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Tool life in cold forging – an example of design improvement to increase service life

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Abstract

The production cost for cold forgings depends significantly on the tool life. This paper summarizes an investigation of different alternatives to improve the life of a tungsten carbide insert used in a cold forming operation performed on an automatic cold header. These alternatives were as follows: (a) double tapered insert, (b) split insert design, and (c) change of insert material. Although, the techniques were applied to a specific case, they might he applicable to other cold forging tooling. To improve the life of the insert, the metal flow and stress analysis of the carbide insert was conducted using the commercial FEM software DEFORM. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Cold forging; Tungsten carbide; Insert

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1. Introduction

Due to the high forging loads and tool stresses, cold forging is one of the most demanding metal forming applications. Therefore, the success of the cold forging process depends upon both the selected tool materials and the die design.

Emphasis is put on finding materials with a combination of high strength and toughness to withstand the high forging pressure typical of cold forging [1]. Tungsten carbide inserts are used in numerous applications of this sort. However, the resistance of carbide to fail by fatigue is greatly reduced if there are tensile stresses present in any portion of the tool during the forging cycle. Therefore, it is important to free the carbide tooling of tensile stresses or at least lower them to the minimum value allowed by the economics of the process.

It should be noted that the properties of carbides are being improved to give more ductility, and therefore more toughness, while keeping its hardness and wear resistance [1]. Also, little is known about the fatigue behavior of carbide, except its reduction in strength due to tensile stress [2]. Therefore, at this moment it is only possible to improve on the carbide tooling in cold forging processes by reducing or eliminating tensile stresses. To perfect the process more research and knowledge on the fatigue failure of carbide is needed.

1.1. Fatigue failure of cold heading die

This paper describes the failure of tungsten carbide insert used in the second operation of an automatic cold header. The insert was used in the process of making an AISI 1015 tubetitting component. At the time this paper was written, the insert life was approximately 50000 parts before it failed in the radial direction. Fig. 1 shows the insert and the point of failure.

1.2. Objectives and approach

The main objective of this research is to improve the tool life of the carbide insert for the above-mentioned process. However, the ideas given in this report can be used to solve similar problems where carbide tooling fails prematurely.

The approach taken to solve the current problem was first outlined by Knoerr et al. [3], to analyze the fatigue failure of a hot forging die for an aerospace component. This approach consists of the following tasks:

- Process simulation to determine the point of highest load during a forging cycle and the corresponding contact stress distribution at the die workpiece interface.

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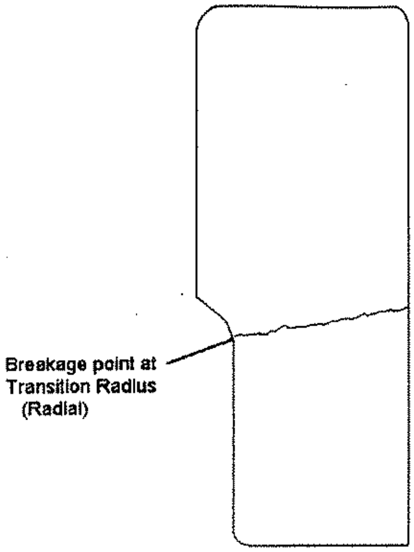

Fig. 1. Current insert design and breakage point.

- Stress analysis of the tooling using the previously determined stress distribution as load input data.

In both cases the software DEFORM could be used to perform the simulations.

After the steps above were followed the simulation results were studied and possible solutions were generated. Then, stress analysis was performed for each possible solution to test its feasibility. Finally, based on the above procedures and practical experience, several feasible alternatives to the current insert design were found.

2. Die failure of forming dies in automatic cold headers

The leading cause of failure in tooling used to produce highvolume cold forged parts is fatigue [4]. In this case specifically, fatigue failure occurs at the transition radius as shown in Fig. 1. The cause of this failure is due to the tensile maximum principal stresses near the transition radius. Before loading, the maximum principal stresses are compressive due to the pre-stress imposed by the shrink ring. However, under the forming load the maximum principal stresses reach high tensile values at the transition radius. Consequently, cracks are initiated and propagate if these stresses exceed the tensile yield strength of the tool material [4]. To solve this problem, the tensile stresses must be reduced to insignificant values or compressive values. If this cannot be accomplished then a tougher material must be used.

