"SOME ASPECTS RELATED TO THE DURABILITY OF FORGING DIES"

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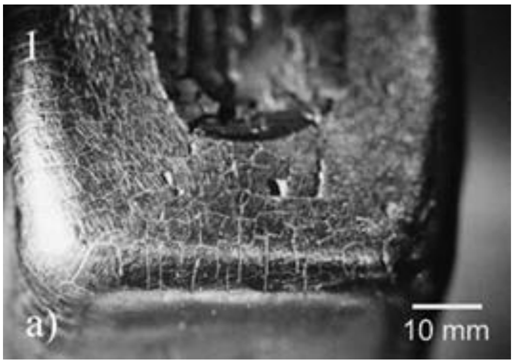
Abstract: Improvement of forging dies in terms of fatigue and wear is briefly reviewed and corresponding analysis is performed through 2D and 3D simulations examples using the QForm software.

Introduction: It has been pointed out by several authors (1-7), that durability of forging dies depends on several factors, the most relevant being **wear** and **mechanical fatigue** (3). As shown in the research of Lapovok (4,5), the improvement of fatigue life of hot forging dies is of primary concern to design engineers. The fracture usually starts at the working surface of the die that is subjected to repeated thermal–mechanical loading (fig 1). Quite often, cracks on the surface of the die become visible after only a few thousand forging cycles.



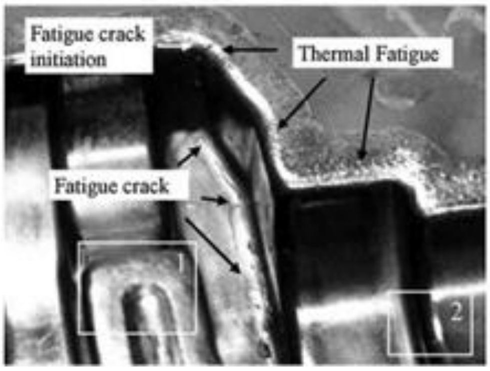
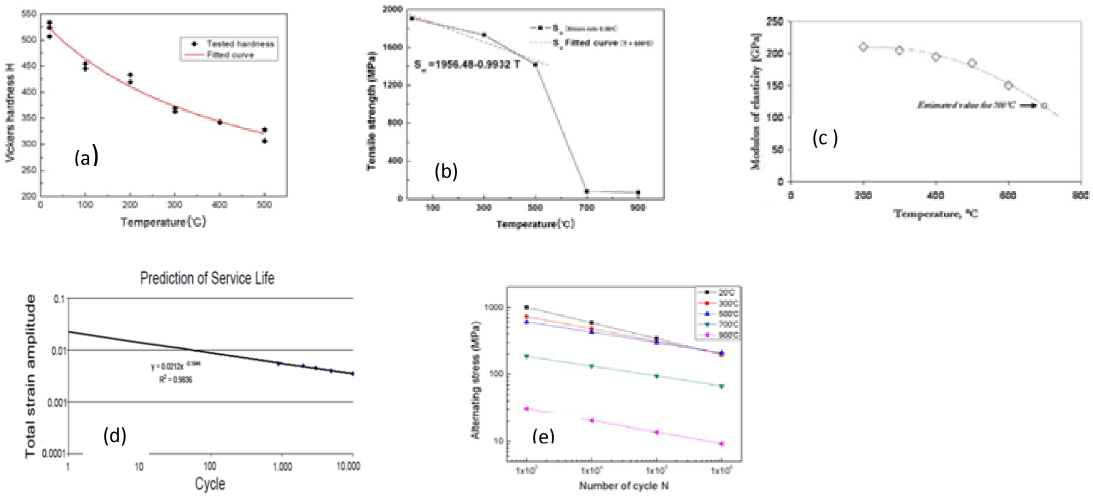


Fig.1- Damage in the hot forging tool – overview (2)

Tools for most hot forming techniques are repeatedly subjected to elevated temperatures and loads. Cracks initiating at the most critical areas propagate under applied loading which can lead to a complete die failure. In hot-forging dies thermomechanical loading is large enough to produce stresses(σ >~ 1500 MPa) that are beyond the yield point of the die material, especially at critical regions of stress concentration, such as geometrical irregularities of the surface, apart from a non-homogeneous distribution of stress. (In an analogous way, these aspects are applicable to cold forming operations). This causes the accumulation of plastic strain and, therefore, accumulation of damage in the critical areas of the die. To ensure these severe conditions the tools are made of hot-work tool steel, designed to have an adequate combination of strength, hardness, modulus of elasticity, fatigue and other basic properties, such as those presented in Fig. 2 (6).

