Increasing of tool life in cold forging by means of fem simulation

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Abstract

Estimation of the die wear is the one of the part of the forging technology development. Due to investigations /1/ about 80% of the causes of die life for cold forging are attributed to wear. The number of the forged parts with one dies set characterizes the die life. In cold forging two main reasons cause to shot tool life:

- damage which limits die life occurs when the die steel strength cannot withstand the load during forging process;
- die wear when material is actually removed from the die surface by pressure and sliding of the deforming material.

The die wear investigation and results applicable for the technology where is using high-speed machine for high production volume and the effect of the die extension would be significant. The typical machine is Hatebur. Development forging simulation software and computational algorithms opens the ways for calculation the possible die wear, low cycle fatigue failure and prediction die life.

1 Die wear calculation

The mechanism of the adhesive die wear during deformation includes appearance the adhesion metallic bounds after damage of the chemical combination between metal and oxygen into the oxide film and then the plastic deformation of the metallic bounds. As the result the product of damage of the dies and forged metal go out from the contact zone with deformed material. The main mechanism of damage of the adhesion bounds during plastic deformation is dislocation.

For estimation the adhesion die wear let us consider the following assumptions. The contact between die and forged material is considering in the points of the die surface.
For estimation the values of the adhesion die wear we will consider the following assumptions. The contact is considering in the points of the die surface. For any point it is possible to calculate the power of the friction forces

$M_\tau=\tau\cdot v_\tau$

Where
v_τ – relative tangential velocity of the deformed material.
τ – shearing stress of deformed material in the point of the die surface;
$\tau=m\frac{\sigma_s}{\sqrt{3}}(1-e^{-1.25(\sigma_n/\ \sigma_s)})$;
σ_s – flow stress of deformed material;
σ_n –normal stress in the contact point4;
m – friction factor.
The power of the friction forces during plastic deformation of the workpiece equals the power of plastic deformation of the die's adhesion film δ where it destroys.

$M_\tau=M_\delta$

Where
M_δ – power of plastic deformation of the die's adhesion bound δ with the thickness Δ.

Due to work /2/ the value Δ equals the average distance between glide lines. It depends on the value of the microasperities, die hardness, machining and temperature of the dies. The power of plastic deformation of the die's adhesion film when it destroys and go out from the plastic zone can be calculated as

$M_\delta = \overline{\sigma}\cdot\dot{\varepsilon}_v$

Where

$\overline{\sigma}$ - flow stress of the die surface;

$\dot{\varepsilon}_v$ - volumetric strain-rate of the adhesion film where the die damage takes place.

The value $\dot{\varepsilon}_v$ can be calculated as

$$\dot{\varepsilon}_v = V_n / \Delta$$

Where

V_n – normal to the die surface velocity of the adhesion bounds damage in arbitrary point;

Δ – average thickness of the adhesion bound due to /2/.

Consequently, the value of V_n may be calculated as $V_n = \dot{\varepsilon}_v \, \Delta$.

The depth of the adhesion wear of dies in any points of the surface during the contact time t may be calculated with the following equation:

$$W = \int_0^t V_n \, dt,$$

Where

W – depth of die wear, m;

V_n – normal velocity of the adhesive bound damage, m/s;

t- the time of the contact of the point on the die surface with the deformed metal, s.

The previous expression may be written as the following:

$$W = \int_0^t \frac{a \cdot \tau \cdot v_\tau}{\overline{\sigma}} dt \qquad (1)$$

Where

a – empirical coefficient.

The formula (1) corresponds to well known Archard's formula /3/ where the die wear is proportional to the normal die pressure and material sliding distance along the border between material and dies.

The wear formula proposed here is verified whether it is applicable to dies of different shapes of different materials and of different die lives.

1.1 Comparing results of the die wear calculation with an experiment

QForm is FEM code that provides forging simulation for material in cold, warm and hot state in different forging equipment /4/. For calculation of die wear in code was introduced the calculation of the W value due to the presented above formula (1). The W is calculating during metal forming simulation for contact points of the die surface.

