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From the forging to the complete manufacturing chain Simulation

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Abstract: After a long period where the car mass reduction was more a discussion topic than a real fact, the process is now really in progress. To make it possible, part's mechanical properties have to be improved and this can only be obtained through a global optimization of the manufacturing chain including, of course, heat treatments. To make this possible and user-friendly, all the stages have to be simulated within a unified environment.

After a brief description of the cold forming challenges, we illustrate the concept of the complete manufacturing chain simulation with the example of a gear (2 forming stages, carburizing, quenching and tempering) and of a screw (cable drawing, 2 stages forging and thread rolling).

Keywords: Complete manufacturing chain simulation, 'in use properties'

1. Introduction

Forming process simulation started in the 80th with, as a main objective, the prediction of forming defects such as under filling, folding and possible cracks. With this more or less achieved, focus switched to the dies with the goal to predict and improve die life and reduce production costs. If they are still some progress to be made, stress distribution and die wear are now available in most commercial simulation packages. Focus is now back on the component with a specific attention to "in use properties". These properties are the result of the whole manufacturing chain from the wire drawing to the final heat treatment. In this paper, after a brief chapter devoted to cold forming specific simulation difficulties, we use two different examples to show how recent developments have made significant progress possible in properties prediction and validation.

2. Specific difficulties of cold forming simulations

Most typical defects in case of forging are under-fillings and folds. Simulation predictions for these type of defects are commonly available today. Our purpose, in this chapter is to show more specific cold forming effects.

2.1 Die elastic deformation consequences

Cold forging is often a near shape process with the goal to either eliminate or dramatically reduce machining. Consequently, precise control of the shape is very important. Figure 1a displays a typical die set up for cold forging using several carbide inserts as well as a pre-stressing ring. Figure 1b shows the final shape differences between a simulation taking into account deformable dies and one using rigid dies.

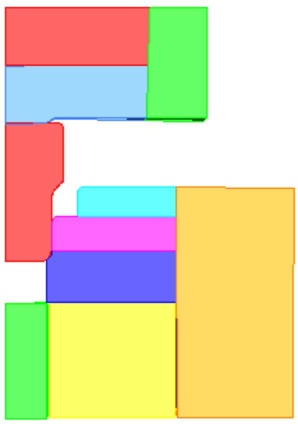

Figure 1a Die set

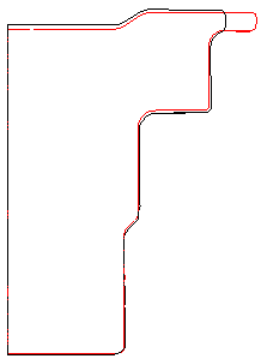

Figure 1b Die deformation influence

2.2 Elastic springback

In case of hot forming, most computations are done using either rigid-plastic or viscoplastic material assumptions. In the case of cold forming, the elastic phenomena can be very important and as such needs to be taken into account. This point is illustrated on Figure 2 and Figure 3. Figure 2 displays situation at the beginning and at the end of a small plate cambering process.

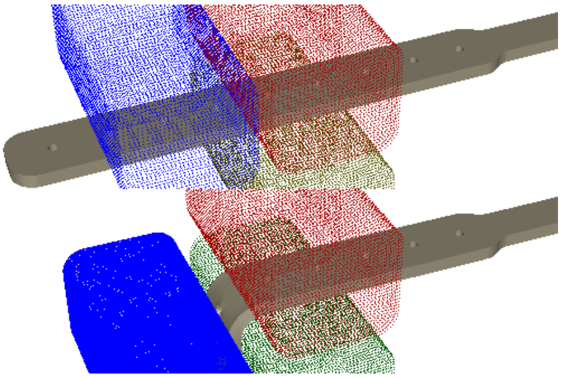

Figure 2 Cambering

In such a situation, the effect of springback can be very important. In Figure 3, geometry after unloading is represented in grey while the dark red line corresponds to the end of the forging. In this example, the displacement can reach several millimetres.

Figure 3 Springback

2.3 Sucking deffect

The part presented below is very small and designed to be used in a printer. The process used is direct extrusion but, with the thickness of the preform, a huge defect arises during the forming.

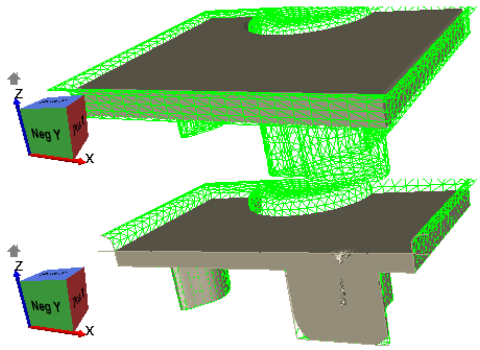

Figure 4 Initial situation and defect

3. Screw forming example

Usually, the forming process simulation and the numerical validation of part design under pre-defined loading cases are two independent activities. The purpose of this example is to show how results of the forming simulation could be used in the stress analysis.

