

# Optimization of cold forging process technology by means of simulation

*Hendrik Muntinga*

Hendrik Muntinga Ingenieurbüro, Rosenthal, Herscheid

*Nikolai Biba, Sergei Stebunov*

QuantorForm Ltd, Moscow, Russia

**Abstract:** The paper presents an approach to increasing of cold and warm forging process quality and economical efficiency by means of computer simulation. The main ways for achieving of stable product quality, long tool life and high accuracy are analysed. The technology improvement is reached by modification of perform and die design that eliminates flow induced defects, reduces stress concentration in critical areas through optimising of fillets and/or introducing splits in combination with shrink rings and hard inserts. Finite element simulation allows finding optimal value of interference that provides compressive stress state in hard but fragile inserts under actual forging load. Simulation also generates profiled shape of the die that compensates elastic deformation of tooling set and provides precise geometrical accuracy of a forged part. Ductile fracture of the forged part can be predicted and minimised by means of simulation. Presented model is realised in commercial metal forming simulation program QForm.

## 1. Introduction

Besides of great advantages, cold forging technology has drawbacks that make its implementation sometimes difficult. They are:

- Potentially higher contact stress that may cause tool fail or excessive tool deflection
- Probable fracture due to deformation limit of cold material

Nevertheless the practice shows that these drawbacks can be minimised by means of

- Optimal design of preforming operations to avoid flow induced defects, reduce contact stress and fracture probability
- Optimisation of die assembly to provide longer tool life and to keep die deflection within tolerance

Numerical simulation is the most effective way to reduce the cost and development time required for such optimisation. Meanwhile specifics of cold forging apply special requirements to the simulation software. Particularly they are:

- Especially effective automatic adaptive remeshing is necessary for simulation of the material flow in the dies with small fillet radii that are typical for cold forging
- Advanced capabilities for simulation of complex pre-stressed tool sets are required as a routine option including tool life prediction due to cycle fatigue and die wear
- Reliable damage prediction facilities are necessary for optimal design of preform shapes to reduce fracture probability

Forging simulation program QForm developed by QuantorForm Ltd. [1] completely fulfils the above requirements. The program is based on the most modern and sophisticated programming technique and advanced FEM algorithms. QForm is the next generation forging simulation software and has the following main features:

- QForm is object-based and naturally integrated with Windows environment. Graphical interface makes it clear and easy even for PC users of begin level.
- The user operates the program for simulation of 2D and 3D problems through the same interface.
- Completely integrated architecture of QForm provides synchronous work of all parts of the program (all-in-one design). Pre-processing is performed in parallel with source data preparation that makes user's work vivid and understandable. The user is guided by so-called Data Preparation Wizard that eliminates possible mistakes or missed data.
- Meshing and re-meshing is absolutely automatic and the program never requires user's interference during simulation. There is no access to specific simulation control parameters in QForm at all. It makes accuracy of simulation independent of user's qualification.
- Post-processing is performed concurrently with the progress of simulation that allows immediately to interpret the results.
- The user works not just with simulation of a single forming operation (blow) but with complete technological chain that includes the sequence of blows separated by intermediate cooling/heating or clipping/piercing operations. Simulation of such technological chain is performed automatically without user's interventions that makes "what if" analysis very fast and effective.
- Reliable and accurate import of source geometrical data from CAD systems through STEP and IGES formats as well as direct interface.
- Facilities to pierce the holes and trim the flash between forming operations.
- Manual and automatic positioning of the workpiece on the dies.
- Simulation of workpiece motion as a rigid body subject to gravity, friction and inertia to find out its stable position before forming simulation (gravitational positioning).

The software is easy to learn and very reliable in everyday use. The user friendliness of QForm is boosted by effective remote support via Internet that works perfectly regardless of distance between the user and the supplier and ensures minimal time losses.

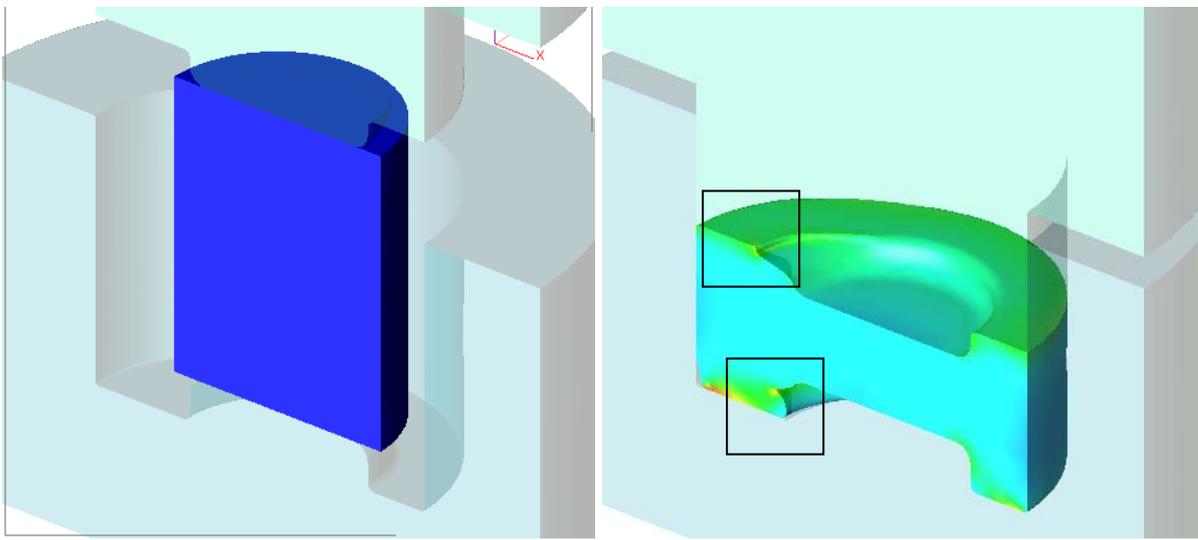
## 2. Material flow optimisation in cold and warm forging