Selection of material for the manufacture of dies, working in conditions of hot/warm deformation, is based on the consideration of the following properties of the tool materials: 1) Wear resistance, 2) Low cycle fatigue resistance and 3) Resistance to erosion due to plastic deformation. The selection of material for the die manufacturer for hot and warm forging depends considerably on the surface temperature of the die and loading conditions during the process. The main tool steels for hot forging are medium carbon and high-alloy steels. Chromium steels (H10, H11, H13, H14, and H19) are the most widely used for dies. It is known that chromium steels have good hot hardness up to 425 ^{0}C, steel with the addition of tungsten (H21...H26) keep good hot hardness up to 620 ^{0}C. (7).



Typical Wohler curves for tool steel EN 1.2367 (X 38 CrMoV5-3) and for H13

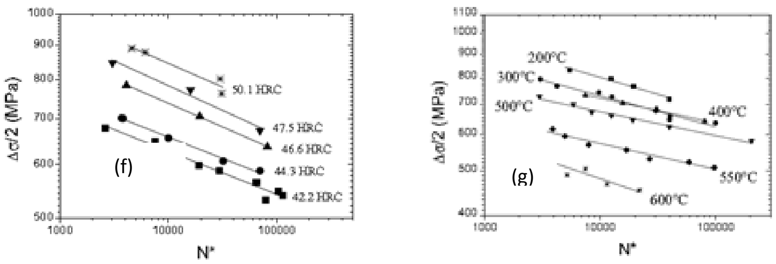


Fig 2. Several typical mechanical properties for tool steels (3, 6)

Low cycle fatigue (LCF) - Durability of dies is one of the most important factors affecting the cost of hot forging products. The prediction of the tool life during the preparation of the die design increases the effectiveness of the associated technology development. Abrasive wear and low cycle fatigue (LCF ~10 ^{2} to 10 ^{5}cycles) have the greatest influence on the durability of the dies. The deformation model of Manson-Coffin-Lapovok is the classic model for the calculation of LCF (7). However, the pulsating cycle of loading dies and the phenomenon of cyclic thermal softening doesn’t provide an implementation of the full Manson-Coffin- Lapovok´s (8) model for the analysis of the tool life. This is due to the fact that majority of researchers do not take into account the plastic strain component and use only the elastic component of the Manson-Coffin-Lapovok law, as explained in more detail in fig.3 (7).

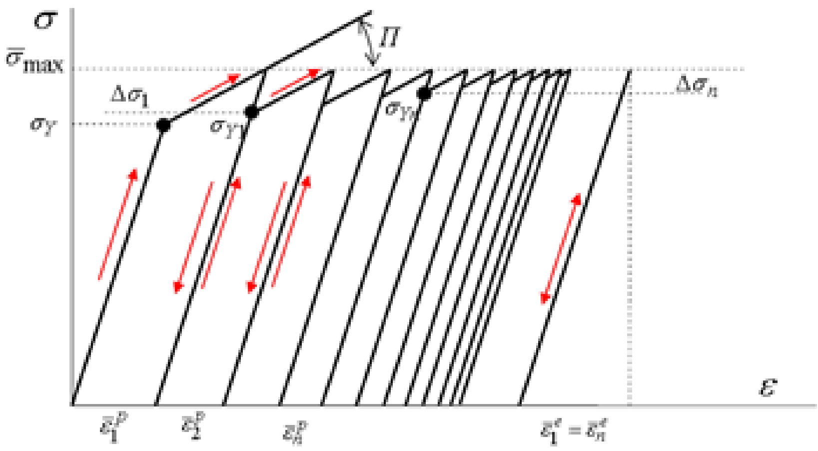


Fig 3. - The accumulation of plastic strain at a cyclical loading of the dies taking into account the softening of the die material(7)

The number of forging cycles N_i until beginning of macroscopic fracture can be calculated using the following formula: (7)

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

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 a 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 effective stress in a point.

