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A finite element analysis of cold-forging dies using two- and three-dimensional models

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Abstract

The cold-forging process analysed in this paper deals with the production of a hexagonal shape on the head of a bolt. The process utilises a die known as a ‘‘Standard Trim Die’’ which is forced at velocity onto the workpiece to form the bolt head. This process is a combination of cutting and forging. By definition, a cold-forging operation occurs at a temperature below the recrystallisation range of the metal being forged. Due to this fact very high forging loads are required, which in turn cause very high stresses within the die material. These high stresses can cause die failure due to overloading or fatigue. The main focus of this analysis was to predict the level of these stresses during the forging operation, and if possible to find the optimum operating conditions which would increase tool life. The analysis consisted of creating a range of different trim die geometry's using AutoCAD/mechanical desktop and importing them into the finite-element analysis (FEA) package DEFORM. Due to geometrical considerations and computational limitations the initial tests consisted of two-dimensional (2D) models. Extensive analysis of these results enabled a more accurate simulation of the forging operation using three-dimensional (3D) models.

Full elasto-plastic FEA, including contact and friction, was performed in order to produce the most realistic results possible for the stress distribution within both the tooling and workpiece. The FEA analysis indicated that the highest stress concentration occurred within the body of the tool and not along the contact surfaces as might first be expected. Results showing the variation in tool stress as a function of changes to the trim die cutting edge corner geometry are also presented. From these results it was possible to predict the corner fillet radii required to give the optimum geometry and hence produce the lowest stress concentration within the trim die.

Keywords: Trim die; Cold forging; Finite-element analysis; DEFORM

1. Introduction

In the last few decades, the mass production of components by cold forging has increased dramatically. Cold forging has various advantages including little loss of material, improved strength, geometrical precision of components, and high production rates. However, considerable difficulties can be encountered due to the high stresses induced within the workpiece and tooling because of the very large forming load [1]. Obviously, prediction and reduction of these high stresses within the tooling is paramount. A significant economical effect can also be achieved through an increase in the service life of tool elements [2]. Reducing the stress level in cold-forging tooling by modifications in the design has the greatest influence on tool life [1]. With this in mind a research project has been initiated to examine the influence of corner geometry on the stresses within a cold-forging die. The particular forging process analysed is the method used to ‘‘trim’’ a hexagonal shape on the head of a bolt. Fig. 1 shows a three-dimensional (3D) representation of the cold-forging operation considered. The typical bolt blank, known as the *cheese head*, with the Standard Trim Die underneath before and after the ‘‘trimming’’ operation is illustrated. The cheese head material was 0.9% carbon steel, while the trim die material was M2 tool steel. The manufacturing process is achieved by forcing the die, known as a *trim die* because of its function, onto the workpiece, whereupon a forging and cutting action produces the desired hexagonal shape for the bolt head. The size of the trim die analysed is classified as an M6. This relates to the size of bolt produced. An M6 refers to a metric-dimensioned bolt that has a diameter of 6 mm on the threaded shank. Later on, in Section 3.6, analysis is presented out on an M20 trim die. Again this relates to a metric bolt having a threaded shank diameter equal to 20 mm.

Initial work was carried out on this topic in 1994 [3], but at that time the finite-element analysis (FEA) packages available where insufficiently developed and could not provide a complete analysis of the forging process or the tool stresses.

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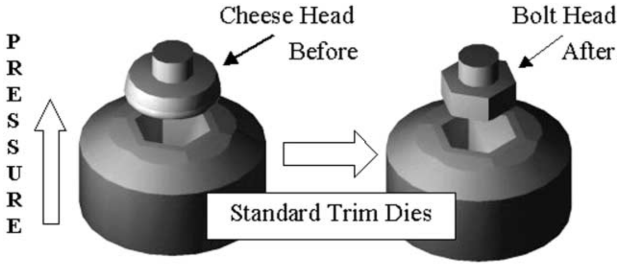

Fig. 1. Workpiece and trim die before and after the forging process.