The verification of the proposed approach for die wear calculation was verified by comparing the results of simulation with experimental investigations of the die wear depth and its evolution.
The experimental results of the die wear evaluation were received by collaboration with CVUT[1]. In the frame of this cooperation the tests of die wear were preformed in the forge. Conditions:
Forged material: carbon steel AISI 1030
Input shape: round bar diameter 13 mm,
Output shape is shown in Fig.1
Forging temperature: 1100 - 1150ºC
Machine: Counterblow hammer Smeral KJH2, (max. energy of one blow 20 kJ)
Number of blows: mostly 2 blows

The goal of this research was to evaluate the progress of abrasive wear of the die cavity. The progress of wearing was measured from the hammered forgings. The shape of forging cross section from partially worn-out die was compared with the original shape.

The change of profile was measured by means of Zeiss Profile Projector (type 320) with magnification of 10 or 20. To get the clears images the samples were finely regrind. On the Fig.1 is depicted the scheme of the experiment. The round bar in the beginning and end of the forging. The samples were cut off from the forgings taken out after forging 1 piece, 500 pieces, 1000 pieces, 1500 pieces and 1900 pieces. The numeration of samples was No.1, No.2, etc. up to No.5.

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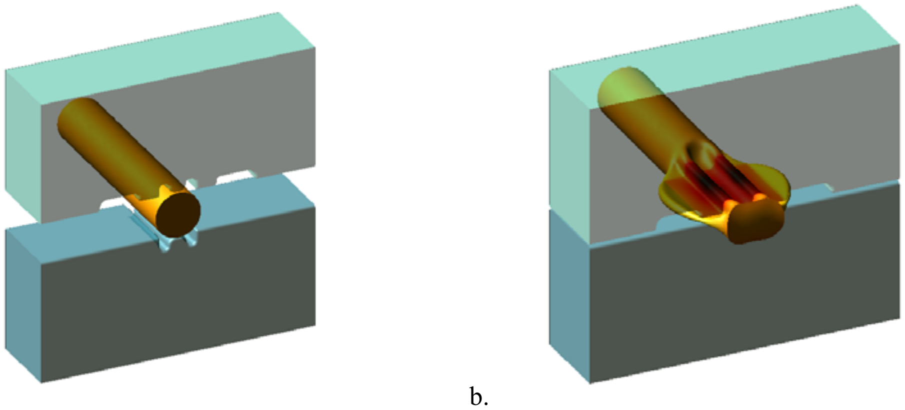
[1] Czech Technical University in Prague, Dr. Jan Cermak



a. b.

Figure 1: Forged part in the experiment in the beginning (a) and end of forging (b)

The maximum depth of the die wear evaluation versus the number of the forged parts is shown in the Fig.2

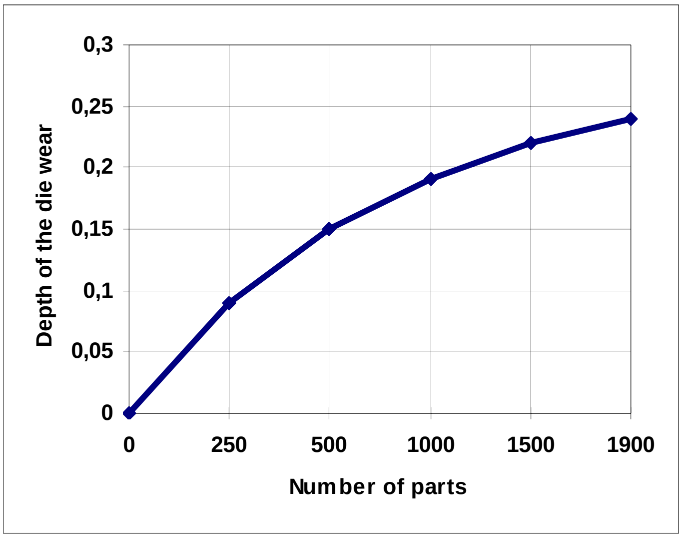


Figure 2: The maximum depth of the die wear(mm) evaluation versus the number of the forged parts for the upper die

Calculations of the die wear for experimental conditions using the formula (1) has shown good coincidence between experimental and calculated values of the die wear depth. The comparing was done for the central line of the forged bar like in the Fig.3a.