For the H13 tool steel (~DIN 1.2344), the critical strain is given by:

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

and

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

Wear- Estimation of the die wear is one of the parts of the forging technology development. From several investigations, about 60% of the causes of die life for cold forging and 50% for hot forging is attributed to wear. In bulk forging two main reasons cause to shorten tool life:

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

Development forging simulation software and computational algorithms open the ways for calculation of the possible die wear and prediction of die life.

The <u>depth</u> of the die wear *W* of the die at any point during the contact time *t* may be expressed by the following equation and correspond to the formula of Achard[1].

$$W_p = \int_0^t \frac{K_p \cdot p \cdot V_\tau}{\bar{\sigma}} dt \, ; \; W_\tau = \int_0^t \frac{K_\tau \cdot \tau \cdot V_\tau}{\bar{\sigma}} dt$$

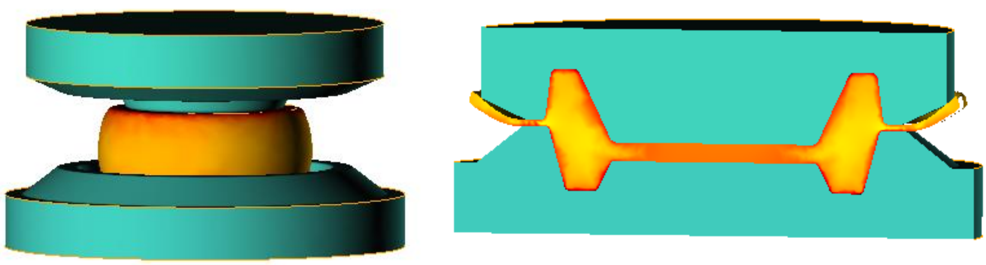
Where: *Wp* and *Wt* are the wear from the normal and shear stresses, *Kp* and *Kt* empirical constants, *Vt* tangential velocity (m/s), *p* the normal pressure(MPa), t the shear stress at the point of contact, σ the tool yield stress, MPa and *t* the contact time of workpiece and the tool(s).

It must be pointed out that the QForm software program provides quantitative estimates of the stress and strain state of the tool material during forging due to the following possibilities:

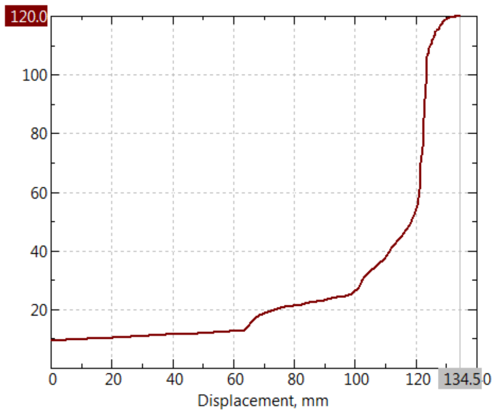
1. The possibility of **coupled simulation of mechanical and thermal problems** in hot forming. The solution is carried out automatically with the possibility of simulating not only the plastic deformation of the workpiece but also elastic-plastic deformation of the die, as well as coupled workpiece - dies thermal problem simulation.
2. The possibility of calculation of the assembled tool.
3. The program includes an option to quickly create and run the user-defined program (UDF) for estimation of the tool life on different criteria. UDF is created based on the programming language Lua (www.lua.org).
4. In the new version of the software, the unique algorithm of elastic-plastic thermomechanical fatigue analysis of forging dies is implemented [3]. The algorithm summarizes damage caused by plastic and elastic deformations in accordance with the strain-kinetic failure criterion.

These several aspects will be presented in more detail using the **QForm VX** software, through **two** basic examples, namely the hot forging of a steel disk (in 3D) and of the rivet cold forging (2D/ 3D) of an aluminum alloy.

Steel disk A stainless steel disk in X5CrNi18-10 (1- 4301) is to be produced in a two-step forging, at a starting temperature T= 1200 °C. Several aspects of the analysis (2^{nd} stage) are illustrated in Fig. 4 (a) to (f).