Of the two packages used in the earlier work, one could simulate the entire deformation process (Form — 2D), but could not simultaneously predict stresses within the tool and workpiece. The other package used was ANSYS, this could predict stresses in both tool and workpiece, but was unable to model the significant plastic deformation the workpiece experiences during forging. With the advantage of software developments and more powerful computers, a FEA package called DEFORM© has enabled the entire deformation process to be simulated, while simultaneously predicting all the necessary stress states, in both die and workpiece. Ranges of different trim die geometries were constructed using AutoCAD/mechanical desktop and imported into the FEA package DEFORM. Due to geometrical and computational considerations, these initial models were 2D. From these simulations the various stress components were plotted against various variables to determine their influence. Conclusions made from these graphs enabled the selection of an optimum trim die shape. A more accurate attempt to simulate the forging process was obtained using a 3D model. An explanation of the analysis carried out along with the relevant results will be discussed now.

2. Work to date

2.1. FEA considerations and assumptions

The trimming of the bolt head was considered as an axisymmetric problem. This assumption is not completely correct due to the hexagonal hole within the trim die. The reason for considering the problem as axisymmetrical was a necessary first step in predicting stresses. If the problem is considered as axisymmetrical, a 2D FEA model can be sufficiently accurate, and greatly reduce the computational time required in comparison to a 3D model. A 3D simulation of the trim die would be beneficial in the vicinity of the internal hexagonal corners (see Section 3.6), but as this area has the least amount of material to remove, it was decided to consider a plane which would represent the "worst case scenario". In the trimming process analysed, the removal of the maximum amount of material would occur across the flats of the bolt head (see Fig. 2).

A section taken through plane A–A would leave the minimum amount of material to be removed, while the section taken through plane B–B, which passes through the flats of the hexagonal hole, represents the maximum amount of material for removal. Now that the plane for the cross-section had been established, a 2D representation of one half of the trim die can be constructed. Inset of Fig. 2 shows the section taken through a solid 3D model of the trim die, and the face, which was used as the trim die outline for the FEA analysis.

2.2. Trim die modelling program

The trim die modelling program can be broken into two phases:

- Phase 1: revisiting previous models from 1994 [3].
- Phase 2: considered alterations in land width, petal and rake angle.

2.2.1. Phase 1: initial models, earlier work

The standard trim dies were divided into two categories, "compound" and "fillet". Figs. 3 and 4 illustrate the difference between the two categories. The compound trim dies consisted of a larger radius, known as the "Averbach radius" which was held constant, while the blend radius between the land and the inner face was varied between 0.07, 0.1, 0.145, 0.2 and 0.25 mm. The fillet trim die had a simple

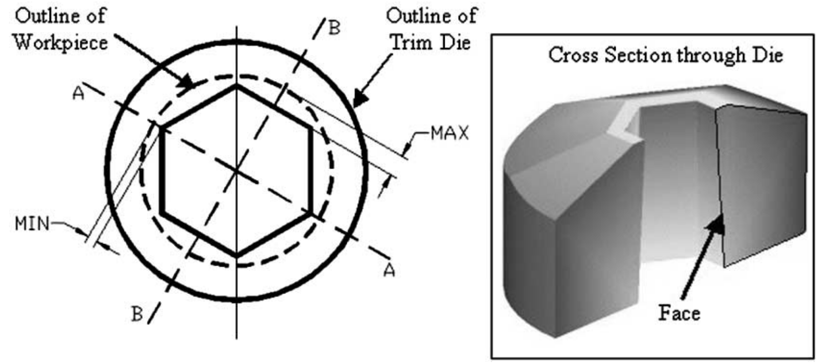

Fig. 2. Plan view of trim die and workpiece: inset: cross-section taken through a 3D model of the die.

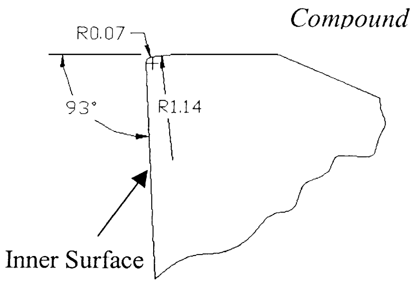

Fig. 3. Detail view of a 0.07 mm trim die.