To achieve this, we will start from a wire, then apply 4 passes drawing followed with 2 forging stages to shape the screw and finally apply a torque to this screw “in situation” to see how it behaves.

3.1 Cable drawing

The cable drawing is always done using in sequence different dies located one after the other in order to achieve the target surface reduction. Final strain distribution can be predicted by computing one reduction stage after the other. But, the fact that all the stages are taken into account in the same simulation will have a large influence on the stress level in the wire and, consequently on the damage evaluation.

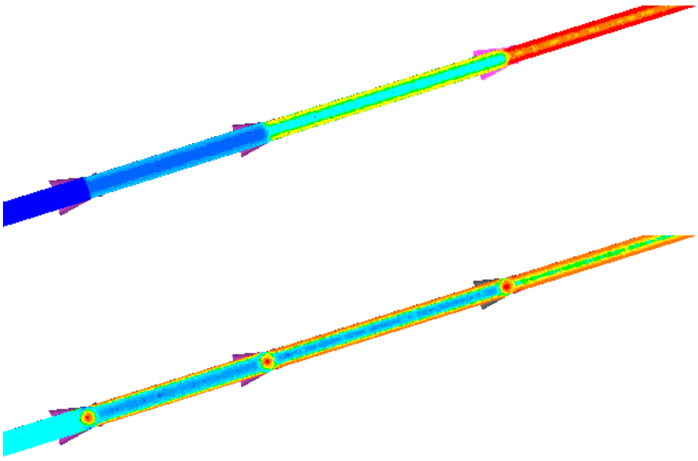

Figure 5. Strain evolution in a cross section as well as stress tensor component in the drawing direction

3.2 Forging

The forging is done in 2 stages: preform and finisher (Figure 6).

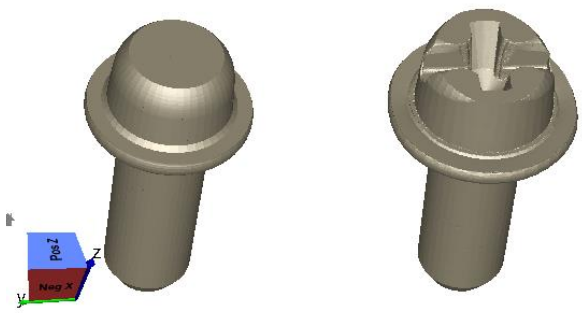

Figure 6. First and Second Forging stage

3.3 Screw testing

An important point for a screw is the ability for the head to sustain a torque without breaking or having too much plastic deformation. To check this, we fix the lower extremity of the screw (in red in Figure 7a), we apply a rotational displacement to a screw driver (light grey in Figure 7a) and we measure the torque. The bigger the torque, the better the screw. Figure 7b shows situation after 1/3 of rotation (see upper part of the screw driver to evaluate the rotation).

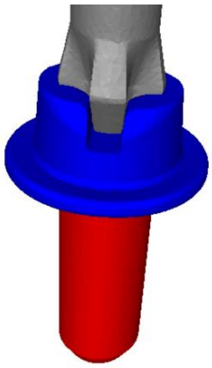

Figure 7a. Fixed nodes on the screw

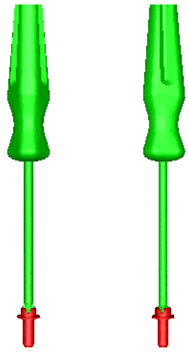

Figure 7b. Initial and final situation

Figure 8 displays the evolution of the torque as a function of the screw driver rotation. On this graph, 3 phases can be seen. In a first stage, we see a more or less linear increase followed by a flat area and finally a decrease.

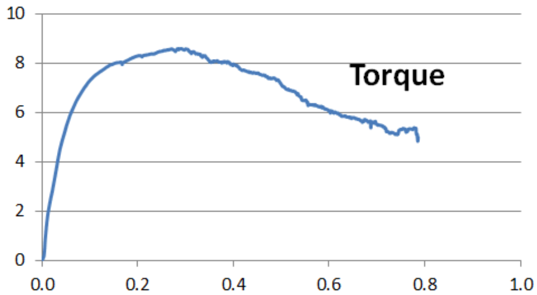

Figure 8. Evolution of the torque

The linear portion of the curve corresponds to elastic screw deformation. Later, the influence of the strain hardening can be seen until the deformation of the head leads to a decrease.