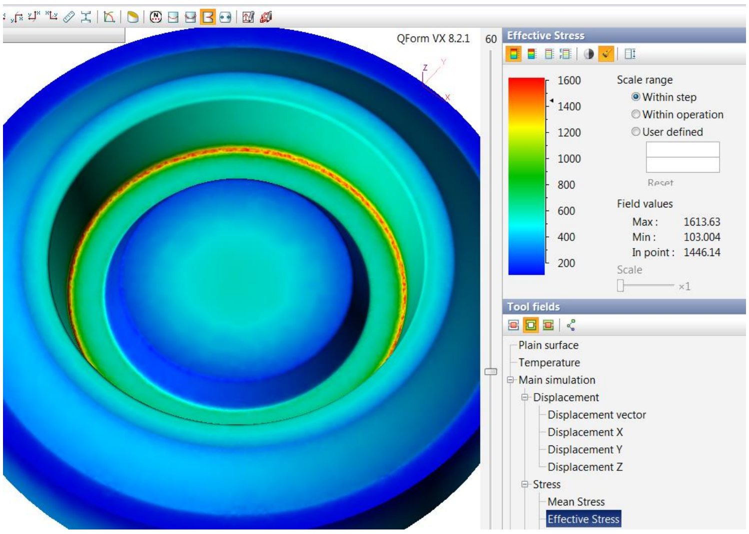


(a) disk forging: start and finish of 2^{nd} stage

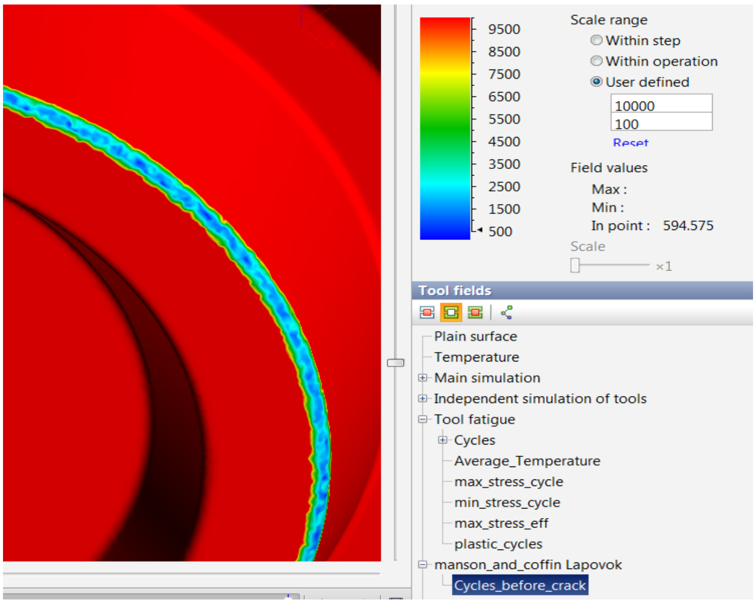


(b) load- displacement

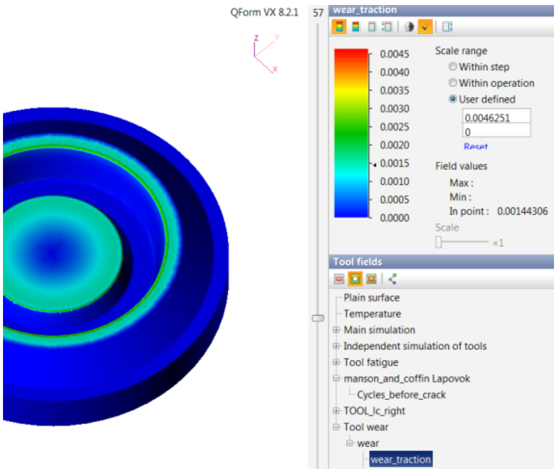
(c) final forging

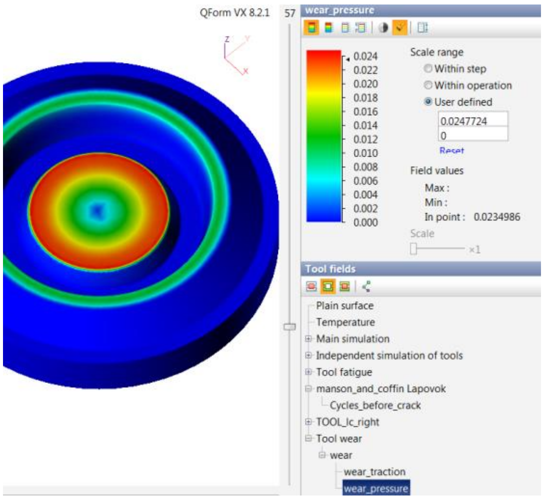


(d) effective stress(1613MPa)