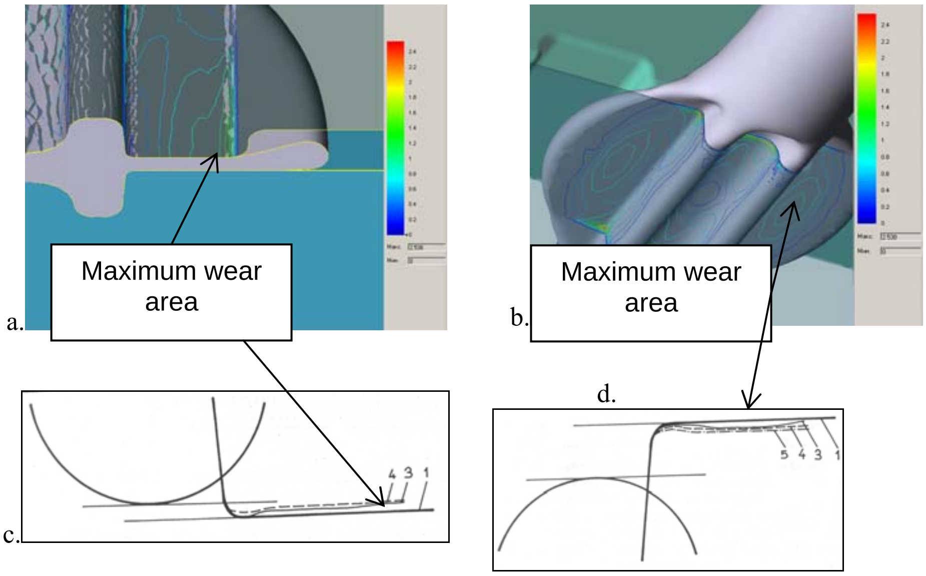
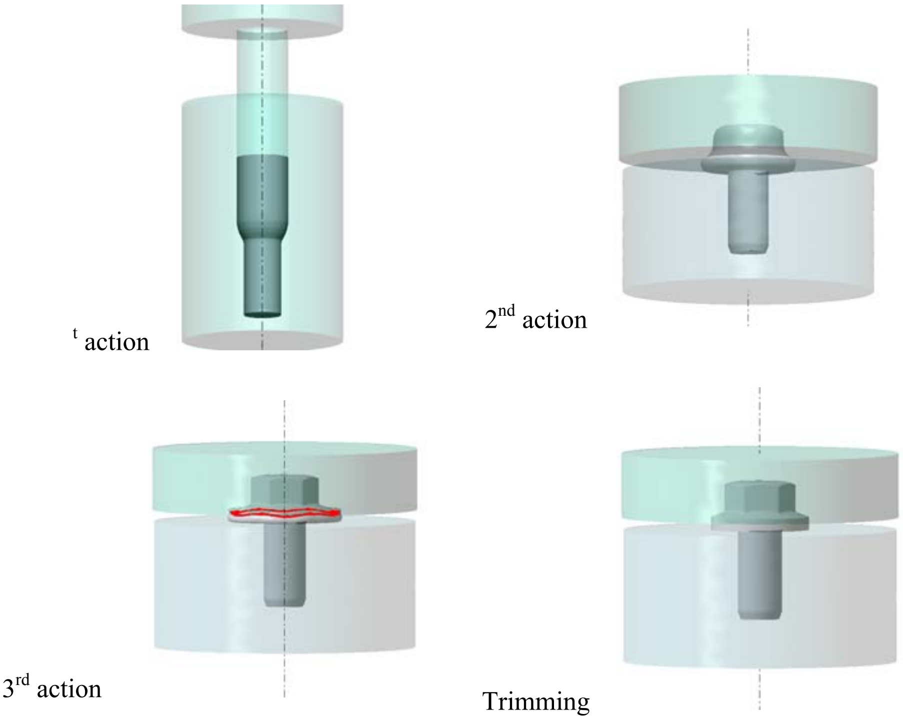


Figure 3: Abrasive wear distribution *10^{-1} mm of the upper die (a) and lower dies (b). a, b – calculation by QForm, c, d – experimental measurement after 1 (1), 500 (2), 1000 (3), 1500 (4) and 1900 (5) parts.

