Numerical modelling of forming high strength aluminium

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Abstract: In recent decades the developments of vehicle materials and technologies have been influenced by the environmental regulations. Reducing the mass of vehicles is important to reduce the air pollution emissions. In order not to break the safety standards with this reduction, the strength of the used materials should be increased. Nowadays the high strength steels have not enough formability, so the base materials of the vehicle need to be changed. The density of aluminium is significantly lower than that of steels, which is positive for weight reduction, but the strength of the traditional aluminium alloys is low, so it needs to be enlarged. However, due to their different alloying elements and the rigid disperse precipitates phase they create, the ductility of high strength aluminium is not sufficient in most cases. The lower formability is a serious technical challenge for automotive engineers. The solution is in the newest dedicated FEM codes. With the help of these software the engineers can more easily plan the technical background of manufacturing a part, or making formability test in virtual environment without using specimen. Because of this, the objective of this paper is the numerical modelling of forming high strength aluminium.

1. