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THIXOFORGING TOOLS MATERIALS: DETERMINATION OF APPROPRIATE FEATURES AND EXPERIMENTAL EVALUATION

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Abstract. Whereas thixoforming of low melting point alloys as aluminium or magnesium is now an industrial reality, thixoforming of high melting point alloys, as steel, is still at the research level. High working temperature, die wearing and production rate are problems that must be solved and are under investigation. The aim of this work is to evaluate the thermal and mechanical loadings applied to the tools during the steel thixoforging process in order to determine if classical hot-work tool steel could be an appropriate tool material. This evaluation has been realized thanks to experimental trials and to simulations on the finite elements code Forge2009©. The effect of the loadings on the tool's failure modes are highlighted and compared to the ones observed in classical hot forging. Beyond this, the failure modes of hot-work tool steel, the X38CrMoV5 or H11, is presented.

1 INTRODUCTION

Due to high slug temperature (usually higher than 1350°C), tools surfaces reach very high temperature. In hot forging, this temperature could already reach 500°C [1-3]; in thixoforging, it could be higher than 700°C. Such a temperature is higher than classical tool steels annealing temperature and could leads to a fall of the mechanical properties. In order to minimize the thermal shocks, dies are usually pre-heated from 40 to 350°C in hot forging.

Thixoforging process, as hot forging is composed of three sequential steps:

- Brutal contact of high temperature slug on the tool. If needed, tool closing could be done before or after this step.
- Forming step during which mechanical constraints are applied to the tool.
- Part ejection and tool cooling.

In production, these steps are repeated in a cycle. Tool damaging could be due to different mechanisms: fatigue cracking following thermomechanical loading cycle, microstructure evolution or scaling due to hot working, geometrical modification generated by wearing or plastic deformation. The common failure modes observed in hot forging are shown on Figure 1.

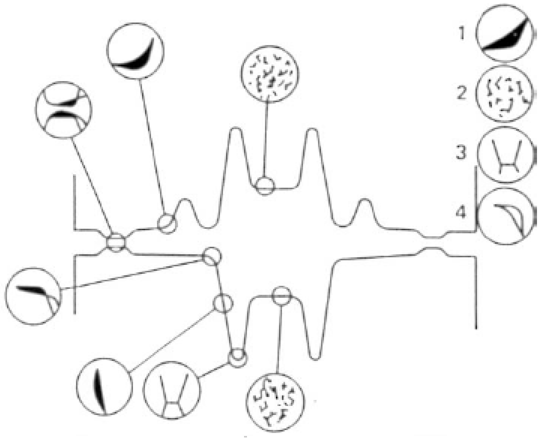

Figure 1: Most common hot forging tools failure modes and their localizations: (1) abrasive wearing, (2) thermal fatigue, (3) mechanical fatigue, (4) plastic deformation [4]

In thixoforging, thermomechanical loadings are quite different as forming loads are lower but thermal loads are higher. The failure modes could be different too. Their determination is the first aim of this paper. The resistance of classical hot forging tool steel (X38CrMoV5) to these loadings is also studied.

2 EXPERIMENTAL

2.1 Tool

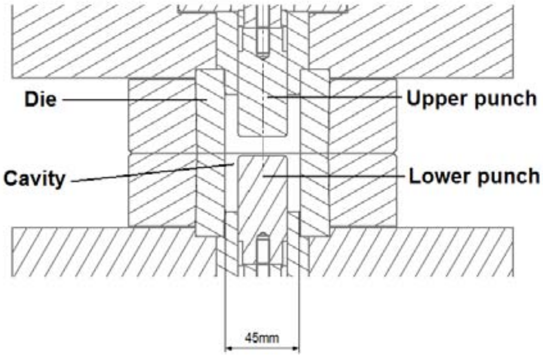

Figure 2: “H” or double-cup tool

The tool used during this work (Figure 2) is made in H11 hot work steel and forms a double-cup part (or axisymmetric H). The deformation is a compression followed by an important reverse extrusion. Due to small thickness of the walls, this geometry highlights the thermal effects occurring during forming. The dies and the punches are instrumented by thermocouples in order to measure their inner thermal fields. At the beginning of cycle, the tool is open and the punches are out of the dies. When heating is done, robot puts the slug in the lower die and moves back. Then, the upper part of the tool moves down to close it and the two punches form the part. It is also possible to form it with the upper punch alone if the lower one is already inside the die at the beginning of cycle. This possibility was used in a former work to determine friction parameters [5].