1.2 Die wear prediction and optimization cold forging technology

In this part are presented the results of optimization of cold multi stroke forging technology by minimization of the die wear function **W**. In the investigation was used the relative value of the die wear **W.** This approach may be used for optimization the multi stroke technology. The purpose of investigation was development a new approach for optimization of multi stroke cold forging technology.

On the Fig. 4 is shown the 4 strokes technology of cold forging on Hatebur machine the fixing bolt. After the 3rd stroke in the existing technology the forgings is trimmed for producing the final shape.



^{t} action

2^{nd} action

3^{rd} action

Trimming

Figure 4: Four actions of cold forging of fixing bolt (initial technology)

The maximum values of the **W** function is observed in the 3rd action for upper die and equals 20.78 (see Fig.5 and Fig.6).

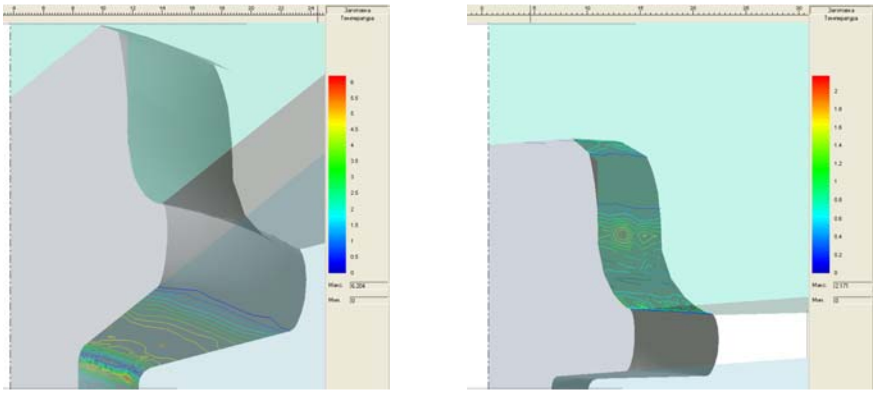
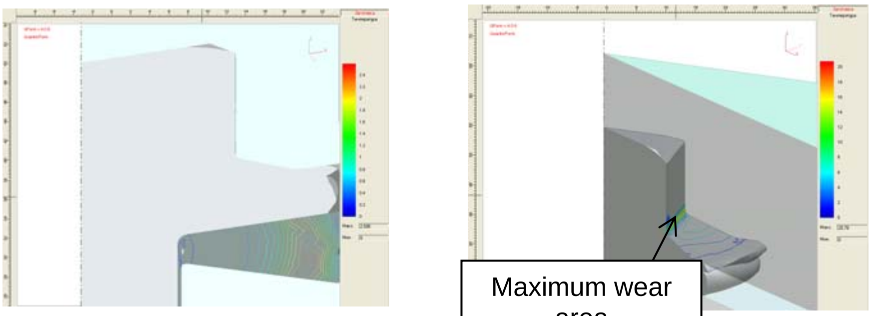


Figure 5: Second action die wear, a – lower die, maximum 6.2, b – upper die, maximum 2.1

