Stress Z).

The maximum hoop stress is generated on P21, and the tensile hoop stress is 2421MPa. It showed such a great tensile hoop stress would be inevitably caused the die core to generate the axial (longitudinal) crack, and the cracking speed is very quickly. Thus, it would be cracked from P21 upward and then downward, which made the die core failure during the forging process.

As for the axial stress (Stress Z), its tensile stress has 2 peaks, one is on P12, and its stress is 570MPa, where is exactly upon the blank position. The other higher peak is on P28, and its stress is 868MPa, where it fell on the upper of the die lower corner. To view from the curve pattern, the P28 position can be considered as a dangerous spot relatively, and it is the tensile stress on this point, but the ones upon and beneath it are sharply converted into the compressive stress. Although the axial stress of 868MPa is about 1/4 of the hoop stress of 2421MPa comparatively, the fatigue phenomenon generated when the machine is operating at full speed, such as the peak of the axial tensile stress on P28, especially its upper and lower positions are the compressive stress with drastic changes, it would have the synergistic effect to crack the tungsten steel, thus shorten the die core’s service life.

As for the radial stress (Stress R), it is almost generated on the workpiece between the position between P15 and P34, and the compressive stress is -2365MPa. Materials provided by the tungsten steel manufacturers are able to bear the compressive stress between 3000~3500MPa normally [9]. Therefore, the radial stress could not crack the die core in this stage.

Figure 7 and 8 shows the 2nd stage die core without the shrink fit, the distribution of the maximum principal stress bore by the section of its cavity and die core. Compared the left line of the maximum principal stress to the line of the hoop stress in Figure 7, they are almost the same except there are a few differences in the upper and lower ends. The maximum principal stress falls on P21 (2421 MPa), which its position and intensity are as same as the hoop stress. And, to view from the vector distribution of the right maximum principal stress, the direction of the on the die core’s inner holes is the hoop
stress, and all of them are the tensile stress. Therefore, the hoop stress is apparently the biggest dead point of the die core within such condition, thus, it needs to be dealt with in priority; otherwise, and this die core cannot be used.

5 DIE STRESS ANALYSIS AND DISCUSSION WITH SHRINK FIT

From the aforesaid analysis results, there are two issues which need to be solved to improve the die’s service life. One is the axial crack of the die core that caused by a bigger hoop stress; the other is the stress concentration phenomenon on P28 that occurred at the turning points of the inner holes on the lower die and the axial stress which changes in this area are very intensively which can be easily caused the radial crack of the die core to affect the die’s service life. Therefore, in terms of these two issues, we chose two preventative measures as shown in Figure 9. When assembling the die and intention to improve the distribution of stress on the die core during the forging formation, as well as intended to protect the die to extend its service life accordingly.

First, as for the crack caused by the excessive hoop stress, we shrunk 1% diameter of the contact surface between the die core and the die case when assembling them, as showed in Figure 9 (left). The main purpose is to use the shrink fit in the assembling process before the die’s forging formation, which made the die core to pre-produce the compressive hoop stress, so as to offset the tensile hoop stress during the forging formation to avoid generating the axial crack on the die core with excessive tensile hoop stress.

In addition, the stress concentration phenomenon occurred on P28 by the axial stress, which may cause the transverse crack, and reduce the die’s service life. In general, for the method of improving such transverse crack, we will first split the die core on the cracking point, that is, split the die core into the upper and lower die cores, and adopt the shrink fit to assemble the die case, as shown in Figure 9 (right). Since the die core has been split into two parts, the original position of causing the stress concentration, its axial stress would be reduced or converted from the tensile stress into the compressive stress accordingly.

Figure 10 shows the comparison of stresses that obtained from using a single die core or the upper and lower die cores to assemble with the die case with the shrink fit. There are 3 types of line in this figure. The first one is a single die core, which assembled with the die case without using the shrink fit. The second one is a single die core, which assembled with the die case with using 1% shrink fit. The third one is the die core that splits into two single die cores, and assembled with the die case with using 1% shrink
fit. The die core is made of the carburize tungsten steel, and the die case is made of the hot working steel SKD61. In this figure, there were 3 different combinations that underwent the forging simulation to obtain the stress data bore by the die core, including the radial stress (Stress R), the hoop stress (Stress Theta), the axial stress (Stress Z) and the maximum principal stress (Max Principal Stress), the comparison of 4 different types of stress.

In Figure 10, it shows the comparison of the radial stress, in addition to the changes in stress obtained around the lower die on P30, there is almost no change in other areas. When assembling the die core and die case without using the shrink fit, the maximum compressive stress would be obtained here for the radial stress, here it is the turning spot of the inner hole curve of the die core, the material flow needs more elastic deformation in this area. Thus it would cause more compressive stress to the die core. 1% shrink fit would relieve the compressive radial stress on the lower die; however, when the die core split into 2 parts, the compressive radial stress would be increased in this spot, but these stress values are within the acceptable range without intensive changes.