2.2 Tool material

Tool has been made of X38CrMoV5 hot working tool steel. It has a good thermal shocks resistance thanks to the presence of chrome, molybdenum and vanadium. It is commonly used as die material in hot forging [6]. The X38CrMoV5 composition is given on Table 1.

Chrome, molybdenum and vanadium make carbides which increase wearing resistance. Chrome and molybdenum delay the softening due to annealing. Chrome and vanadium inhibit the grains coarsening during austenitizing and chrome and silicon increase scaling resistance.

Table 1: Mass composition of X38CrMoV5 hot working tool steel [6]

	C	Cr	Mn	V	Ni	Mo	Si
[%]	0.40	5.05	0.49	0.47	0.20	1.25	0.92

Nevertheless, this steel grade looses a part of its mechanical properties at high temperature. Table 2 gives the mechanical properties of X38CrMoV5 for four working temperatures for a material previously oil-quenched at 1040°C after two tempering at 640°C. At 600°C, resistance is nearly divided by two. Extrapolated until 800°C, Rp0.2 falls to 400MPa, so lower than the locking force applied on the dies. Moreover, the austenitizing beginning temperature (830°C) is closed to the working one [7].

Table 2: Mechanical properties of X38CrMoV5 at different working temperatures [7]

Temperature [°C]	Rm [MPa]	Rp0.2 [MPa]	A [%]
20	1400	1170	12
400	1170	1020	13
500	1050	900	18
600	810	700	25

2.3 Modelling

The Finite Elements code Forge2009© was used for the simulations. The constitutive law used in this work is quite simple and mainly driven by the liquid fraction, and so the temperature. Thus, the structure of the raw material and its evolution are not explicitly represented. Even if this is a limitation of the calculation results, the error on the flow behavior is small for high solid fraction. Thermal exchanges are already taken into account by the FE code.

The constitutive law is a classical Spittel one (which is the default law used by the solver) when material temperature is lower than solidus and a modification of this Spittel equation when the material temperature is higher than solidus. The modification induces a linear decrease of the consistency by multiplying it by a factor going from one to zero between the solidus and the liquidus. There is then a smooth transition between semi-solid and solid behavior during cooling.

The constitutive law is

$$\sigma = Ae^{m1T}\varepsilon^{m2}e^{\frac{m4}{\varepsilon}}\dot{\varepsilon}^{m3} \tag{1}$$

for T < Tsolidus and

$$\sigma = A\left(\frac{T_{liq} - T}{T_{liq} - T_{sol}}\right)e^{m1T}\varepsilon^{m2}e^{\frac{m4}{\varepsilon}}\dot{\varepsilon}^{m3} \tag{2}$$

for Tsolidus < T < Tliquidus

In these equations, σ is the stress, ε is the strain, $\dot{\varepsilon}$ is the strain rate, T is the temperature, T_{liq} is the liquidus temperature, T_{sol} is the solidus temperature and A, m1, m2, m3 and m4 are constants depending on the steel grade. For 100Cr6 steel, the values of the constant parameters are given in Table 3. The values of A and m1 to m4 come from the database of Forge2009© and the values of T_{liq} and T_{sol} have been obtained by Differential Scanning Calorimetry (DSC) [8].