(e) cycles before failure/crack (~ 595)



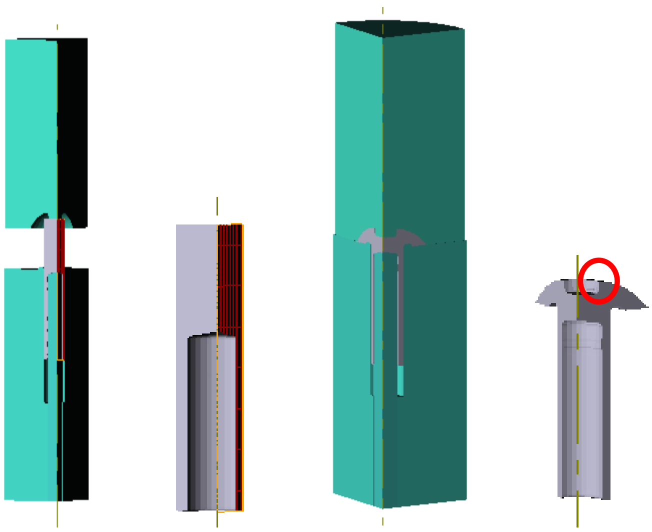


(f) (g)

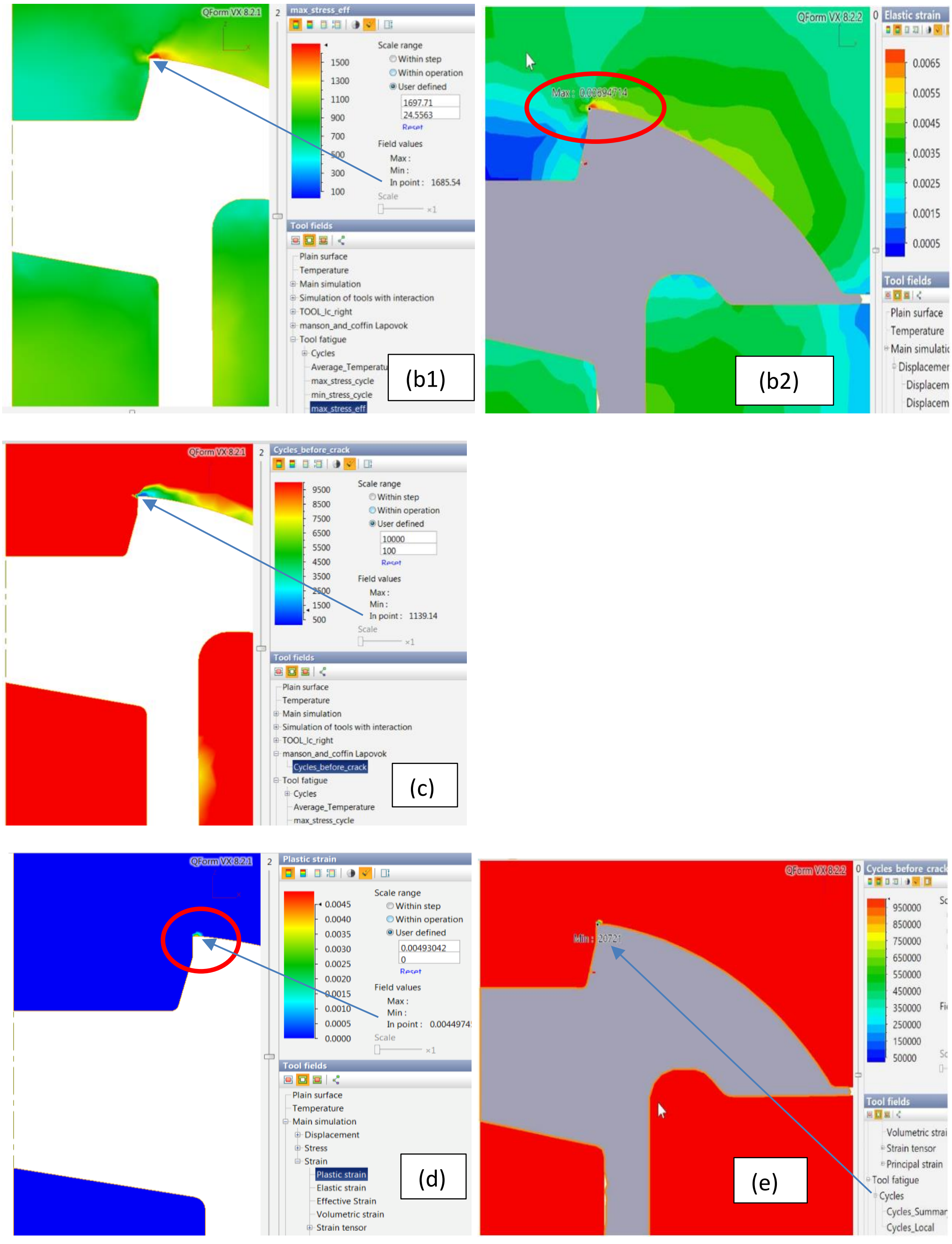
Fig. 4 Simulations: <u>In the forging</u>: Temperature, load-displacement data, <u>In the die</u>: Stresses, strains, number of cycles to fracture, wear due to traction/pressure