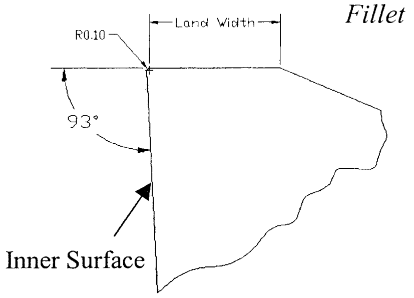

Fig. 4. Detail view of a 0.1 mm trim die.

blend radius between the land and inner face which varied from 0.1 to 0.4 mm in steps of 0.1 mm. The results from this section are discussed in Section 3.1.

2.2.2. Phase 2: further trim die geometrical alterations

Although the results obtained from Phase 1 were encouraging (Section 3.1), it became apparent that some issues had not been addressed. For this reason, it was decided to modify the trim die and consider the effects of such parameters as "land width", "petal angle" and "rake angle". Fig. 5 illustrates the trim die profile showing the location of land width, petal and rake angle. The land width was varied from 0.5 to 1.5 mm in steps of 0.25 mm. The rake angle varied from 1° to 3° in steps of 0.5°, and finally the petal angle varied from 20° to 45° in steps of 5°. A new problem now became apparent with the addition of these parameters, the possible number of combinations for standard trim die geometries increased from 9 to 1350. Due to computational constraints, running this number of simulations was impractical. In an attempt to reduce this large number of die geometries to a workable figure, it was decided to consider FEA computer simulations in which only one parameter was changed (at any one time), to analyse the effect this had on the induced stress within the trim die. The results from these tests are discussed in Section 3.2.

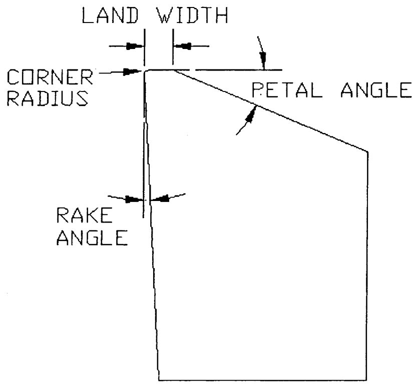

Fig. 5. Trim die profile showing location of land width, petal and rake angle.

3. Results

3.1. Results from Phase 1: initial models

From the phase 1 analyses, the effective stress versus trim die stroke was plotted for both "compound" and "fillet" dies. The "fillet" model, which induced the lowest amount of effective stress, had a blend radius of 0.3 mm. The corresponding "compound" trim die had a blend radius of 0.2 mm [4]. The conclusion from the Phase 1 analyses was that corner geometry consisting of a 0.3 mm fillet blend radius was optimum [4].

3.2. Results from Phase 2: further trim die geometrical alterations

3.2.1. The effect of land width

As discussed in Section 2.2, the large number of possible trim die combinations required reduction. This was achieved by varying only one parameter at a time, while holding the others constant. To study the effect of land width, the corner radius was held constant at 0.1 mm, the petal angle at 20°, the rake angle at 1°. Five models with varying land widths were then simulated to determine what influence each parameter had on the stress distribution within the tool. A feature known as *point tracking* was used, within DEFORM, to acquire the stress components presented in Section 3.2. *Point tracking* allows the user to manually define points within the body of the tooling during the simulation. At these points, all the stress components are recorded for later extraction and analysis. The benefit of point tracking is that it allows comparison of dissimilar models at precisely the same geometric point within both simulations. Ten point tracking points were used for this analysis. The greatest stress values obtained occurred at point one, therefore for this reason, the graphs plotted used values from *tracking point* 1. Fig. 6 illustrates the effective stress versus stroke, at tracking point 1, for the five simulations. Initially all five models recorded high effective stress values (1700 N/mm^2) after approximately 0.1 mm of die stroke. The stresses quickly settled down to a much lower value (500–700 N/mm^2). This can be explained by the fact that a high stress is initially required to cause the material to yield, once this takes place, the necessary stress level within the tooling to maintain