Table 3: Values of the constants used in equations (1) and (2)

Parameter	Value
A	2707.108
m1	-0.00325
m2	-0.00325
m3	0.1529
m4	-0.05494
T_{sol}	1315°C
T_{liq}	1480°C

3 RESULTS AND DISCUSSION

3.1 Mechanical loading

In the case of thixoforming, mechanical loadings are about ten to twenty times lower than in hot forging [9]. Figure 3 shows the Von Mises equivalent stresses, calculated by the Forge2009© software, at the end of forming inside the lower part of the tool. The simulated forming is a 100Cr6 steel slug symmetrically deformed with a tool speed of 170mm/s. It appears that maximum stress, for the areas in contact with the semi-solid material, is around 170MPa. This maximum stress is located in the centre of the punch top surface. If the punch temperature reaches a value for which its material yield stress is lower than 170MPa, there would be a deformation of this punch.

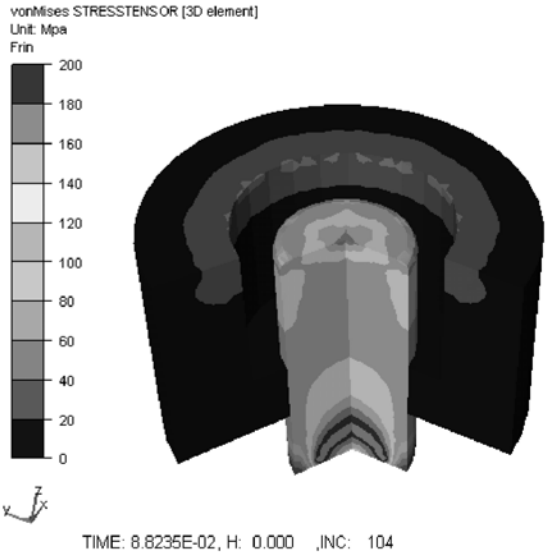

Figure 3: Von Mises equivalent stresses inside the tool at the end of forming

The accordance of the simulation total load to the recorded forming load for the upper punch is shown on Figure 4.

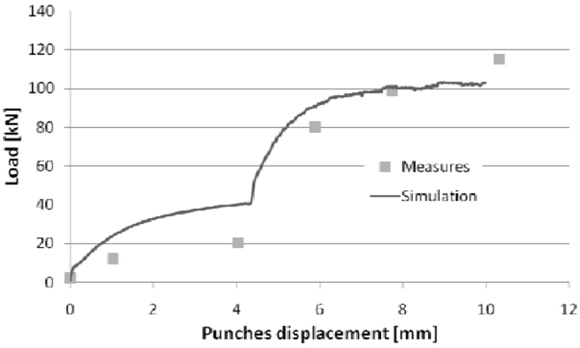

Figure 4: Comparison of the forming load measured during test and calculated by Forge2009©

The simulation did not take into account the locking force applied to the dies to keep the tool closed. In the present case, this force is 2000kN. On a surface of about 3200mm², the pressure is close to 630MPa.

3.2 Thermal loading

In hot forging, slugs are usually heated at a temperature higher than 1000°C. Their contact with the dies could heat these ones up to 500°C. In thixoforming, the working temperatures are still higher, until more than 1400°C. Tools surfaces are then subjected to very high temperature. The double-cup tool has been designed in order to be instrumented by K-type thermocouples. The measures of these thermocouples allowed validating the temperature fields calculated by simulation, as shown on Figure 5.