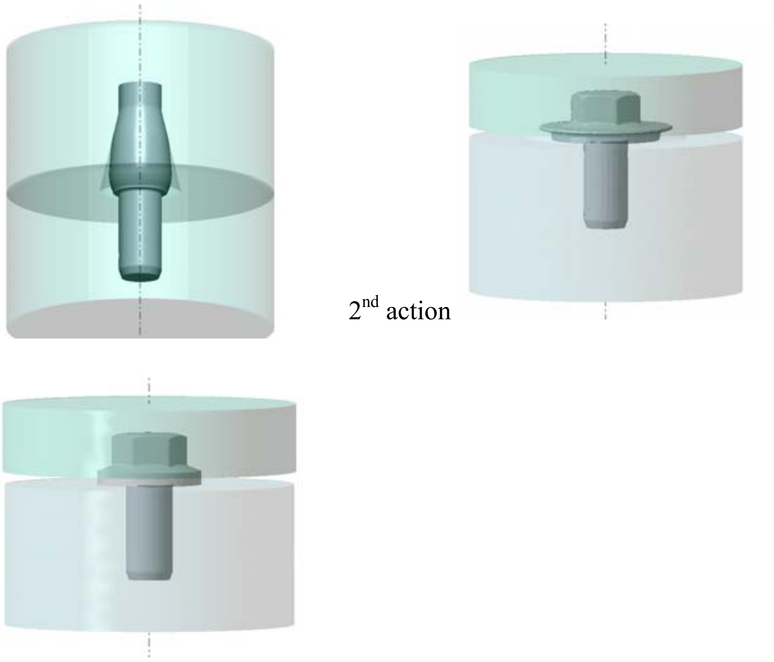


Maximum wear area

Figure 6: Third action die wear, a – lower die, maximum 2.5, b – upper die, maximum 20.78

Three strokes technology was modified for increasing tool life of initial technology where tool life is 1500 units per set of tools.

Modification of the technology includes the replacing 3 forming operations by 2 strokes technology. The most important improvement concerns the changing of the shearing deformation in the existing technology by uniform filling of the dies in the modified technology.



1st action

2nd action

Trimming

Figure 7: Three actions cold forging technology (modified)

The maximum values of the **W** function reaches in the lower die of the 2nd action and equal 9.9. On the upper die **W**=7.28 (see Fig. 8).

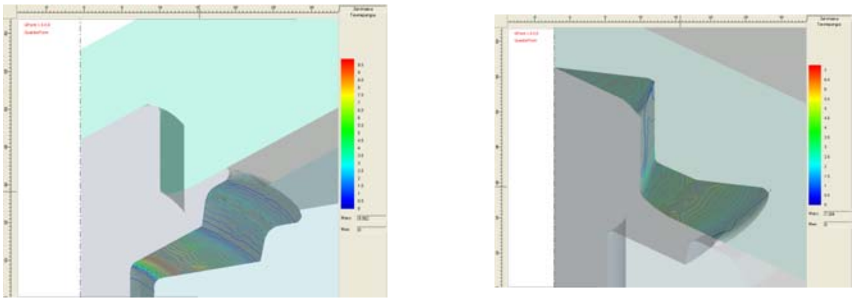


Figure 8: Second 2nd action, die wear, a – lower die, maximum 9.90; b – upper die, maximum 7.28

Changing the scheme of the material flow provided considerable decreasing of **W** value. In the initial technology in the 3rd action the upper die cuts the material and we can observe the intensive sliding with shearing deformation the forged material along edge of the upper die. See Fig.9a. While for modified technology we observe quite uniform material flow (see Fig 9b).