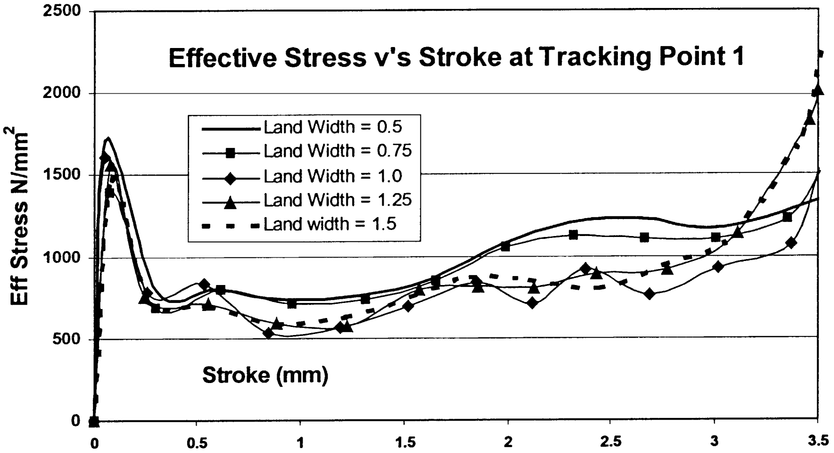

Fig. 6. The effect of land width. Comparing effective stress versus stroke.

yielding is greatly reduced. At a stroke of approximately 1.0 mm, all five models start to follow the same trend. When the stroke reaches between 2.0 and 2.5 mm, a new pattern emerges. The effective stress for the simulation with the largest land width of 1.5 mm starts to increase rapidly, achieving an effective stress value in the region of 2250 N/mm^2. This is dangerously close to the yield stress of the M2 tool material. The reason for this can be explained by the fact that the workpiece material at the end of the stroke is trapped between the trim die and the top tool (see Section 3.4, Fig. 10). The conclusions from this series of tests were that altering the land width had an effect on the induced stresses. Increasing the land width increased the stresses especially at the end of the stroke. Therefore, there is a benefit in keeping the land width as small as practical.

3.2.2. *The effect of petal angle*

Six simulations were performed involving tools with constant corner radii, land width and rake angle. The only parameter remaining, the petal angle (see Fig. 5) was altered from 20° to 45° in steps of 5°. A graph showing effective stress versus stroke for tracking point 1 is illustrated in Fig. 7. As with all the graphs, the initial stress (1700 N/mm^2) required to overcome the resistance of the material to flow is high, and then reduces down to a lower value (1500 N/mm^2). From these results it can be concluded that increasing the petal angle increases the stresses within the trim die. The reason for this is simple. With reference to Figs. 5 and 7, if the petal angle were exaggerated to 90°, the area in contact with the workpiece would be less than if the petal angle were 5°. Stress is equal to force divided by area, therefore, if the contact area is reduced (by increasing the petal angle) the stress within the die will increase. In conclusion, an optimum petal angle of 20° induced the lowest level of effective stress in the trim die.

3.2.3. *The effect of rake angle*

In Fig. 8, the two simulations compared had common corner radii, petal angle and land width. One simulation had a rake angle of 1°, denoted by the line with the square, while the other simulation had a rake angle of 3°. Both simulations experienced the high stresses (1300–1400 N/mm^2) required to overcome the materials initial resistance to flow. Once this occurred the stress level in both simulations dropped. The 1° rake simulation had a minimum stress value of 781 N/mm^2,