3.4 Threads rolling

So far, we have been focusing on the screw head, making the assumption that the threaded area was idle. This is not mandatory as threads forming can be simulated and then taken into account.

Figure 9 displays the thread rolling simulation (Initial situation in the upper area and final shape in the lower area).

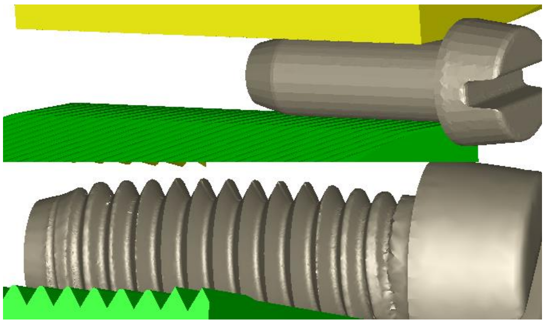

Figure 9. Thread forming simulation

When the simulation is completed, it is the possible to import results in the stress analysis computation.

Figure 10 illustrates the example of a bolting simulation. The case is made of 5 different deformable bodies (screw, bolt, washer & 2 sheets)

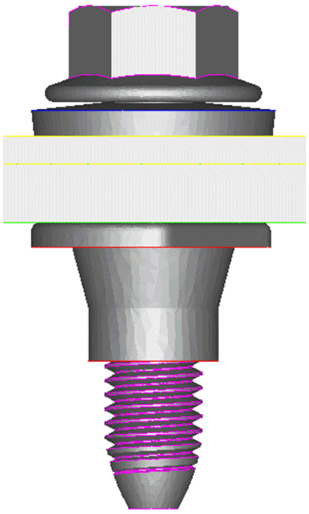

Figure 10a. Initial situation

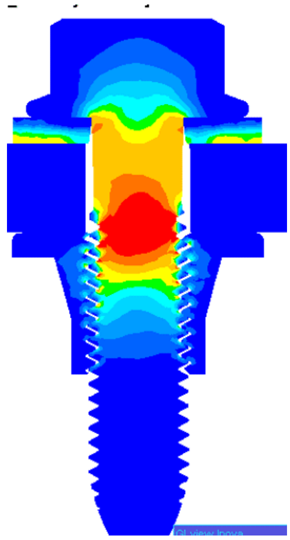

Figure 10b. Stress distribution

In this section, we demonstrated it was possible to holistically simulate the different stages of a screw life. Different stages were illustrated using different geometries but nothing would prevent to follow the same geometry from the beginning to the end.

4. Gear example

The following example is the forming of a bevel gear. The manufacturing process starts with 2 stages forming then piercing and machining. After the forming, the heat treatment is applied using a carburizing stage followed by quenching and tempering. To perform the analysis, the simulation chain is the following:

- The 2 forging stages are computed,
- Stresses and strain results are remapped on the machined geometry
- Carburising simulation is performed on this geometry
- Quenching simulation is done using carburizing results
- Tempering simulation is performed using quenching results

4.1 Two stages forging

Figure 11 represents the 2 forging stages. Initial temperature is about $300^{\circ c}$ and the material is a 20MnCr5 Manganese Chromium steal.

Initial and final situations of the first stage can be seen on the upper area of the picture. The lower area displays geometry seen from both lower and upper side after unloading at the end of the second stage.

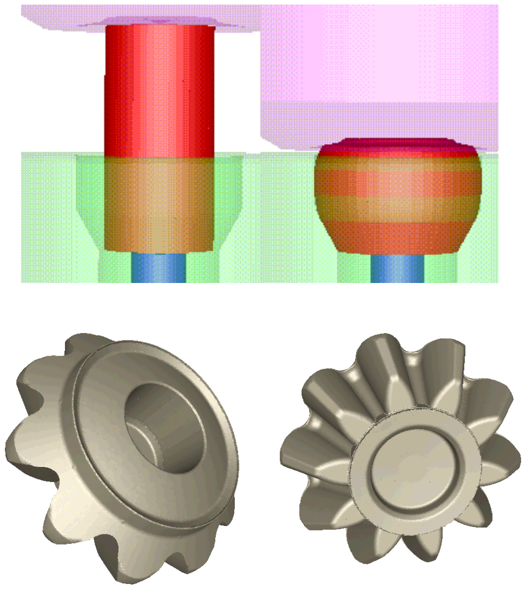

Figure 11. Two stages forging

4.2 Carburizing

The purpose of carburizing is to increase the quenchability of low carbon steels by increasing the carbon rate on surface. In order to achieve this, the component is located in a container where atmosphere contains high level of carbon and the temperature is kept around $900^{\circ c}$.