### 2.1. Avoiding laps

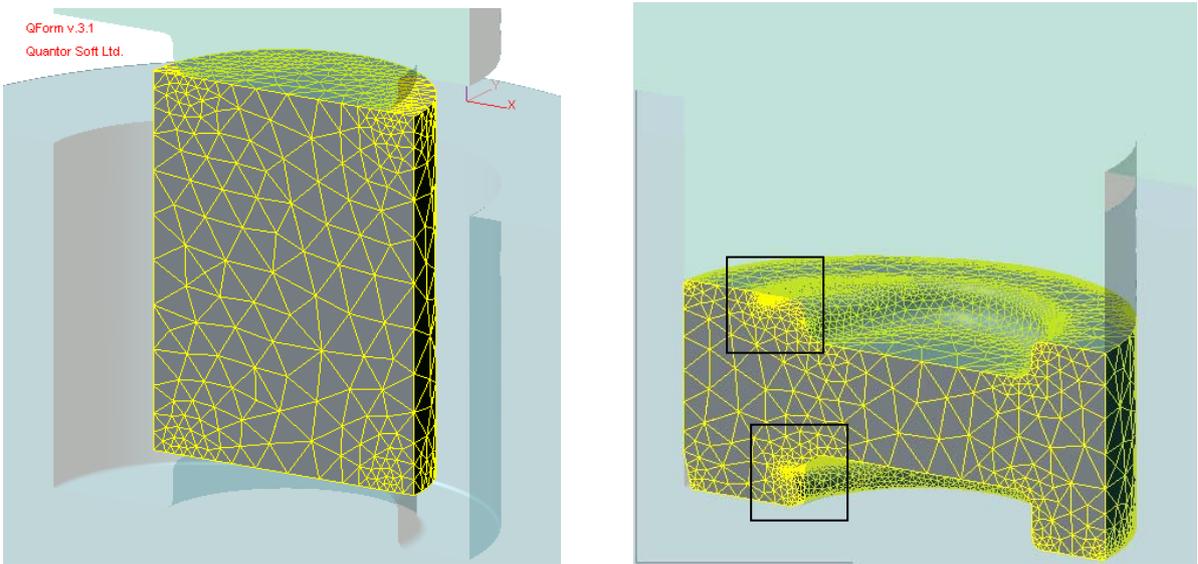
In certain conditions of deformation the material can buckle causing collapse of free surface resulting in laps and folds. *Laps are the defects that appear when free surface of material folds over itself.* From practical point of view the laps are very annoying kind of defects because they tend to appear each time when we want to intensify deformation for cost reduction, for example, when we try to skip preforming operation. The lap can occur in rib-web forging at a variety of locations where the rib may buckle. Sometimes laps can appear when we try to upset a billet with diameter to height ratio within admissible limit but due to small deviations from ideal shape or non-parallel cuts the billet may buckle.

The fully automatic finite element mesh generation implemented in QForm ensures simulation of surface-to-surface contact that happens in a lap area. It is very important for reliable prediction of this defect. The program automatically increases mesh density in critical area when the surface starts to collapse.

This feature is illustrated by practical example of warm forging of the cam of oval shape with two round off-centre cavities of different depth. This is 3D problem. When using cylindrical billet the material first fills the shorter "arm" of the cam and then flows in circumferential direction towards its long "arm" and the laps occur on its upper and lower surfaces (Fig 1 b). The pin on the lower die is higher than on the upper die and lower lap is more developed than upper one. The program automatically detects the zones where the lap potentially may occur and automatically increases the mesh density there (Fig 2.b). Thus the program is able to detect the finest peculiarities of the material flow and is very sensitive.

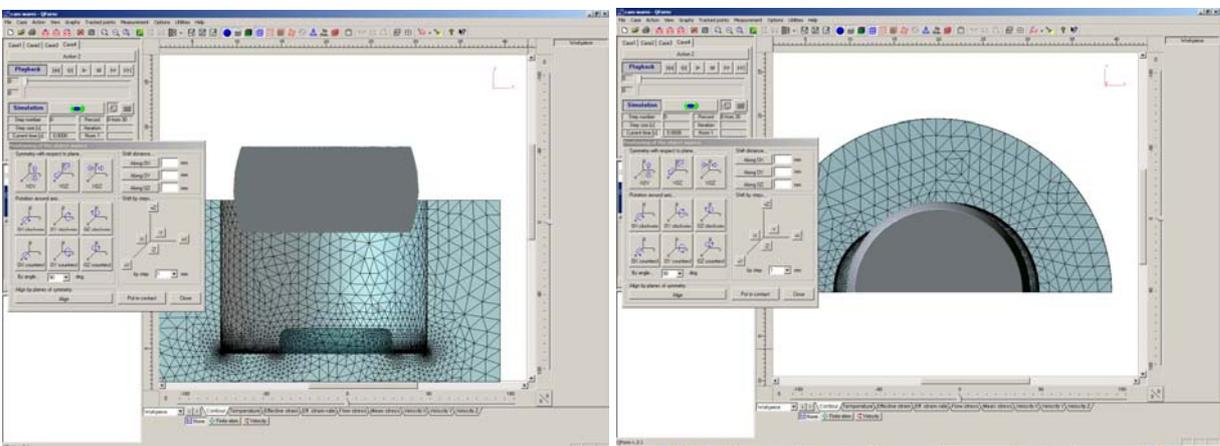


a.   
 b.   
 Fig.1. Cam forging using cylindrical billet (a). The laps are shown in the boxes (b).



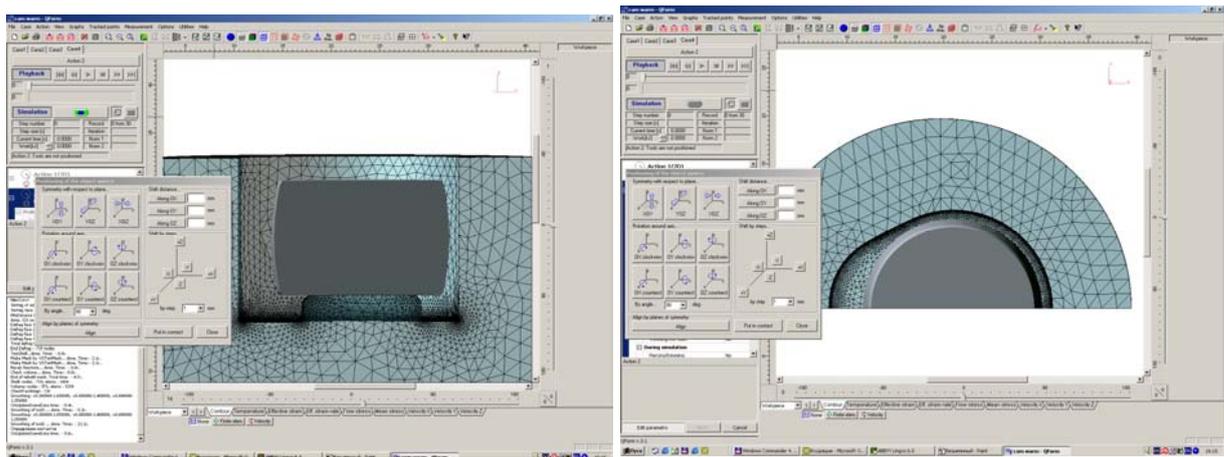
a.   
 b.   
 Fig. 2. Cam forging. Mesh density increases in the zones where the laps occur (in the boxes).