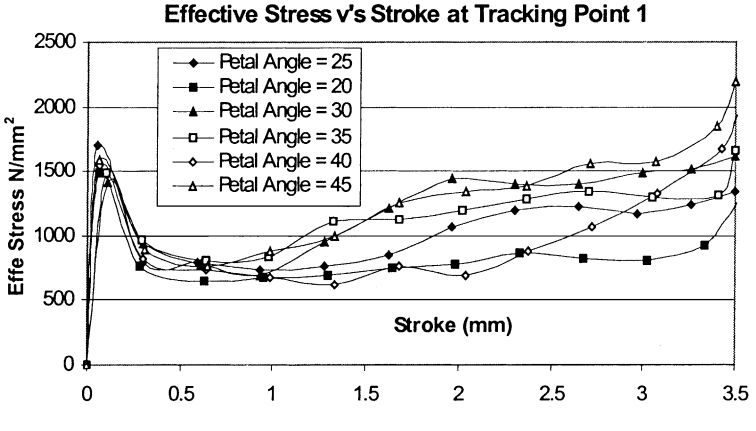

Fig. 7. The effect of petal angle. Comparing effective stress versus stroke.

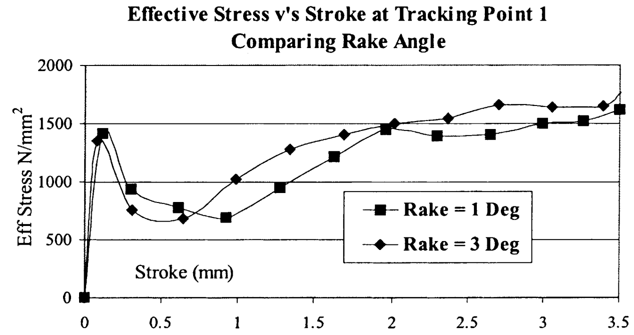

Fig. 8. The effect of rake angle. Comparing effective stress versus stroke.

while the 3° simulation had a minimum value of 676 N/mm^2. The stress levels in both models start to increase at a stroke of between 0.5 and 1.0 mm as seen in the previous graphs, with little to choose between the two over the remainder of the stroke. The final stress values at the end of stroke (3.5 mm) for the 1° and 3° simulation were 1618 and 1763 N/mm^2, respectively. Due to the very similar stress values obtained at the initial, middle and final stages, it was concluded that the rake angle had little effect on the induced stresses.

3.3. *Optimisation of trim die models*

The conclusions obtained from the previous section in relation to land width, petal and rake angle were applied to the models simulated in Phase 1. The land width was held at a constant value of 0.8 mm due to difficulties when using a smaller dimension during production. The petal angle was held constant at 20° and the rake at 1°. This reduced the number of possible simulations from 1350 to 9. These nine models were then simulated and the effective stresses were plotted against each other for investigation. The optimum "fillet" trim die (0.2 mm blend) is compared against the optimum "compound" trim die (0.25 mm blend) in Fig. 9. There is very little to choose between the two simulations, both following the same trends. There is a small difference initially, with the "compound" model, which continues for the majority of the remaining stroke. It was concluded from these graphs that the optimum M6 trim die geometry would have the following details:

- Corner geometry: 0.25 mm compound.
- Land width: 0.8 mm.
- Petal angle: 20°.
- Rake angle: 1–3° dependent on the material being forged.

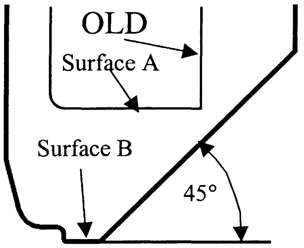

Fig. 10. Old and modified top tools.

3.4. *Modified top tool*

The old top tool had a flat "surface A", which caused the material to become trapped. The modification to this design had a small flat portion, "surface B" followed by a relief angle of 45° (see Fig. 10). This relief angle facilitated the expansion of the trimmed material upwards as well as outwards, during the later stages of the forging process, hence greatly reducing the induced stresses in that region.

3.5. *The effect of friction*

To study the effect of friction, one of the models was chosen and the coefficient of friction varied to see what effect this would have on the induced tool stresses. Fig. 11 illustrates a graph of axial stress versus stroke for a "fillet" trim die. The corner radius was held constant at 0.1 mm, the land width at 0.8 mm and the petal angle at 20°. The coefficient of friction (μ) was varied from 0.05 to 0.15. The three simulated models produced virtually the same amount of stress up to a stroke corresponding to 2.5 mm. From this point on separation begins, the model having the lowest coefficient of friction produces the lowest stress value. This only becomes an issue at the end of the stroke.