In high volume, closed die cold forging applications, resistance to wear is very important. The material commonly used in these applications is tungsten carbide. Tungsten carbide inserts are made by powder metallurgy (PM) techniques, which give them a high hardness and consequently, good wear resistance. However, as mentioned previously, tungsten carbide cannot withstand high forging pressures that cause tensile stresses during the forging cycle. Tungsten carbide's good wear resistance is useless if these tensile stresses are not reduced or eliminated.

While the tooling material chosen can have a significant effect on the life of the tooling, the design of the tooling is more important to the success of the cold forging application. If the tooling is designed incorrectly, choosing a different material may increase the tooling life, but until the tooling design is improved, the optimum output for the tooling might not be achieved. In industry today, the process to designing tooling has not changed much from the past. Designers rely on formulas, standards, and experience to aid them in their tasks. However, many times problems wit the tooling design arise during tryout and these must be corrected. Thus, the tool design process is driven by trial and error, which can be costly and time consuming.

An alternative to this procedure is the use of FEM analysis. An FEM software such as DEFORM could be used to calculate the forming load, investigate die fill, and also perform stress analysis of the tooling to determine any possible problems. This software can help the designer detect problems in advance before the job is actually run. Cost savings may be obtained from the avoidance of scrap parts, less machine downtime, less man–hours, and lower material costs. Plus, the design engineer may spend less time fixing problems and more time on new jobs, which might shorten the development time of new parts.

3. Metal flow simulations for forming process

Since the carbide insert in question is used in the second operation of the cold heading process, information like strain hardening and workpiece geometry must be transfer from the first die operation. The problems that may arise in the second operation could be caused by the first operation of the heading process. Consequently, the first deformation stage of the heading process must be simulated to carry the strain hardening of the workpiece to the simulation of the second operation. Fig. 2 shows a schematic of the process for the first two heading operations.

The tooling and billet geometry imported into DEFORM for the first operation are shown in Fig. 3. Due to axisymmetry only half of the geometry for each component is shown. The setup consists of the front die insert, the hammer pin, the knockout pin, and the geometry of the billet after cutoff. It

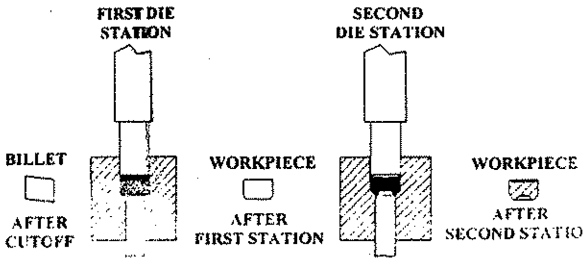

Fig. 2. Heading sequence (first and second stations).

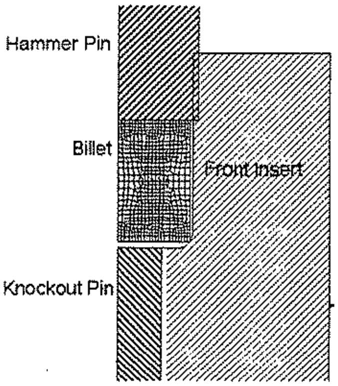

Fig. 3. Tooling and billet geometry – first operation cold header.

should be noted that in the actual process the billet shown in Fig. 3 is not a perfect cylinder, however, the billet used for the simulations is based on the average volume given by the tolerances of the billet alter cutoff. All the tooling in this simulation was assumed to be rigid since we are mainly concerned with the material flow and geometry of the billet. The billet was considered to be plastic. The billet material used is AISI 1015.

In the simulation the hammer pin moves down to form the billet into the shape of the insert. The billet geometry after the first operation is shown in Fig. 4. A forming load of 27.6 t was calculated for this operation.