As far as simulation is concerned, we start from the part's geometry after machining and we remap on this geometry both stress and strain results of the forging stage. We apply to this geometry the thermal cycle defined in the real process and we add the Carbon rate as a supplementary unknown. The reason to transport stress and strain is because at high temperature, the flow stress will decrease and some residual stresses will relax creating some part deformations. Obviously, a real machining simulation would improve the quality of the result but at this stage, such a simulation remains difficult.

Figure 12 represents the equivalent strain at the beginning and carbon distribution at the end of carburizing.

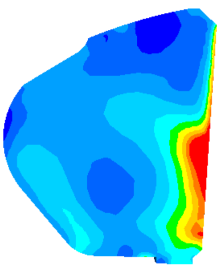

Figure 12a Strain distribution

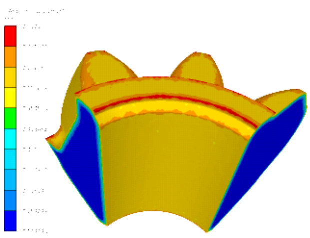

Figure 12b Carbon distribution

4.3 Quenching

After carburizing, an oil quenching is performed. Figure 13 displays the rate of martensite, bainite, perlite and ferrite. As it could have been anticipated, the local increase of carbon produced mainly martensite on the surface. With the original carbon rate, and in the same cooling condition, martensite appears only at the extremity of the teeth.

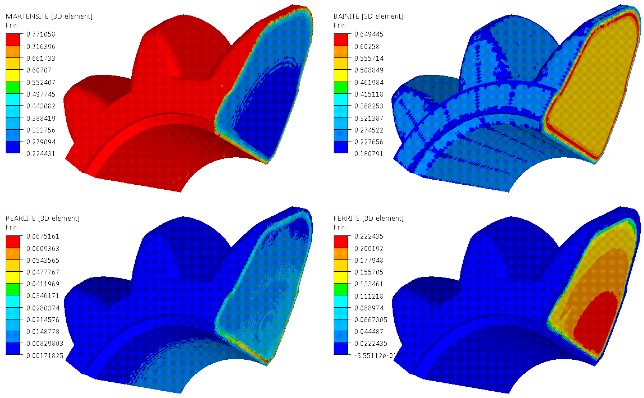

Figure 13. Phase distribution after quenching

This carburizing/Quenching doesn't only affect the different phases in the part. Due to the slightly different density, phase changes as well as heating and cooling phenomena create some plastic deformation which can be incompatible with the part acceptable tolerances. Figure 14 displays the shape of the part after quenching with magnified deformation.

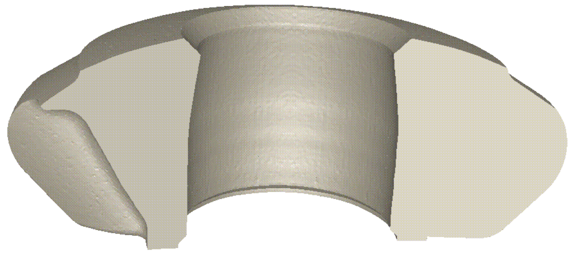

Figure 14 Deformation of the central area

With the central hollow shape represented above, the contact area between the gear and the shaft is reduced to two lines at the upper and lower extremity of the gear which is not acceptable. In real life, the issue is avoided by anticipating this deformation at the machining stage.

4.4 Tempering

The aim of this last phase is mainly to release residual stresses. The higher the temperature, the more efficient it is. But a decrease of hardness will be also more important. In this case, tempering phase is short and performed at low temperature. Consequently influence on hardness is limited. Figure 15 displays hardness distribution before and after the tempering.

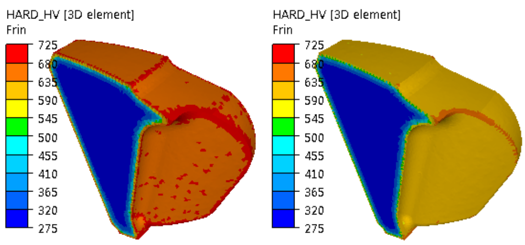

Figure 15 Influence of the tempering on hardness

5. Conclusion

As demonstrated in the different examples presented above, most of the forming processes can now be simulated taking into account process specificities. The next stage is to be able to predict component ‘in use properties’. Depending on the situation, some of these properties are already available and it is possible to apply component loading cases on results of the forming simulation. Obviously there is still work to be done but a lot of research work is in progress to enlarge the scope of the covered situations.