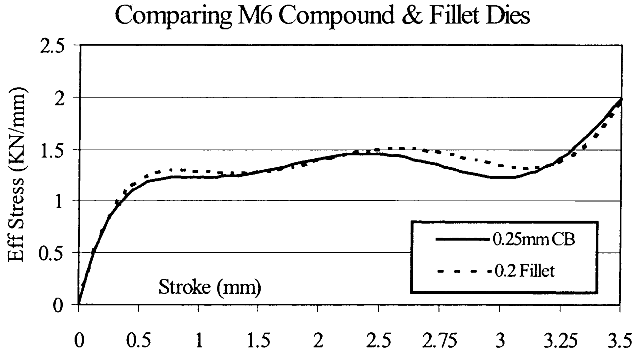

Fig. 9. Comparing optimised M6 compound and fillet trim dies.

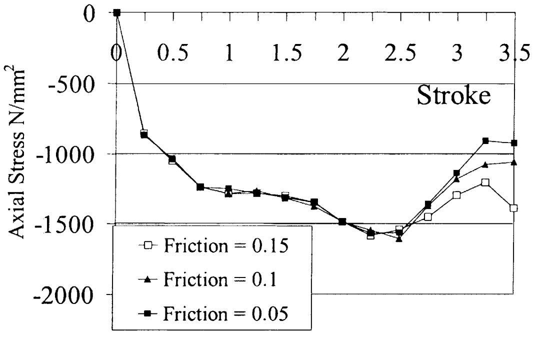

Fig. 11. Varying the friction from 0.05 to 0.15.

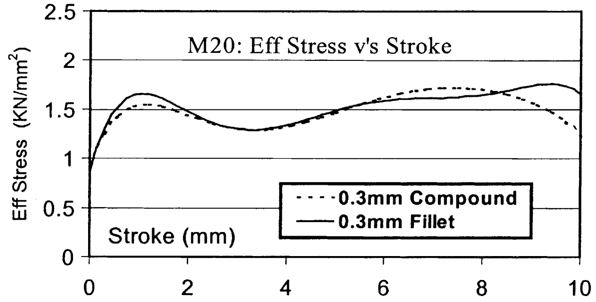

Fig. 12. M20: comparing optimum fillet and compound dies.

The reason for this is because of the ever-increasing surface contact area as the die penetrates into the material. Therefore, as the surface contact area between the tool and the workpiece increases, the coefficient of friction has a greater influence.

3.6. Size effect

All the simulations presented so far relate to an M6 trim die. The question now was what would happen when the size was increased to M20? Taking lessons from the M6 analysis, eight M20 models were simulated and compared to see if they produced the same conclusions.

Fig. 12 shows the graph comparing effective stress versus stroke for the optimum M20 fillet and compound dies. The graph indicates a very similar pattern to the M6 analysis up until approximately 8 mm of the stroke. At this point, instead of the stresses increasing, they actually drop slightly. A possible explanation for this is that at the end of the stroke, separation occurs between the trim die and workpiece. This would reduce the stress value, due to friction, as the area of contact has decreased. This can be better explained by looking at the deformed workpiece shape predicted by the FEA package (see Fig. 13). The conclusion from these size effect studies was that an M20 having a blend radius of 0.3 mm "compound" was optimum. This is due to the lower induced effective stresses at the initial and final stages of the stroke (see dotted line in Fig. 12). The corner geometry on the M20 0.3 mm "compound" trim die is very similar to the M6 blend radius of 0.25 mm. Therefore, both sets of analyses, comparing the M6 and M20, seems to indicate that increasing the size of the trim die has little or no effect on the optimum tool geometry.