The tooling for the second operation and existing billet geometry imported into DEFORM for the second simulation are shown in Fig. 5. In heading sequence used by the manufacturer (see Fig. 2), after the first operation, the fingers grab the billet and rotate it 180° in a circular path. Since the workpiece in the simulation cannot be rotated, the front insert for the second operation must be rotated 180° from the position of the insert for the first operation.

Also in this simulation the tooling is assumed to be rigid and the billet plastic. The last step of the simulation for the second operation is shown in Fig. 6.

Notice that load increases significantly at the end of the forging process as shown in Fig. 7. This is due to overfilling of the die. Using the load at the end of the stroke could lead to misleading results in the stress analysis of the tooling. It was determined that at 98.7% of the stroke (step 180) the shape of the workpiece from the simulation is very close to geometry of the actual part. The billet geometry and die fill

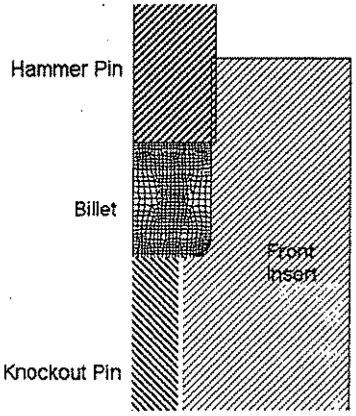

Fig. 4. Geometry of the workpiece after the first operation (100% stroke).

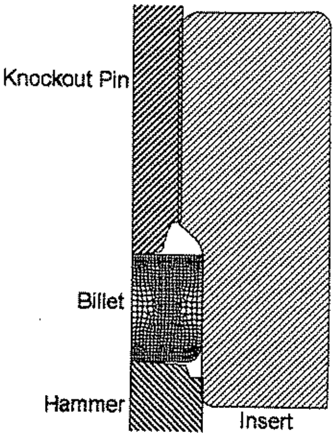

Fig. 5. Tooling and billet geometry – second operation cold header.

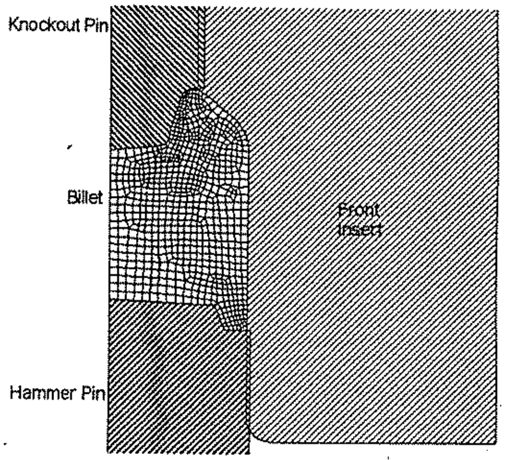

Fig. 6. Die fill and workpiece geometry after second operation (100% stroke).

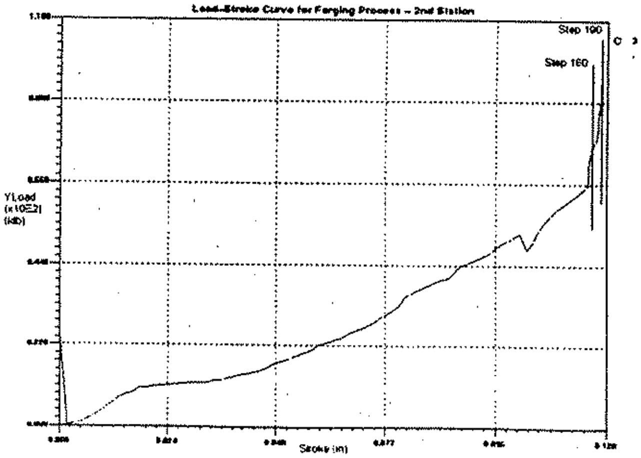

Fig. 7. Load-stroke curve for forging process (second station).