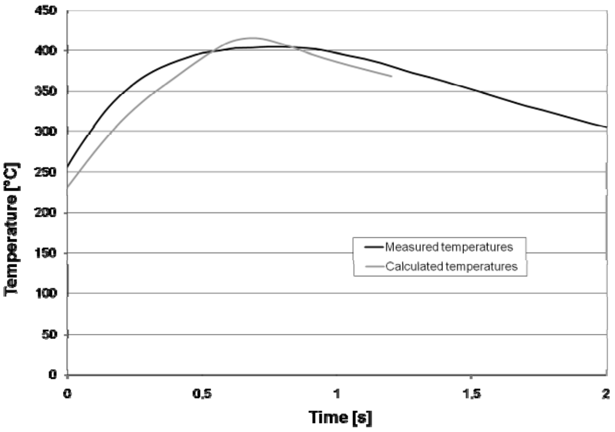

Figure 5: Comparison of the temperatures inside the tool measured by thermocouples and calculated by Forge2009©

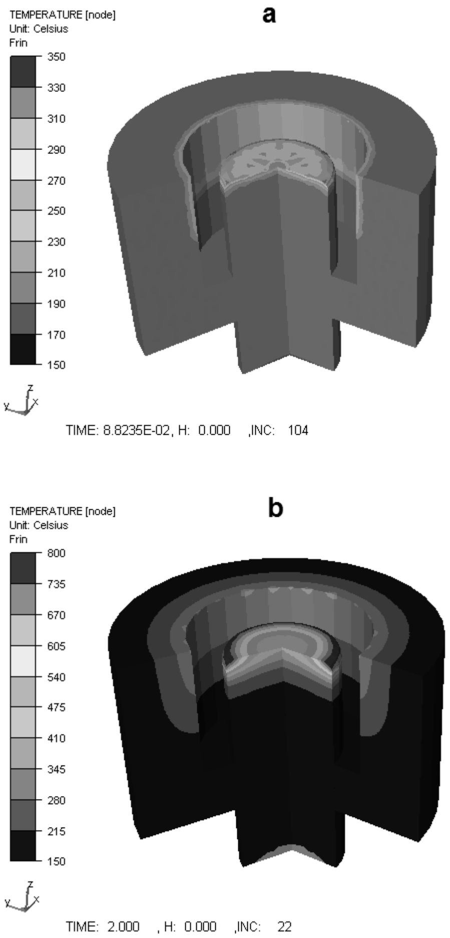

Figure 6: Temperature fields inside the tool at the end of forming (a) and at ejection time (b)

Figure 6 shows the temperature fields inside the lower part of the tool at the end of the forming and two seconds after, when the tool opens and the part is ejected. Simulation shows that, at the moment of the ejection, the surface temperature could reach 800°C. In this case, if the stresses are important, because of galling during the ejection for example the tool could easily be damaged.

Simulation has been run for hot work tool steel. In the case of another tool material, and thus another thermal conductivity, the surface temperature should be different. In the case of a lower thermal conductivity, the surface temperature would be higher, which will be interesting from the forming point of view as the flowing material temperature would stay higher during a longer time and thus, the forming load would be lower. At the opposite, from the tool point of view, this higher surface temperature would increase the risk to overrun the tool material yield stress and to damage the tool. Thermal stresses, coming from thermal gradients, depend of these gradients value and of the thermal dilatation coefficient.

3.3 Wearing

Figure 7 shows the area of maximum wearing. As in hot forging, they are located where sliding speeds are the higher, thus mainly at the punch edge. On the die, there is not any wearing at the joining plane level as the tangential speed is null on this area in the case of a symmetric deformation. As the working temperature is higher in thixoforming, the tool wearing resistance is lower than in hot forging.

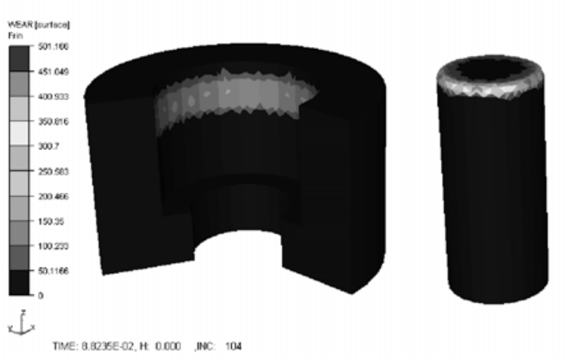

Figure 7: Wearing areas inside the tool

3.4 Hardness

Hardness of the tooling's lower punch has been measured after 50 cycles of forming. Figure 8 shows the hardness values measured on the punch and the line along which the measured have been made.