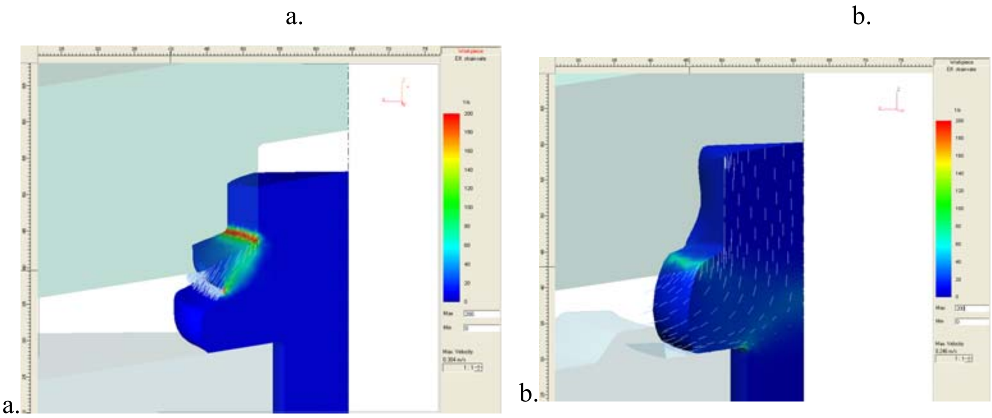
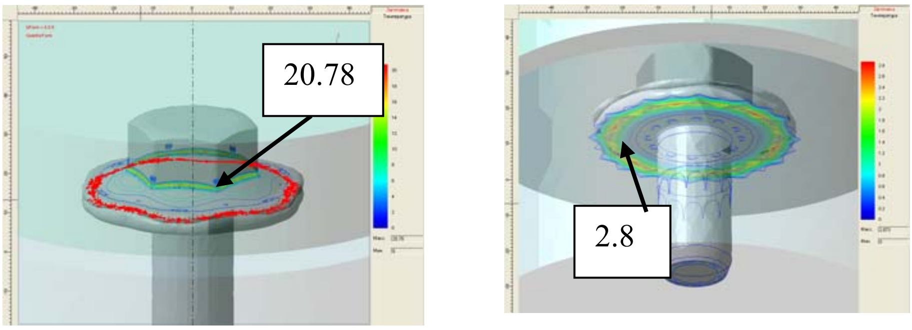
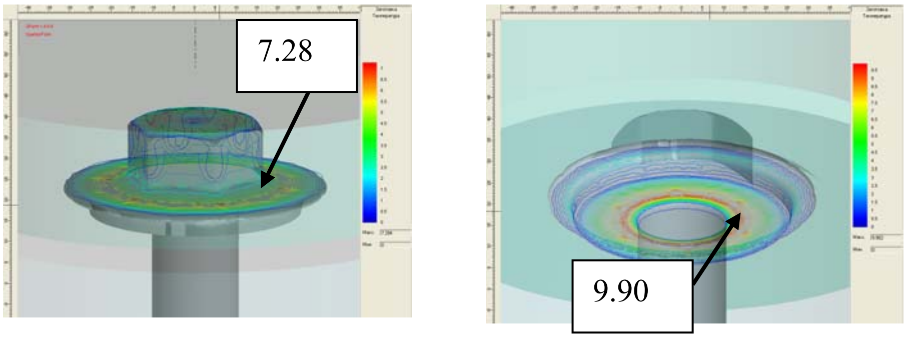


Figure 9: Intensive sliding forged material at the 3rd action of the initial technology under the upper die (a) and filling of the die cavity for modified technology (b) with equal sliding material along upper and lower dies. Velocity vectors and effective strain-rate is depicted



Upper die a. Lower die



Upper die b Lower die

Figure 10:Comparing the die wear for two technologies. a – existing technology, maximum die wear 20.78 exactly on the edge of the upper die; b – modified technology, maximum die wear 9.90 on the lower die

Comparing of two technologies (see Fig. 10) has shown the advantages of the new sequence of the forging from the die wearing point of view. The expected increasing of the die life with new technology is 2-3 times.