It may be observed that the effective stress reached a value very close to the yield stress of the die steel, hence the possibility of unwanted plastic deformation of the die. Furthermore, at the lower die, at the bottom end, such a high stress conduces to a low number of cycles(~595) before failure, requesting careful reviewing of the project (see fig 5 (e). Wear in this die is more related to pressure than to traction/ sliding, during deformation. If the data available from fig 2(b) are taken into consideration, we may observe that the die temperature should not exceed ~200 C.

Rivet forging - an aluminum AA 2024 rivet is to produced by cold forging (only the 3rd stage is here reproduced). Several aspects of the simulation are shown in figure 5.



(a)



QForm VX 8.2.1
max_stress_eff
Scale range
Within step
Within operation
User defined
1697.71
24.5563
Reset
Field values
Max :
Min :
In point : 1685.54
1500
1300
1100
900
700
500
300
100
Tool fields
Plain surface
Temperature
Main simulation
Simulation of tools with interaction
TOOL_lc_right
manson_and_coffin Lapovok
Tool fatigue
Cycles
Average_Temperatu
max_stress_cycle
min_stress_cycle
max_stress_eff
(b1)
QForm VX 8.2.2
Elastic strain
Max : 0.00694714
0.0065
0.0055
0.0045
0.0035
0.0025
0.0015
0.0005
Tool fields
Plain surface
Temperature
(b2)
QForm VX 8.2.1
Cycles_before_crack
Scale range
Within step
Within operation
User defined
10000
100
Reset
Field values
Max :
Min :
In point : 1139.14
9500
8500
7500
6500
5500
4500
3500
2500
1500
500
Tool fields
Plain surface
Temperature
Main simulation
Simulation of tools with interaction
TOOL_lc_right
manson_and_coffin Lapovok
Cycles_before_crack
Tool fatigue
Cycles
Average_Temperature
max_stress_cycle
(c)
QForm VX 8.2.1
Plastic strain
Scale range
Within step
Within operation
User defined
0.00493042
0
Reset
Field values
Max :
Min :
In point : 0.0044974
0.0045
0.0040
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
Tool fields
Plain surface
Temperature
Main simulation
Displacement
Stress
Strain
Plastic strain
Elastic strain
Effective Strain
Volumetric strain
Strain tensor
(d)
QForm VX 8.2.2
Cycles before crack
Min : 20721
950000
850000
750000
650000
550000
450000
350000
250000
150000
50000
Tool fields
Strain tensor
Principal strain
Tool fatigue
Cycles
Cycles_Local
(e)