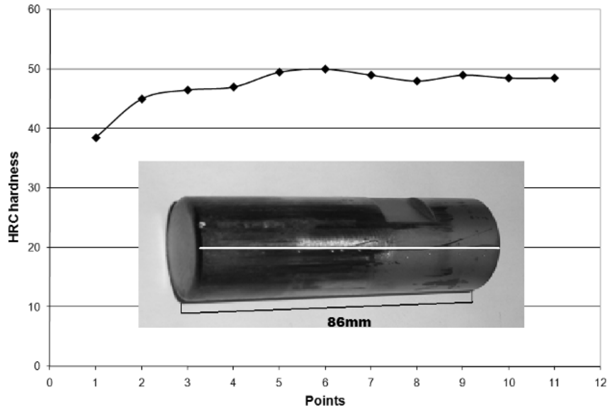

Figure 8: Hardness measured along the lower punch after 50 parts forming

The graph shows that the lower part of the punch has kept its original hardness, around 48-50 HRC. But the hardness of the last three centimetres has noticeably decreased. The closest point to the plane surface has a hardness of only 38.5 HRC. This softening is due to annealing occurring at high temperature. This means that the punch is more easily deformable. Moreover, some marks are visible on the punch surface, due to galling and abrasive wearing.

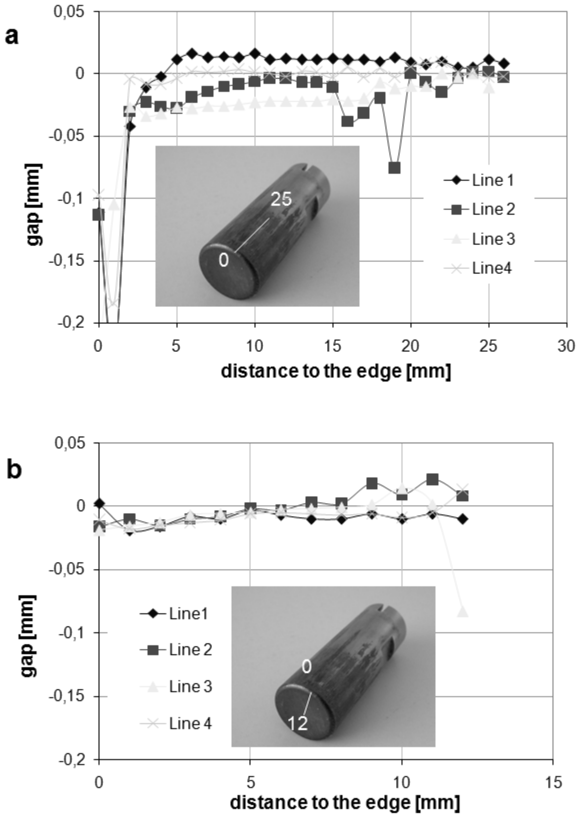

Figure 9 Profile measures on the punch after 50 formings along the lateral (a) and top (b) surfaces

3.5 Mechanical resistance

Figs. 9 and 10 give profile measures of the upper punch (Figure 9) and die (Figure 10). These profiles have been measured on four different lines in order to limit the impact of local damages.

The profile of the punch lateral surface (Figure 9a) does not show significant modification of this surface. On the top surface (Figure 9b), a small modification could be noted, as the point zero, corresponding to the punch edge, is few hundredths of millimetres lower than point 12, corresponding to the surface centre. This slight deformation is due to the punch diving inside the semi-solid steel. It seems thus that mechanical resistance of the punch is high enough to avoid great plastic deformation.