2 Die cracking due to low cycle fatigue

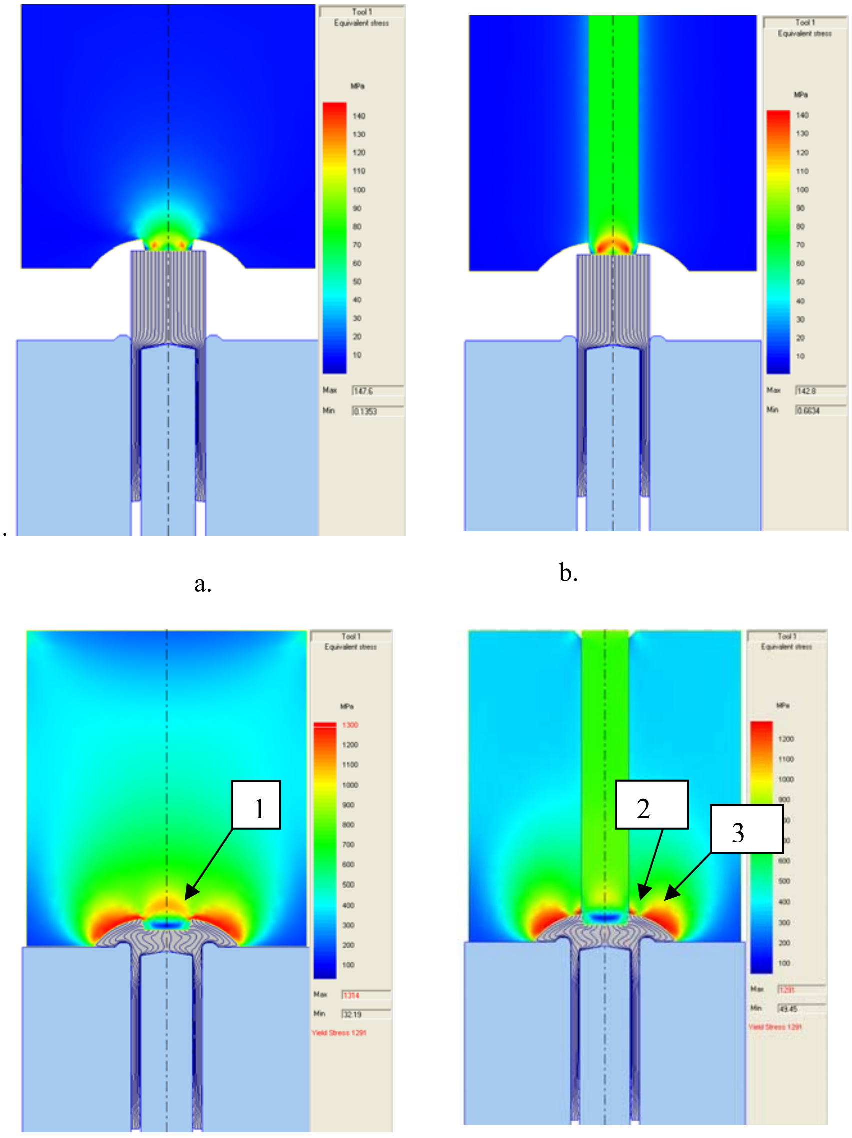
One of the main reasons of premature die fracture in cold forging is low cycle fatigue /5/. The low cycle fatigue happens when the equivalent stress in the die during the forging blow reaches the yield stress and small elastic-plastic deformation takes place. It has the following four basic stages depending on the accumulation of the dimensionless “damage” parameter ω /6,7/:

- cyclic loading without defects while due to plastic deformation a network of dislocation forms ($0<\omega< 0.2 \ldots 0.3$)
- initiation of microdefects (micropores) nucleated at the grain boundaries ($0.2 \ldots 0.3<\omega< 0.5 \ldots 0.6$)
- coalescence of the microdefects into form of microcracks ($0.5 \ldots 0.6<\omega< 0.7 \ldots 0.85$)
- a front of microcracks forms and starts to move that causes macroscopic fracture ($0.7 \ldots 0.85<\omega< 1$)

This mechanism to large extent is similar to the damage accumulation in plastic deformation of ductile materials thus the damage theory can be applied to the low cycle fatigue. The method of the adaptive damage theory applied to the prediction of the plasticity limit in cold forging was presented in our work /8/. In the case of cycle loading of the die the non-linear theory can be simplified due to small deformations /7/. Thus the number of forging cycles N_i until beginning of macroscopic fracture that corresponds to $\omega=0.7$ can be calculated using the following formula:

$$\omega = 2N_i\left(\frac{\Delta\varepsilon}{\varepsilon_{cr}}\right)^a = 0.7$$

Solving it with respect to N_i we have



a. b.

c. d.