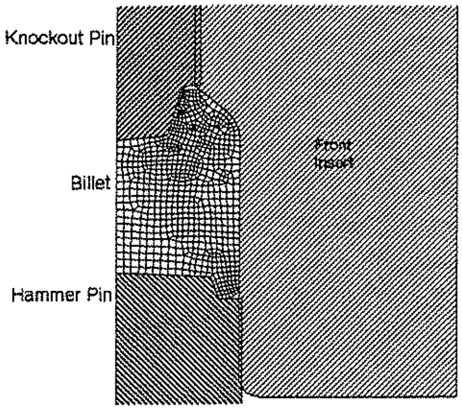

Fig. 8. Die fill and workpiece geometry after second station (98.7%).

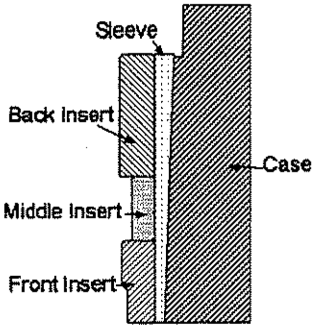

Fig. 9. Die assembly for the second operation.

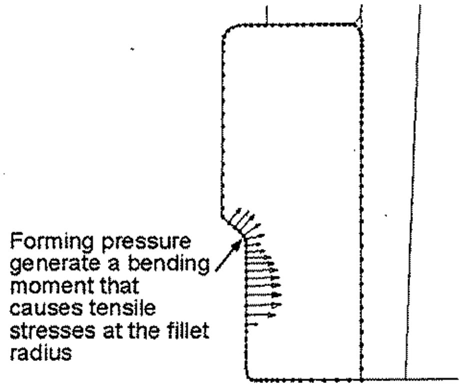

Fig. 10. Forces interpolated from the workpiece.

for this assumption is shown in Fig. 8. A forming load of about 38.0 t was calculated for 98.7% of the total stroke in the simulation.

4. Stress analysis of current die design

After metal flow simulations were completed and studied, the emphasis was put on the stress analysis of the current carbide insert design. Since there are no premature failure problems for tooling of the first operation, stress analysis of it was not conducted.

To perform the stress analysis of the second operation the die assembly shown in Fig. 9 is needed. This includes the case, the sleeve, the middle insert, the back insert, and the front insert.

Since the back insert does not interact with the front insert it was modeled as rigid while all the other components were modeled as elastic.

The Young's Modulus and Poisson's Ratio are required for the DEFORM simulation. The shrink fit between the case and the sleeve was simulated by a radial interference of 0.055 in. on the OD of the sleeve.

The forming loads generated by the forging process were interpolated to the surface of the front insert from the material flow simulation of the second operation as shown in Fig. 10.

Fig. 11 shows the maximum tensile stresses in the carbide insert during the forging process. At the point of failure the

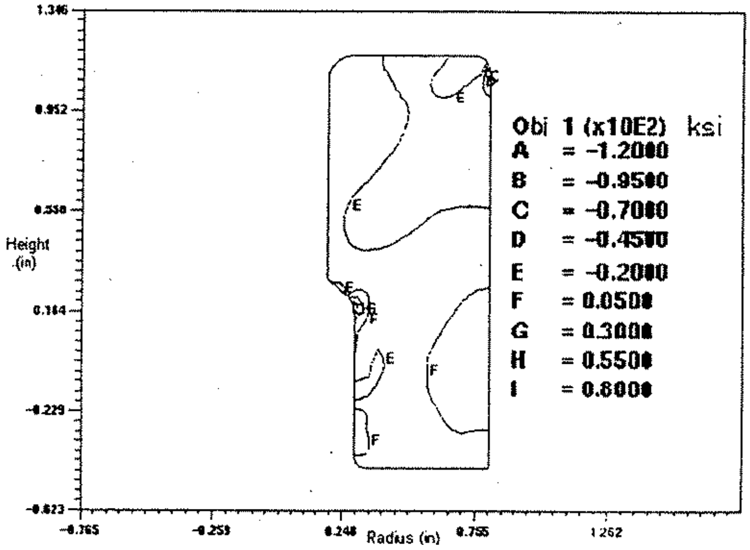

Fig. 11. Maximum principal stresses (98.7% stroke).

highest maximum principal stress is tensile (78 ksi). These stresses are primarily caused by high axial tensile stress (69 ksi) rather than the tensile hoop stress (30 ksi). Thus, a larger axial pre-load is needed.