To avoid the laps the billet should be upset and then placed into the die. Meanwhile the height of upsetting is the question because the billet must fit into the die as accurate as possible. It is difficult to guess the optimal height just using volume constancy rule because of barrelling the billet may not fit the dies as shown on Fig. 3.



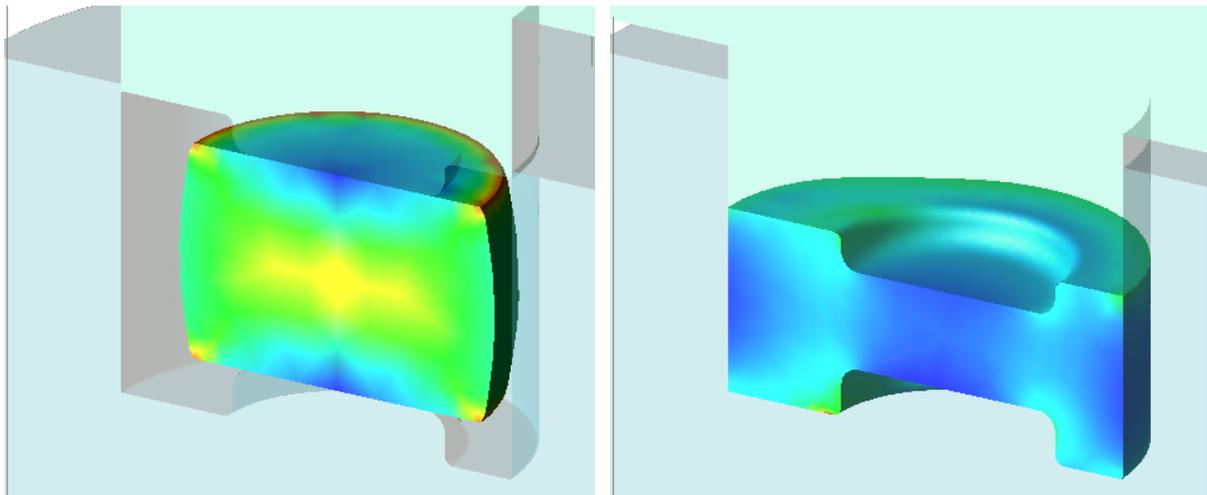
a.   
 b.   
 Fig. 3. The upset billet that does not fit the dies: front view (a) and top view (b).

Using QForm it is easy to select the height of upsetting that allows the billet to fall into the die. To be the most close to reality the program also can simulate gravitational motion of the billet that allows to find its stable position on the lower die (Fig.4).



a. b.  
Fig. 4. Optimal shape of the billet after upsetting that provides its stable position in the lower die: front view (a) and top view (b).

The simulation has shown that using upset billet that exactly fits the die the material flows without laps providing the product of sound quality (see Fig. 5b comparing to Fig 1b).



a. b.  
Fig. 5. Forging of the cam using upset billet: initial position of the billet (a) and its final shape (b).

## 2.2. Detecting and fixing flow-through defects

Flow-through defect occurs when the material is forced to flow past a recess after it was filled or regions that have stopped to deform because of chilling. As written in [2] “*Similar to laps in appearance*, flow-through defects may be shallow but indicative of an undesirable grain flow patterns or shear band that extends much father into the forging”. *It is important that in flow-through defect there is no collapse of free surface*. Meanwhile this kind of defect can be reliably detected by means of simulation.

Let us investigate a forging defect that appears in aluminium part produced in one blow. This is round part and can be simulated in 2D. The picture on Fig. 6,a shows its cross cut. There is a circular defect around the central area that looks like a crack or, maybe, a lap. The shape of the defect is better seen on magnified right picture (Fig 6,b). Thus just looking at polished cross cut it is difficult to say what particular kind of the defect we have, how to classify it (crack, lap or flow-through defect) and how to fix it.

On the picture of macrostructure (Fig. 6a) we see the zone of extremely intensive shearing deformation that begins from the defect. It means that the defect was caused by intensive shearing deformation. The small “crack” (Fig. 6b) is just visible part of the defect while it goes deep into the billet body.

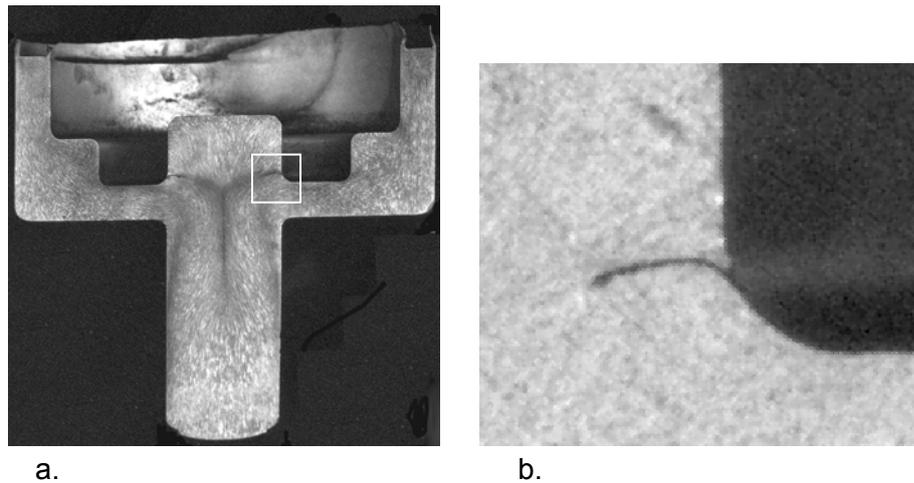


Fig. 6. Cross cut of aluminum part after surface etching. General view (a) and the area in the box that is magnified to show the defect (b).

Simulation shows that the defect appears in the area where there is no free surface. Looking at the series of pictures (Fig. 7) we see that at initial stage the upper part of die cavity was completely filled. Then the material flows downwards filling the lower die.

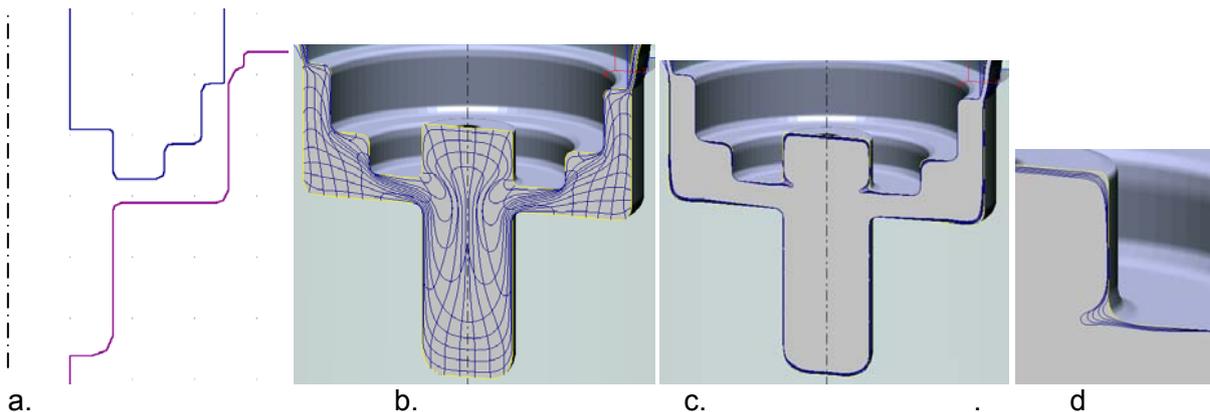


Fig. 7. The sketch of the dies in the area of the defect (a), vertical and horizontal flow lines (b), under-surface flow lines detecting the defect location (c), magnified fragment of the defect area (d).