In Figure 10, the comparison of hoop stress showed that the assembly of the die core and die case with 1% shrink fit obtained a better effect, thus the hoop stress reduced from 2421MPa to 161MPa on the original P21. Therefore, it obviously possessed a better effect on reducing the hoop stress when assembling the die core and the die case with the shrink fit. However, when splitting the die core into the upper and lower parts, the hoop stress would be reduced even lower around the lower die on P30. But as for the end surfaces of the die core from P1 to P14 areas, that is, it is the upper end after completing the formation of the workpiece, the stress may be higher than the stress in the die core before splitting; however, all of them are the compressive hoop stress.

In Figure 10, as for the comparison of the axial stress, when assembling the die core and the die case without the shrink fit, the drastically changed line type of the axial stress obtained on P28 has sharply changed from the compressive type into the tensile type, and then converted back to the compressive type. When the forging machine started the high-speed operation, the stress bore in this spot would be shifted between the compressive and recovered types or the tensile and recovered types continuously. Thus after a period of time, the fatigue phenomenon would appear accordingly. As a result, the key to change the die design is to correct and reduce the peak values of the tensile axial stress in this area, in order to increase the die’s service life. For the comparison diagram of the axial stress, the first die, the axial stress is the tensile type of 868MPa on P28. When the second die using the shrink fit, the axial stress is still the tensile type on P28, but already reduced to 290MPa. For the third die with using the...
shrink fit, and split the die core into the upper and lower parts, the axial stress has reduced to \(-307\)MPa on P28, which has become the compressive type. However, from P1 to P12, this area is exactly upon the blank with completing the forging process, since the die core has split into two parts, its axial stress has increased from \(570\)MPa to \(900\)MPa, but the line type is relatively moderated on P28, and smaller effect on the die core’s service life.

Lastly we combine these three aforesaid stresses to observe the line change of the maximum principal stress in Figure 10, while the intensity and stress type of the maximum principal stress is shown in Figure 11. When it is a single die core without a shrink fit, the maximum principal stresses between the die case and the die core are almost the distributed, vector value and stress type of the hoop stress as showed in Figure 8, the maximum value is \(2421\)MPa on P21. Figure 11(left) shows an assembly of a single die core and the die case with using \(1\%\) shrink fit, the maximum principal stress distributed by the hoop stress that inside the die core’s inner holes were all reduced, and only remained on the height of the final blank with the hoop stress surrounded. However, the maximum principal stress on its upper and lower positions has changed into the axial stress, the axial stress is \(456\)MPa on P28, and it still is the tensile type, but its upper and lower parts are the compressive types. Figure 11 (right) presents owed the die core split into the upper and lower parts which assembled with die case by using \(1\%\) shrink fit, the die core’s inner hole, turning point P28, which the axial stress \(456\)MPa is the tensile type originally, and then converted to the compressive type with \(-729\)MPa hoop stress.

6 CONCLUSIONS

For the die’s service life, we could use the shrink fit to assemble the die core and the die case and made use of adjusting the intensity of shrink to reduce the tensile hoop stress or change into the compressive hoop stress, thus it can avoid generating the axial crack for the die during the forging formation. In addition, since the drastic changes of the axial stress in the die core caused by the stress concentration, it would generate the transverse crack on the die core. Then it needs to adopt the preventive measure to split such stress concentration into two parts, so as to reduce the drastic change in such axial stress. Therefore, the use of the simulation software cannot only obtain the proper forming method, but also can pre-adjust the die design in order to improve the die’s service life.

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References

<table>
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List of tables and figures

Table 1 Property assumptions for the objects used in the FE simulations

Fig. 1 Fastener size diameter

Fig. 2 Fastener forming methods

Fig. 3 Actual forging parts for each stage

Fig. 4 Crack generated from the inappropriate design of the die core

Fig. 5 Relative positions between the blank and the tungsten steel die core in the 2nd stage

Fig. 6 Various stresses distribution of the die core in the 2nd stage without shrink fit

Fig. 7 Comparison of 3 stresses cavity bore of the 2nd stage die core without the shrink fit

Fig. 8 Distribution of the maximum principal stress bore by cavity of the 2nd stage die core without the shrink fit

Fig. 9 Assemble die core and die case with using different methods and 1% shrink fit

Fig. 10 Comparison of stress obtained by assembling the die core and the die case with using different shrink fits

Fig. 11 Comparison of the maximum principal stress distribution obtained from assembling the die core and die case with different shrink fits

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Fig. 11 Comparison of the maximum principal stress distribution obtained from assembling the die core and die case with different shrink fits