Therefore, due to the cyclic nature of the loading (stresses at the point of failure) DEFORM predicts that the insert will fail by fatigue at the transition radius as in the actual insert. It should be noted that another simulation was run using the maximum possible interference between the sleeve and the case (0.8% of the sleeve OD). For this simulation the maximum principal stresses were reduced, but not by a significant amount.

5. Proposed solutions to improve die life

5.1. Use of tougher insert materials

The change of the insert material could only be successful if the new material has a hardness comparable to carbide, but with higher ductility. A tungsten carbide is being developed with a nanophase structure, which keeps the hardness of PM tungsten carbide, but is more ductile. At the present time general carbide was still in the development stage of such material, so very little information is available. It is believed, however, that it will be useful in the future for cold forging applications [1].

Other materials that have the properties discussed above include commercial AISI M4 and a steel bonded carbide. The properties of these two materials are shown in Table 1 along with the properties of the tungsten carbide that is currently used. Both of these materials have about the same hardness as the tungsten carbide, but they have a higher transverse rupture strength, which indicates that the material is more ductile. Therefore, it will withstand tensile stresses better than tungsten carbide. Consequently, the insert may have a longer life.

The drawbacks to changing the material to a more ductile one include:

- A loss in the ability to keep tight tolerances due to the increase in deflection of the tool.
- The transverse rupture values for the alternative materials are not significantly larger that for tungsten carbide, thus the insert life may not increase considerably.

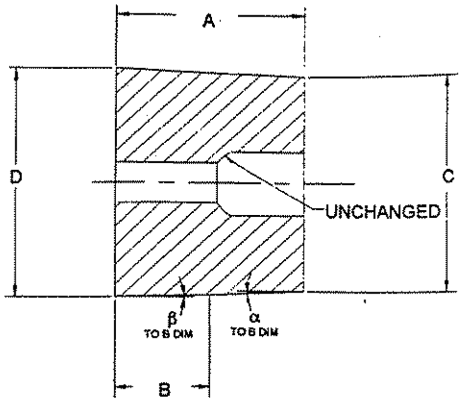

Fig. 12. Insert design for variable interference.

Therefore, changing the die material would only be necessary if the tensile stresses in the tool could not be reduced to compressive or minimal values by redesigning the tooling of the heading operation.

5.2. Insert design with variable shrink fit interference

A tooling design with complex variable interference was suggested by Nagao et al. [5], to induce compressive stresses at the transition radius of a die to cold forge the outer race of a constant velocity joint. However, in this case the cost of such tooling would not be justified. A simpler design to achieve the variable interference is shown in Fig. 12. This design consists of machining two tapers at angles β and α where $\beta < \alpha$. The tapers intersect at the distance B from the base of the insert. The optimum values for these parameters were found by performing a sensitivity analysis with the aid of the simulation.

Fig. 13 shows the assembly of the insert in the tooling set up. Notice that the insert is in direct contact with the case. The sleeve used has been shortened and is only used to produce the interference on the middle insert. The tapers machined on the insert OD together with the interference with the case produce an axial pre-load. The resulting variable interference is also shown in Fig. 13. Notice that the interference is not uniform along the length of the OD of the insert. The interference is highest at each end and steadily drops off toward the middle of the insert. This results in a "bending" effect that causes a higher compres-

Table 1
Properties for selected die materials

	General carbide 25% cobalt tungsten carbide	Crucible CPM REX M4HC(HS)AISI M4	National machinable carbide NMC WC35 steel bonded carbide
Modulus of elasticity (psi)	64×10^6	31×10	39×10^6
Hardness (Rc)	66	63.5–65.5	60–66
Transverse rupture strength (psi)	430 000[a]	550 000[a]	480 000[a]

Note: all properties were obtained from the manufacturer.
[a] Value was found using a three-point bending test.