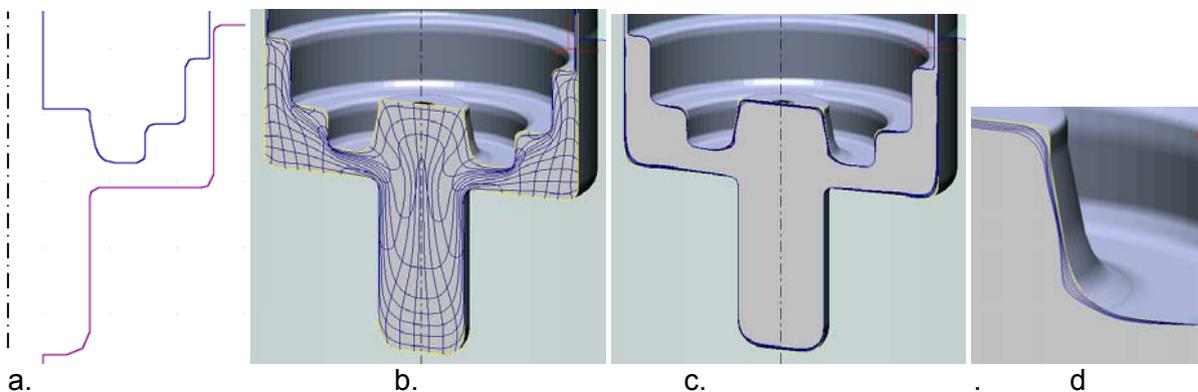


Fig. 8. The sketch of the modified upper die (a), vertical and horizontal flow lines (b), under-surface flow lines showing no defect indication (c), magnified fragment of critical area (d).

This flow pattern causes flow-through defect. On the contrary to lap, flow-through defect has no indication by red line created by the program but it can be detected by means of “under-surface” flow-lines that are available in QForm. These lines are generated along billet surface

in its initial configuration. In regular deformation they flow with the material keeping their location close to the surface. In the case of irregularities such as material flow directed inside the billet body, under-surface lines change their shape indicating penetration of the surface layers inside the material (compare their shape on Fig. 7b with the photo on Fig. 6b).

Understanding the reason of the defect it is possible to fix it by means of correction of die design as shown on Fig. 8. Using bigger draft angle and bigger fillet radius on the upper die it is possible to avoid material flow inside the billet body and provide sound quality of the product in critical area (Fig. 8d).

### 3. Optimal design of assembled dies

In cold forging technology the tooling design is critical both from technical and economical points of view thus increasing of tool life and reduction of tool cost is vitally important. The dies can failure due to cracks caused by overloading, low cycle fatigue or abrasive wear. On the other hand, due to high contact load the elastic die deflection may considerably deteriorate the shape of the forged part. To prevent premature die fracture and its excessive deformation the pre-stressed dies are usually used. Meanwhile to utilise the advantages of pre-stressed dies their parameters must be optimised.

The dies with inserts and pegs as well as shrink fitted dies are widely used for increasing of tool life. They have several advantages. Firstly, inserts can be made in a higher grade of die steel. Secondly, when insert is replaced it is not necessary to re-machine the other parts of the die. Thirdly, shrink fitting (pre-stressing) of dies increases their load carrying capacity by creating compressive stresses in the shrunk insert, which oppose the tensile stresses occurring during forging.

The design of die assembly is a complicate task and usually empirical rules are used for the development of the shape of the assembly parts and setting required shrinkage between them. With the help of modern metal forming simulation software it is possible to reduce the development time, to reach a new level of efficiency of die assembly design and to increase tool life [3]. Meanwhile to ensure such effect the program has to provide true-to-life metal forming simulation to calculate actual contact stress distribution on the die surface and to be able to simulate elastic-plastic deformation of the dies consisting of several parts assembled with clearance or shrinkage.

The main reasons to use die assemblies instead of solid dies are the following:

- To reduce intensive abrasive wear due to material flow along the convex parts of the die. To increase the tool life we can create die design with insert or a peg using more hard and wear resistant material.
- To avoid low cycle fatigue due to local plastic deformation in the corners of the die cavity
- To eliminate stress concentration in the die areas that are not in contact with the deformed material but may occur because of design limitations.
- To compensate excessive elastic deformation of the die that causes considerable deflection of die cavity shape.

There are some practical rules for die assembly design and manufacturing (see, for example, [4]). Meanwhile when considering each particular case of the die assembly these rules are difficult to implement without trials. Simulation helps to avoid expensive trial and error approach and provides the most effective die design.

With the help of FEM program QForm it is possible to search for the most optimal die design. For example on Fig. 9 we can see the results of simulation of disk forging when the die consists of single piece (solid die block). The lateral surface of lower die block is free (no shrink rings). Yield stress of die material is 1200 MPa. As seen from the results of simulation at the end of forging stroke when the load reaches its maximum value there are very high local stresses in the die. The maximum stress is in the corner of lower die cavity due to small fillet radius. The equivalent stress here is bigger than yield stress and the program detects

the zone of local plastic deformation. Local plastic deformation considerably reduces tool life because of low cycle fatigue cracks.