Figure 11:Equivalent stress distribution in the upper solid die (a,c) and assembly die (b,d). Initial positions of the dies (a,b), finish position of the die (c,d).

$$N_i = \frac{0,35}{\left(\frac{\Delta\varepsilon}{\varepsilon_{cr}}\right)^a} \qquad (2)$$

where $\Delta\varepsilon$ is the plastic strain introduced into the die material during one forging cycle and ε_{cr} is the maximum (critical) strain when microscopic fracture happens and a is the power index. Both ε_{cr} and a are the parameters of the die material and depend on stress state indicator $\frac{\sigma_0}{\sigma_{eq}}$, where σ_0 is the mean stress and σ_{eq} is the equivalent stress in a point. The dependence of the critical strain ε_{cr} on stress indicator is very essential for reliable prediction of the tool life. The critical strain is growing rapidly with increasing of compressive mean stress while in case of the tensile mean stress it becomes smaller. For example, for tool steel H13 these parameters are the following /9/:

$$\varepsilon_{cr} = 4.5 * \exp(-1.2 * \frac{\sigma_0}{\sigma_{eq}})$$

$$a = 1.8^{(1+0.238*\frac{\sigma_0}{\sigma_{eq}})}$$

Below is the example of the cold heading operation of a steel part. In the case of the solid die block the highest equivalent stress exceeds yield stress in the fillet of the upper die and plastic deformation appears (Fig. 11. a, c, point 1). The evident solution is to make the assembly die with the insert and by these means to reduce the stress concentration in this point as shown on Fig. b, d. Nevertheless the highest stress on die contact surface is still bigger than the yield stress in the points 2, 3 and the efficiency of the modification is not clear. Thus in both variants the dies subject to low cycle fatigue and it is necessary to estimate the expected amount of forging blows before crack.

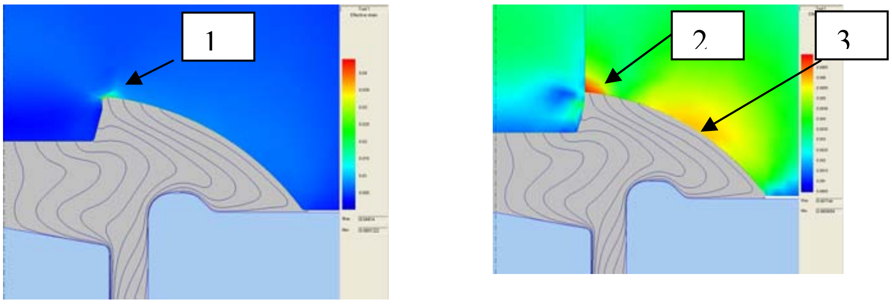


Figure 12:. Effective strain distribution in the upper solid die (a) and assembly die (b)

The comparison was done for the points with maximum value of equivalent stress (points 1, 2, 3 on Fig.12). The distribution of the effective strain (Fig. 12) shows that only points 1 and 2 have its high level thus these two points were taken into consideration. Table on Fig. 13 contains the summary of the parameters required for the expression (2) and the results of calculation.

Point	Maximum equivalent stress, MPa	Maximum plastic strain $\Delta\varepsilon$	Stress indicator	Critical strain ε_{cr}	Power index *a*	Expected amount of cycles
1	1314	0.038	+0.3	3.1	1.86	1257
2	1291	0.001	-0.23	5.9	1.74	127000

Figure 13: The number of forging cycles

Even though the maximum equivalent stress decreasing is negligible (about 1.7%) the greater influence has the strain and the stress distributions. Particularly we observe changing of the mean stress from tensile to compressive one (see stress indicator) and considerable reduction of the plastic strain. According to expression (2) it results in increasing of the expected amount of blows from 1257 to 127000 that is more than 100 times.

Conclusions

Including into the FEM code QForm the possibility of the die wear calculation provides forging technology optimization by minimization of the die wear.

For cold forging technology the main contribution into the die wear have material sliding along die surface and contact pressure.

Using the relative value of the die wear function **W** it is possible to optimize the multi stroke cold forging technology.

For prediction of the die wear depth it is necessary the experimental investigation for estimation the empirical coefficients.

Damage accumulation theory can be successfully applied for prediction of die fracture and increasing of tool life.

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