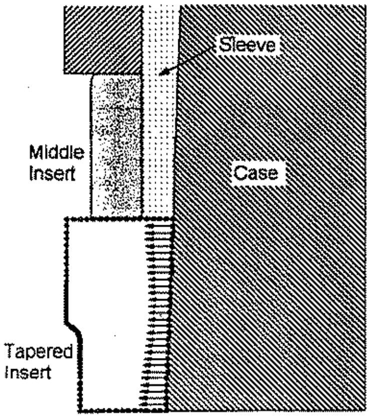

Fig. 13. Tapered insert design with variable interference.

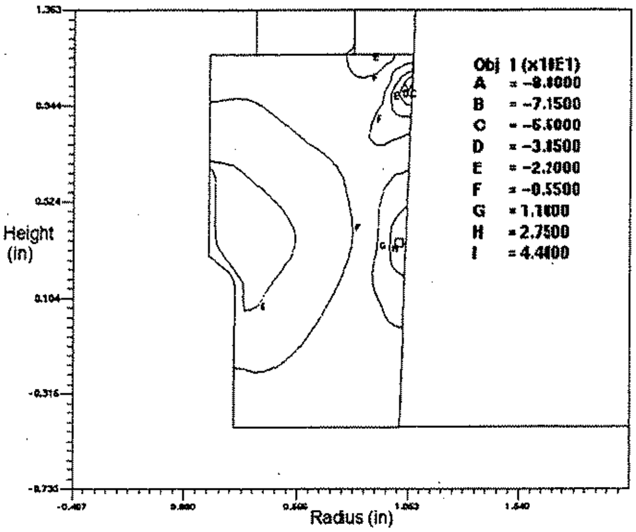

Fig. 14. Maximum principal stresses for proposed tapered design.

sive pre-loading stress at the transition radius than that achieved with the current design.

The simulation results for this design are shown in Fig. 14. Notice that the maximum principal stress at the transition radius is now compressive. However, the maximum principal stresses reach positive values at the middle of the OD of the insert. Fig. 15 shows the pre-loading stresses, i.e., due to shrink fit alone. The maximum principal stress at the middle of the OD of the insert is relatively the same as that achieved at the end of the forging operation. This indicates that the stresses at this location are not. Therefore, it is unlikely that this design would fail by fatigue at this location.

5.3. Split insert design at transition radius

A commonly used alternative when failure at the transition radius appears in cold forging tooling is to split the insert at the location where the maximum principal stresses reach the highest value. The geometry for this tooling is shown in Fig. 16. Notice that the top insert does not contact the entire surface of the bottom insert. This is due to the 1.5° relief angle at the bottom of the top insert (see Fig. 16). This

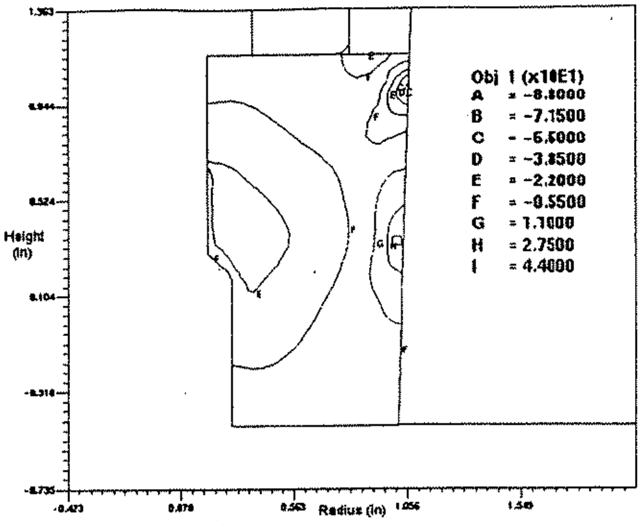

Fig. 15. Maximum principal stresses due to shrink fit (no heading forces).

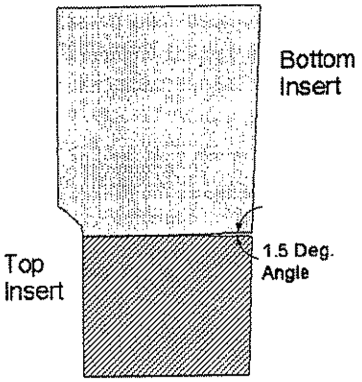

Fig. 16. Geometry of split insert design.