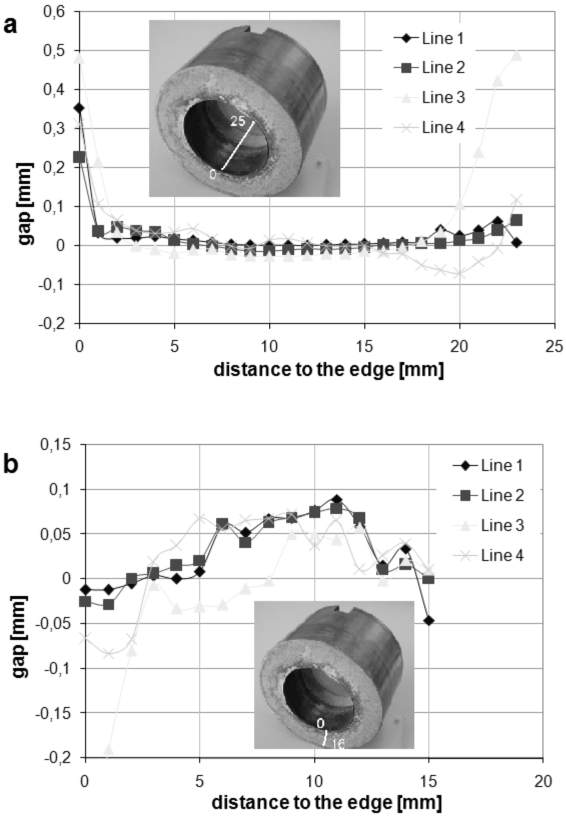

Figure 10 Profile measures on the die after 50 parts forming along the lateral inside (a) and top (b) surfaces

The top surface of the die (Figure 10b) does not show any major modification, except the usual one due to scum (residual lubricant, scaling…) crushing between the dies bearing areas during the locking. However, the inner lateral surface (Figure 10a) shows a great deformation (2 to 5 tenth of millimetre) at the joining plane level. This is due to the dies locking which induces important stresses (about 630MPa). Around this joining plane, the temperature could reach 500°C (Figure 6). In this case, the X30CrMoV5 tool steel Rp0.2 is 900MPa (Table 2), so clearly higher than the locking force. Nevertheless, one must take into account the locking force regulation. As it is not perfect, the locking load often reaches a transient value higher than 2500kN for a setting of 2000kN. In this case, the stress could reach 800MPa, what is close to the X38CrMoV5 steel Rp0.2 value. It is sufficient to create a deformation, really small but increasing from trial to trial. The deformation is thus a kind of fold of the die toward the inside at the joining plane level. This is an important issue, as the deformation acts as a reverse draft during the ejection, locking the part inside the die. At the opposite of the punch case, the hot mechanical resistance of the X38CrMoV5 hot work tool steel does not seem sufficient in this case.

An other super-thickness is visible on Figure 10a close to point 25, but this is only due to lubricant waste accumulation. This is not a die deformation.

4 CONCLUSIONS

Up to now, thixoforming tool lifetime is still the main lock to the technology industrialization. Due to high working temperature, mechanical features of the hot work tool steels classically used in hot forging strongly decrease. In particular, hardness and yield stress are too low to guarantee the tooling integrity.

Hardness could be increased by surface treatment, as nitriding, glazing [10, 11 and 12] or oxidation. The problem is to keep a good adherence of the coating or a good stability of the structural treatment.

Plastic deformation is the main issue. It is due to mechanical and thermal stresses. Compared to hot forging, mechanical stresses are clearly lower but thermal stresses are higher. However, at industrial production rate (6-12 parts per minute), the working temperature should be higher but temperature variation would be lower, so the thermal fatigue should be lower than in the case of laboratory study. An important point is also to minimize the contact time between tool and semi-solid steel in order to minimize the tool temperature. Parts ejection must then be as fast as possible to decrease thermal loading.

The X38CrMoV5 hot working tool steel could be used only for low stresses forming. Its hardness is not sufficient to avoid abrasive wearing at high working temperature.

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