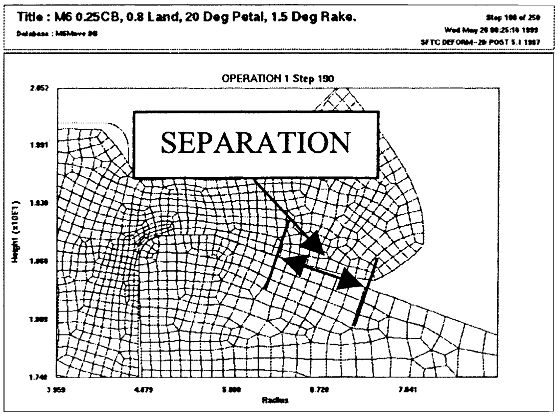

Fig. 13. Separation of contact face.

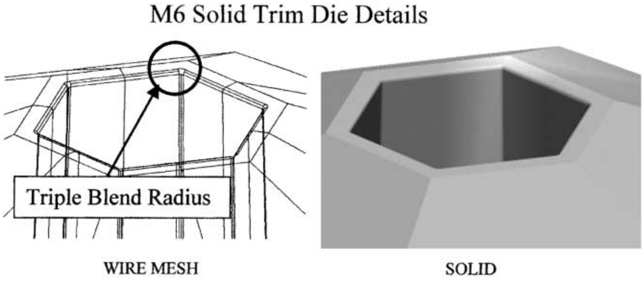

Fig. 14. Detailed view of an M6 3D model showing the area of interest at the triple blend radius.

3.7. Results from the 3D analysis

As discussed in Section 2.1, the initial step was to consider the forging process as a 2D axisymmetrical model. When all the 2D analyses was completed, it enabled a more accurate 3D model to be constructed. This new model could take into consideration the effect that the corners of the internal hexagonal hole had on tool stresses during the forging process. Due to the very complex triple blend radii at these corners (see Fig. 14) AutoCAD was unable to carry out this design. Another CAD package called Mechanical Desktop was used for this task and this enabled the 3D model to be exported in a stereolithography file format, which was required for the 3D version of DEFORM. A detailed view of a 3D M6 model is illustrated in Fig. 14. The difficulty with complex 3D models like this is the computational solution time involved. For this reason this initial 3D model was simulated, instructing the computer to consider the top tool and trim die as "rigid". This tells the FEA program not to take into consideration the stresses in these objects. Even with this stipulation, the run time was considerable. Although the trim die was considered as rigid, and the fact that it was the first attempt to model this forging process in 3D, the results obtained for the predicted workpiece geometry shows a close resemblance to an actual fastener geometry (see Fig. 15). One possible way, to reduce the computational

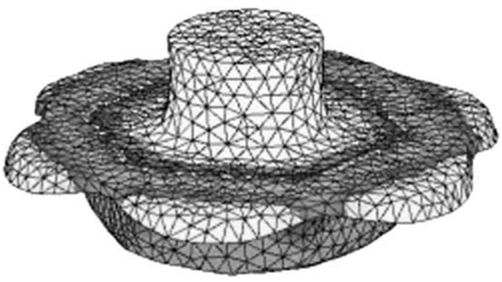

Fig. 15. Isometric view of fully deformed M6 workpiece.

time, would be to only consider one-sixth of the total model, but this solution would require the implementation of complex boundary conditions. In conclusion, although the run time on these models is extensive, it is a necessary step to realistically simulate the trim die forging problem.

4. Conclusions

All the analyses to date have been theoretical, no experimental verification of the FEA predictions has yet taken place. This experimental testing is essential to provide confirmation and confidence in the results. Discussions with bolt manufactures have indicated that the conclusions stated below are accurate. With reference to Fig. 5, the following conclusions can be stated:

- Altering the land width has an effect on the induced stresses, especially at the end of the stroke. The larger the land width, the greater is the induced stress.
- The petal angle should be held constant at the smallest angle possible.
- Altering the rake has little or no effect on the induced stresses. This value is dependent on the flow behaviour of the material being forged.
- The following trim die parameters, if held constant, have been shown to reduce the level of stresses within the tooling during the forging process.
- Corner geometry: M6, 0.25 mm compound; M20, 0.3 mm compound.
- Land width: 0.8 mm.
- Petal angle: 20°.
- Rake angle: 1–3° dependent on the material being forged.

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