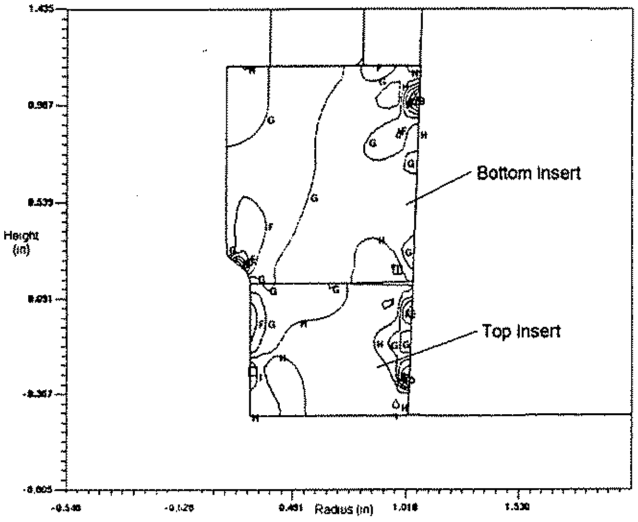

Fig. 17. Maximum principal stresses for proposed split die design.

relief angle is used to achieve a higher contact pressure at the inserts interface and constrain the movement of the insert so that a mark is not produced on the forging.

The shrink fit interference used on this design is uniform along both parts of the insert. However, for this design a larger radial interference is needed to prevent the failure of the insert due to high hoop stresses. A standard of 1.2% (0.013 in.) radial interference was used for the stress analysis.

The results of the stress analysis are shown in Fig. 17. The maximum principal stresses have been reduced to compressive values at the transition radius. As in the previous design, some tensile stresses have been obtained, but are not located at a point where fracture is likely to occur.

6. Cost analysis

A cost analysis was conducted on the carbide insert to justify the time required to investigate how to improve the tool life of cold header tooling. Table 2 shows a cost analysis conducted on the carbide insert. It should be noted that this table only shows the costs associated with the replacement of a broken insert failure. Indirect costs are also important and may even be larger. Indirect costs associated with the die failure are:

- scrap produced;
- labor and engineering time to solve the problem;
- production delays.

Production delays might be the most important because it could lead to unsatisfied customers and the lost of future orders, i.e., from several thousand to millions of dollars.

This justifies both the implementation of the designs discussed in present paper and the purchase of computer aided software for the analysis of both the metal flow and the stresses in the tooling. For a cold forging company with large consumption tooling the costs savings achieved by optimizing the die design with FEM software could be considerable.

Table 2
Cost analysis of carbide insert

Tool failure – estimated annual cost	
Annual usage	40
Carbide insert cost	\$150
Machine run cost/Hr	\$85
Assembly cost/Hr	\$25
Total cost	
Insert	40×\$150=\$6,000
Assembly	40×.5 Hrs×\$25/Hr=\$500
Equipment downtime	40×1 Hrs×\$85/Hr=\$3400
	\$9900
Improve tool life by 25% – will save	\$1237.50
Improve tool life by 50% – will save	\$2475.00

7. Conclusions and recommendations

The following steps have been introduce to improve the life of cold forging inserts:

- Use FEM software to prevent any flow related defects that may affect the performance of either the forging operation or the product.
- Once flow related problems have been solved perform a stress analysis on the tool to determine possible failure sites.
- Change the design of the tooling based on the stress analysis to minimize the possibility of failure occurring.
- Perform stress analysis of the new design and compare with original design.
- If the implementation of the new design is not economically feasible select a more ductile tool material. This may increase the tool life.

Based on the evidence presented in this paper it was concluded to change the insert design to either an insert with variable interference or a design with the split insert. The choice between the two depends on the cost and ease of manufacturing for each design. If neither design is found to be a feasible alternative for the manufacturer, a material change is recommended. At the time this paper was prepared the insert with variable interference was being tested.

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