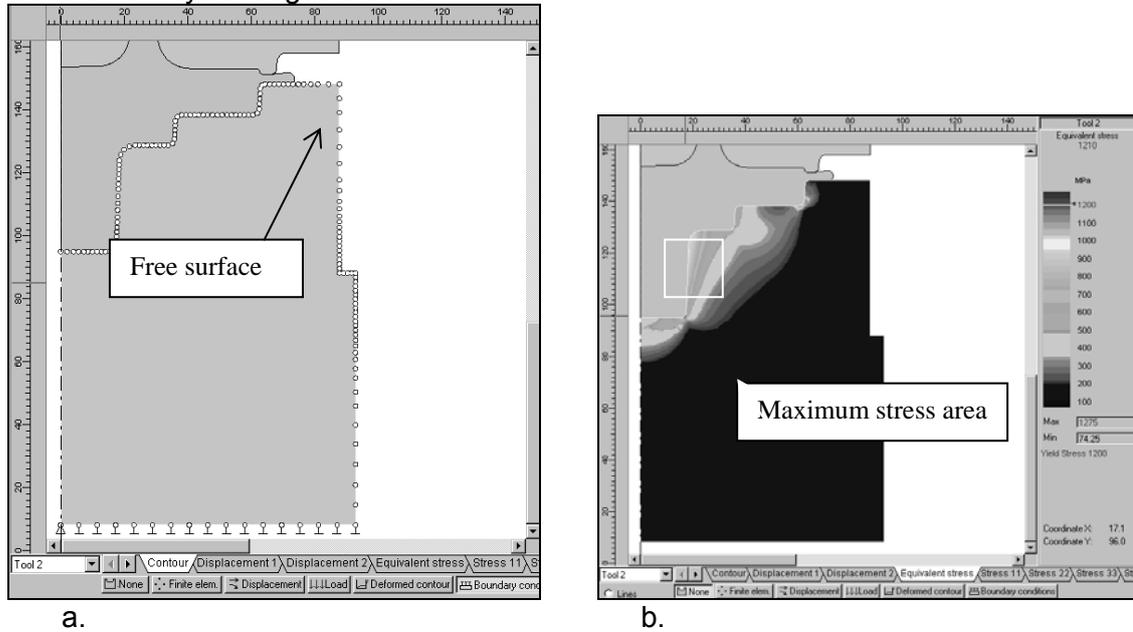


Figure 9. Conditions of support (a) and equivalent stress distribution (b) for solid die with free lateral surface.

Using two shrink rings applied to the outer surface of the die it is possible to reduce maximum equivalent stresses and make it lower than yield stress. On Fig. 10 is shown equivalent stress distribution when outer radius of shrink ring is 150 mm and interference is 0.15 mm per radius. Here we used so called “analytic” method thus the shrink ring and stress distribution in the rings are not shown. Though maximum equivalent stress in the die was reduced, stress distribution remains similar to previous case and die cavity corner is still in danger of cracks (Fig. 10b).

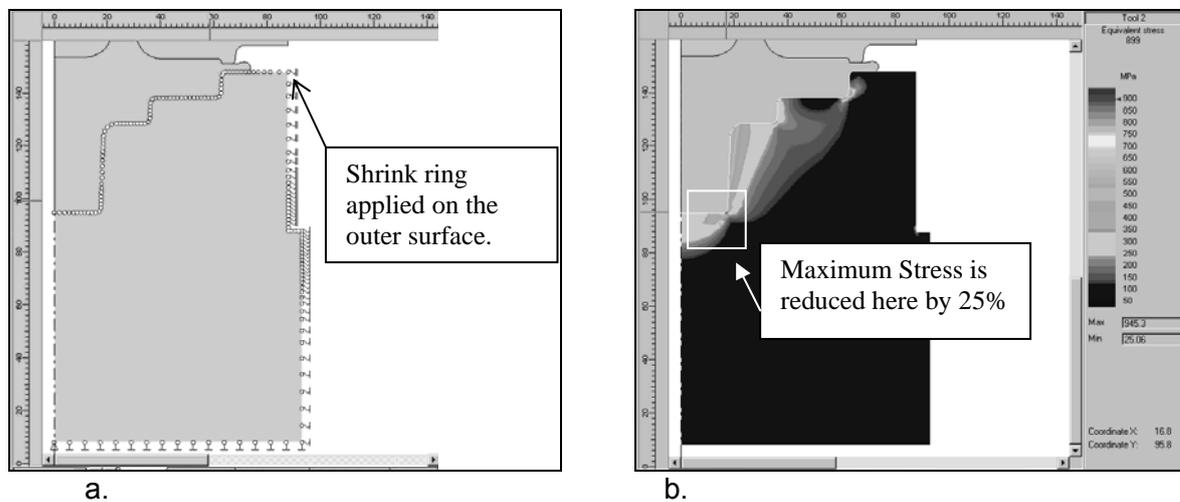


Figure 10. Conditions of support (a) and equivalent stress distribution (b) for solid die with shrink ring on outer surface. Shrink ring is considered using “analytic” method.

The second example is the same die but with the insert and a split in the area where maximum stress was observed (Fig. 11). The insert has size-to-size fitting (zero clearance). Shrink ring has the same interference 0.15 mm and the same outer radius as in the first example.

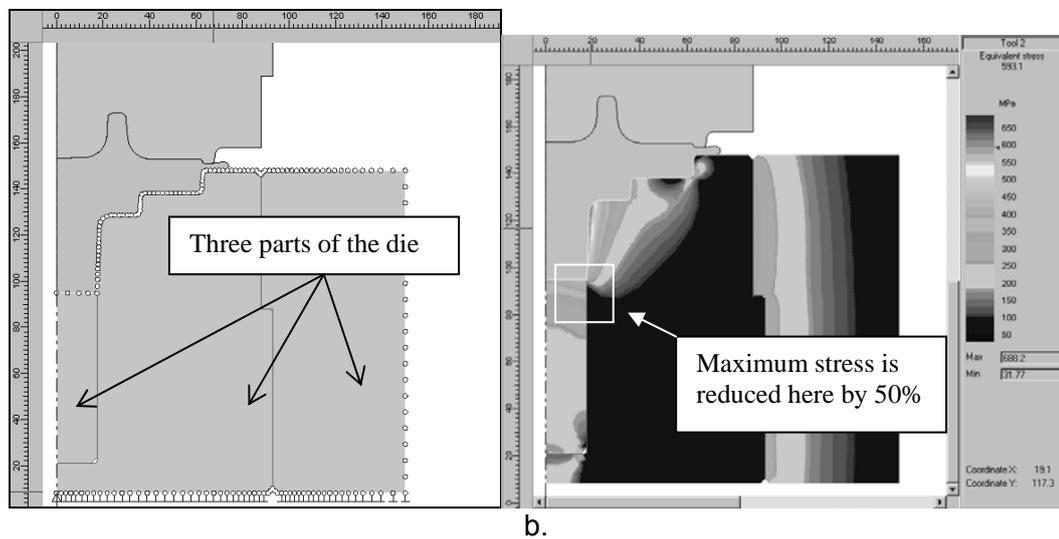


Figure 11. The die with an insert and the shrink ring (a) and distribution of equivalent stress in all parts of die assembly (b).

The difference is that shrink ring is simulated here by finite elements similar to the other parts of the die and the program displays stresses and deformation in it. The die assembly is supported by rigid surface at the bottom surface. The simulation shows principally different stress distribution comparing the first example. Now there is no stress concentration in the die corner while average level of the stress is significantly reduced.