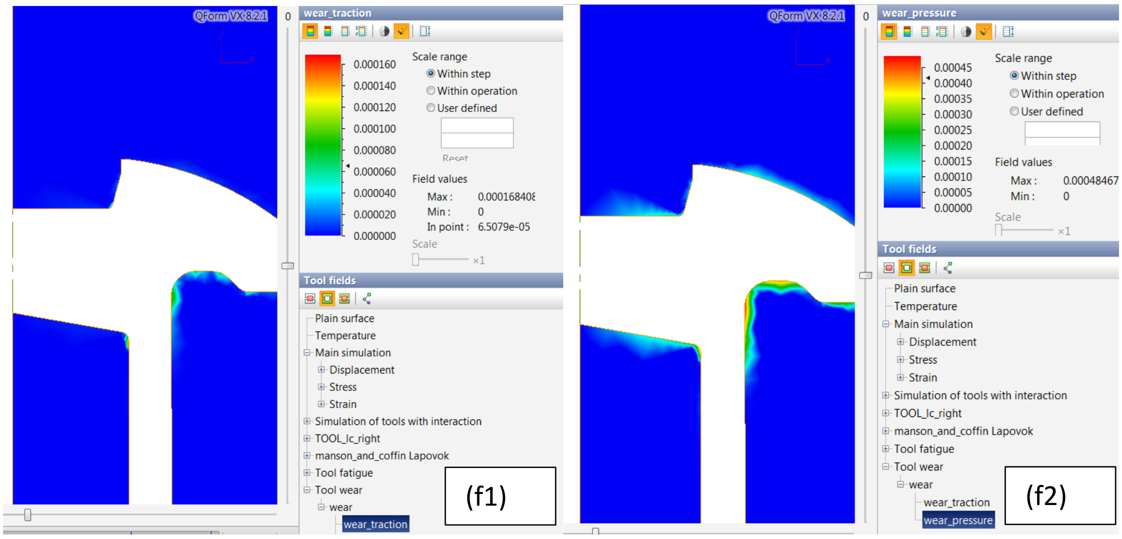


Fig 5. Simulation of an AA 2024 rivet cold forging; (a)- 3rd stage, (b1) max. effective stress, (b2) elastic strain, (c) cycles before failure/crack (d) plastic strain, (e) cycles before failure/crack taking into account both elastic and plastic strains- see Fig 3, (f1) wear due to traction and (f2) wear due to pressure.

In this example (cold forging), it may be noticed that effective stress in the die is higher than the yield stress of the die material fig. 5(b1), hence there is a low number of cycles before failure, fig 5 (c) - according to the Mason Coffin Lapovok criteria related to largest elastic strains (1139), and if plastic deformation is included in the analysis, fig 5(d), a different number of cycles is obtained (2072), fig 5(e), hence, depending on the criteria employed. Wear is more related to pressure than to traction/ sliding.

Conclusions

1) The durability of forging dies mainly linked to low cycle fatigue and wear can be properly analyzed /predicted by software developments linked to basic die tool data, that have shown good correspondence with practical observations.
2) Elastic and plastic analysis has to be performed in the analysis along with the temperature evolution, using a coupled simulation of the deformation (workpiece metal flow/tool stress-strain interaction) as used in the Qfom software. However, greater accuracy, related to the prediction of the number of forgings before crack, can only be obtained with more advanced die fatigue formulations/predicitions.

References:

1- K. Lange, L. Cser, M. Geiger, J. A. G. Kals, Annals CIRP, v41, 1992, pp. 667- 675
2- J.Sjostrom, J. Bergstrom, Scand. J. Met. V.34, 2005, pp 221- 231.
3- A. Vlasov, N.Biba, S.Stebunov, Key Engineering Materials,v. 716, 2016, pp.667 - 676.

4- R. Lapovok, J. Materials Processing Technology v.-80–81,1998, pp. 608–612
5- R. Lapovok, S. Smirnov, V. Shveykin, Int. J. of Fracture, v. 103, 2000, pp. 111-126.
6- Y.-Jo Kim, C.-Hyok Choi, Int. J. Precision Eng. Manuf. v. 10, n. 3, 2009, pp.105-113.
7- S.Stebunov,N. Biba, private communication.
8- D. Delagnes, F. Rezia-Aria, C.Levaillant, Procedia Eng. , v.2, 2010, pp. 427-439