#### 4. Damage problem in cold forging

Stress state in bulk cold forging is quite complicated and is developing either in monotonic or non-monotonic conditions. In certain circumstances the stress components during deformation can even change their sign from compressive to tensile and vice versa. Usually the material in bulk forging subjects to large strain that in combination with unfavourable stress state causes creation of micro and macro defects that may result in fracture. Cold forming is usually performed in several impressions while intermediate annealing can be applied between forging blows to recover the accumulated damage. Damage accumulation depends on many parameters that make trail and error method expensive and ineffective for searching for the optimal technology.

On the other hand the optimal technological solution can be found by means of numerical experiments using the adaptive phenomenological damage model [5,6] combined with simulation.

According to phenomenological theory the ductile fracture in metal forming can be characterised by so-called “damage factor”  $\omega$  that is a scalar parameter. Before the deformation  $\omega$  is equal to zero while  $\omega=1$  when the fracture happens (Fig. 12). The damage factor can be considered as the ratio  $\omega = \chi / \chi^*$  where  $\chi$  is the concentration of the defects and  $\chi^*$  is maximum concentration of the defects that corresponds to macroscopic fracture. The parameters  $\chi$  and  $\chi^*$  are auxiliary for the model. They do not subject to direct experimental determination and are not included into the model equations while only their ratio  $\omega$  is important.

Damage recovery during annealing depends on temperature, time, metal composition and actual damage value  $\omega_0$  before annealing. Generally there are three intervals of the damage defined by two critical values  $\omega^*$  and  $\omega^{**}$ . If the damage before annealing  $\omega_0$  is in the interval  $0 < \omega_0 < \omega^*$  it can be completely recovered. Microscopic investigations have shown that  $\omega^*$  corresponds to energetically stable micro pores while the level  $\omega^{**}$  corresponds to coalescence of micro pores and creation of micro defects and micro cracks. The values of  $\omega^*$  and  $\omega^{**}$  are different for different metals and alloys but usually vary in the ranges  $\omega^* = 0.2-0.4$  and  $\omega^{**} = 0.6-0.8$ .



Figure 12. Photo of the cold forged cap with crack.

The program traces material particles in the deformed body and records all the parameters required by fracture model for calculation of damage accumulation (Fig. 13)

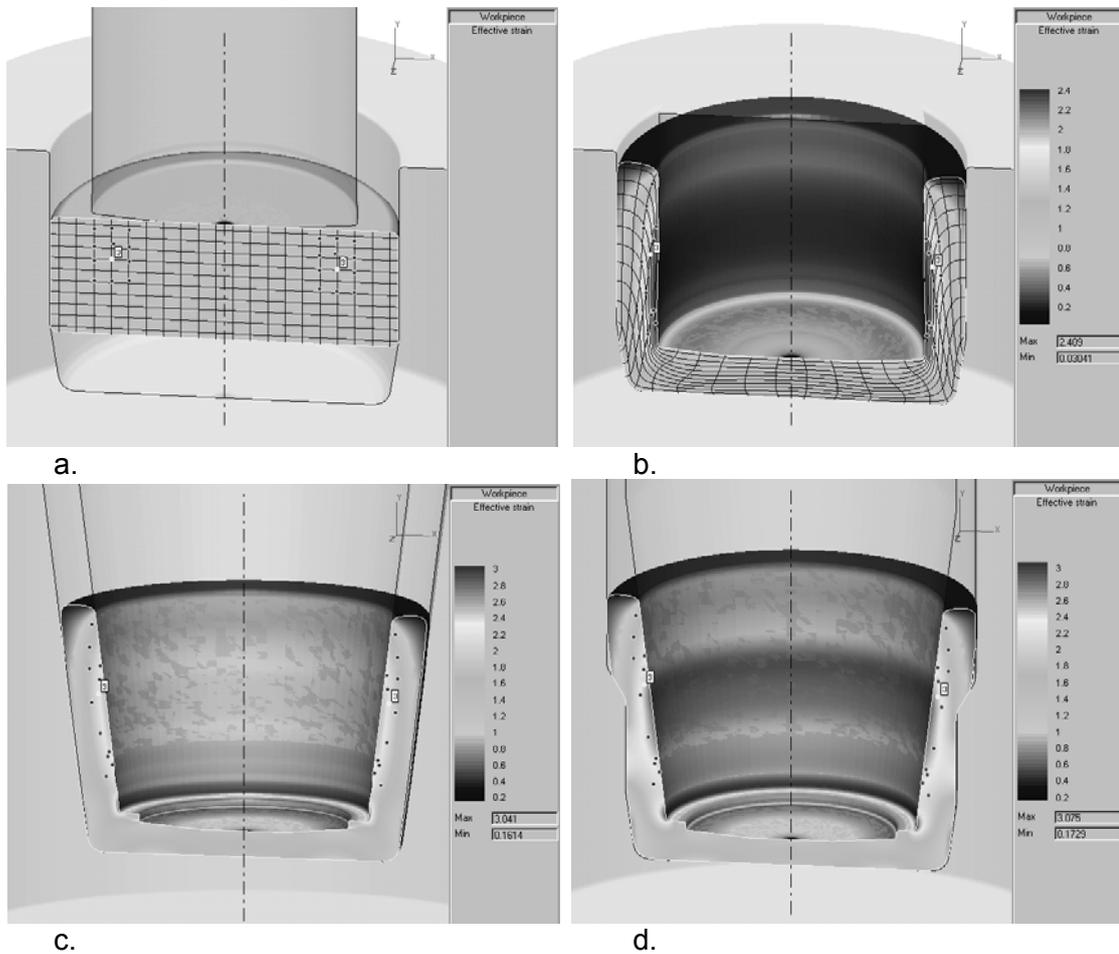


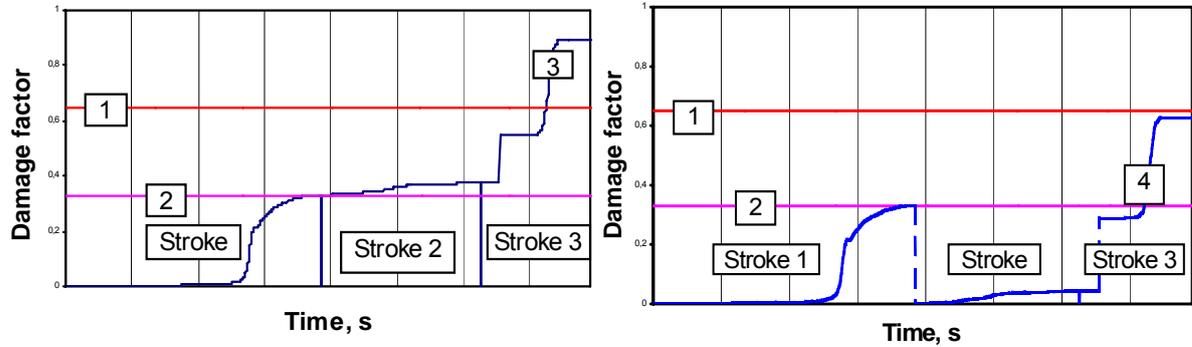
Fig. 13. Initial location of tracked points (a) and their locations after the first (b), second (c) and third (d) blows. Effective strain distribution is shown.

The model [7] allows detecting the areas in the forged part where accumulated damage reaches the highest level and the material fracture is the most probable. Varying intermediate shapes in preforming impressions and, if necessary, using annealing between forming operations it is possible to reduce damage to acceptable level. The accumulation of damage is calculated in each tracked point according to evolution of stress state and strain in them.

As seen from Fig. 14a the most intensive accumulation of damage factor  $\omega$  happens in the first and third strokes (line 3). The critical value  $\omega^{**}$  (line 1 on the picture) is reached in the third stroke that means irreversible damage factor accumulation that finally causes the fracture.

The graph of damage accumulation during the process gives us vital information when the annealing can be effectively applied. As seen from Fig. 14a the damage after the first stroke is still below critical value  $\omega^*$  shown by horizontal line 2. After the second stroke the damage is above of  $\omega^*$  and it cannot be completely recovered by means of annealing. Annealing applied after the first stroke completely recovers the damage and its value accumulated in the second and the third blows (line 4 on Fig. 14b) does not reach critical value  $\omega^{**}$ .

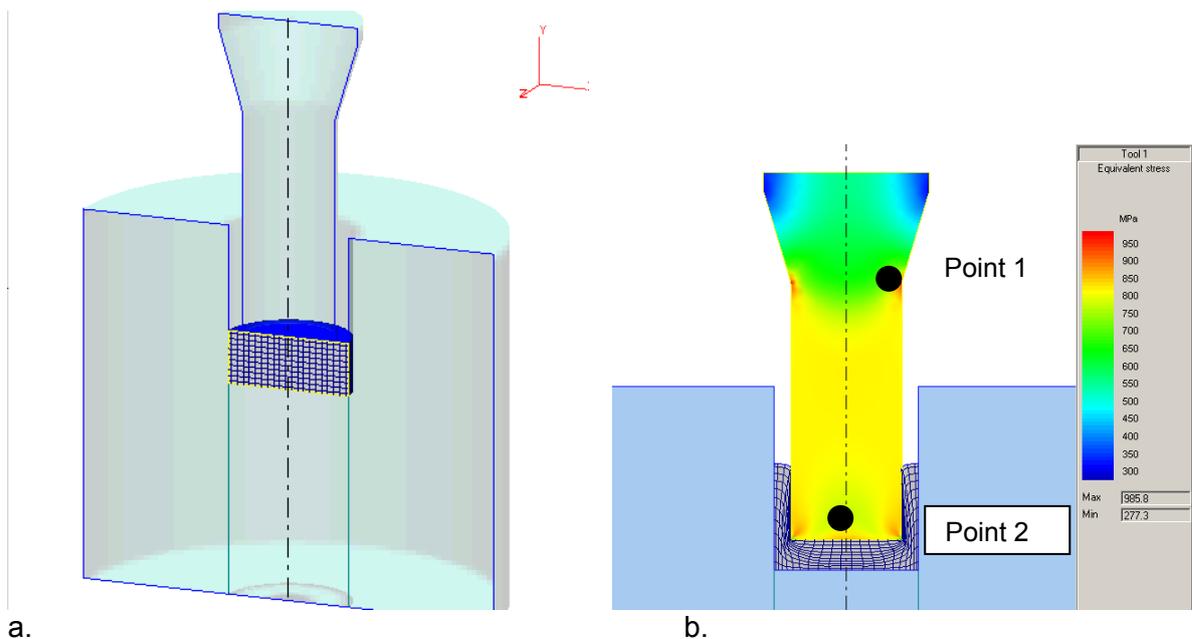
Such damage prediction and correction analysis can be routinely performed for any kind of cold and warm forged parts. The program is supplied with the database of fracture properties for large number of materials while the developed experimental methods allow getting necessary characteristics for new materials using limited number of tests.



a. b.  
Figure 14. Accumulation of damage factor  $\omega$  versus deformation process time in the critical point in three sequential strokes. No intermediate annealing (a), annealing after the first blow (b).

## 5. Die life prediction

Ductile damage model can be also applied to prediction of the die life subject to low cycle fatigue. For this purpose tool steel H13 has been tested and material parameters characterising the damage accumulation in it were determined. The process is backward extrusion of the cap made of copper alloy. Outer diameter of the cap is  $D = 23,4$  mm, inner diameter is  $d = 18,3$  mm (Fig. 15). The subject of investigation is to estimate the number of loading cycles (the number of produced parts) before the punch crack.



a. b.  
Fig. 15. The tools set consisting on the assembled die and the punch before (a) and after (b) forming. Strain distribution in the punch is shown and two critical points are marked.

In both critical points the equivalent stress is below yield stress thus no plastic deformation is expected (Fig. 16a,b). Meanwhile in both points the equivalent stress is above fatigue limit thus the damage will be accumulated with growing of the number of cycles.

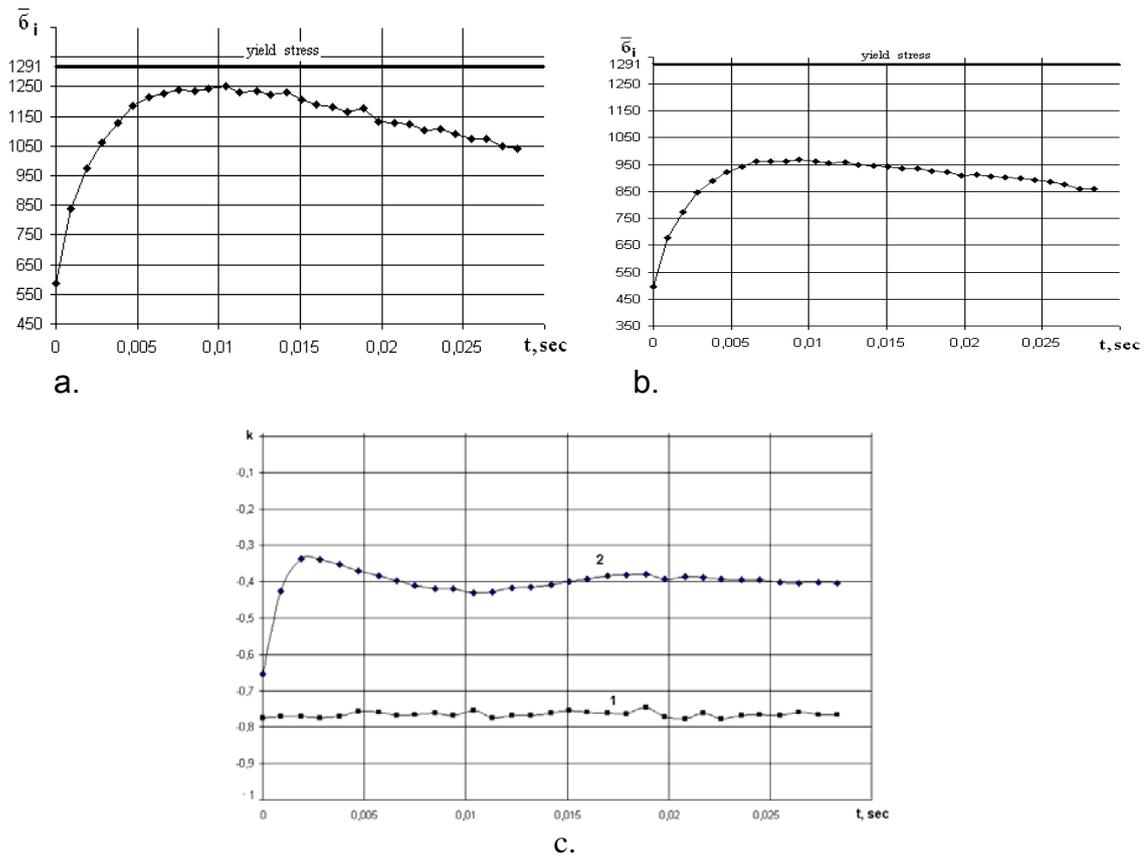


Fig. 16. Equivalent stress evolution during the forging cycle in point 1 (a) and point 2 (b), and evolution of stress state index in points 1 and 2 (c).

As seen from the graphs on Fig. 16 the value of the equivalent stress is bigger in point 1 but on the other hand the stress state in this point is more compressive than in point 2 that in turn may reduce damage. Applying ductile damage theory we get the results summarised in Table 1:

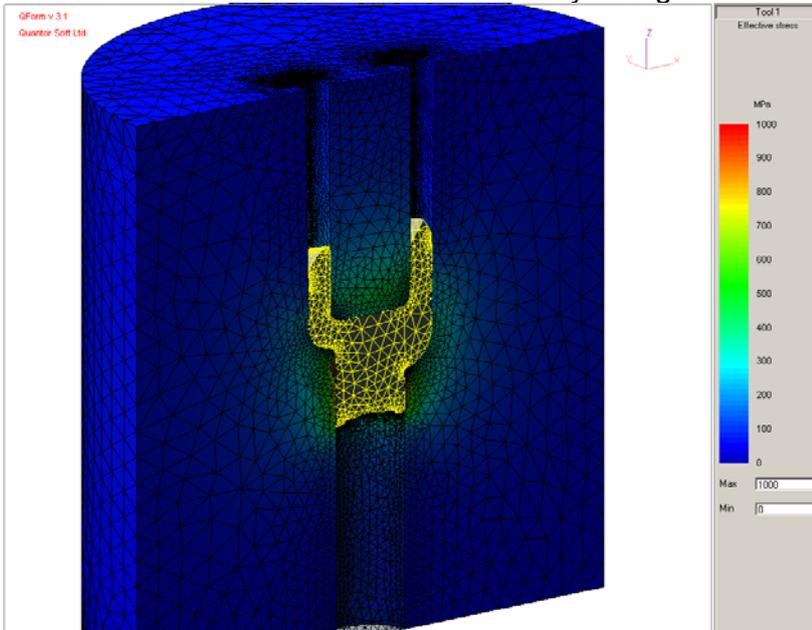
Table 1.

Point	Damage increasing per cycle	Predicted number of cycles to crack appearing
1	$1.8 \cdot 10^{-4} - 5 \cdot 10^{-5}$	56300
2	$1.5 \cdot 10^{-3} - 3 \cdot 10^{-4}$	6750

It is seen that the damage increasing per cycle is bigger in point 2 though it has lower equivalent stress. It is because of the influence of compressive stress that effectively reduces the damage accumulation.

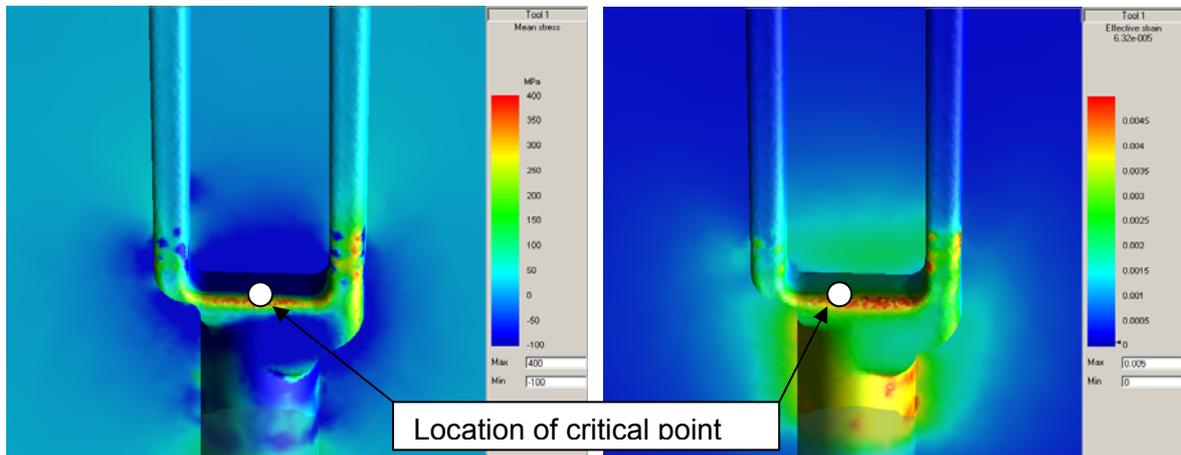
The same approach can be applied to 3D problems like shown below example of fork forging by means of forward extrusion (Fig. 17). Deformed material is AISI AA6101 at temperature 300 C while the die is made of steel H13. Location of critical point is shown on Fig. 18. It is on the inner surface of the die where the material flow is split up into two canals. Using the same method as above the number of cycles until crack was estimates as 36718.

Making experimental investigation of other tool materials and applying ductile damage model it is possible to estimate die life limited by fatigue failure in cold forging



processes.

Fig. 17. The die set and the deformed workpiece during extrusion of the fork. FE mesh and the equivalent stress in the die are shown.



a.

b.

Fig. 18. Distribution of the mean stress (a) and effective strain (b) on the inner surface of the die at the end of stroke.

## 6. References

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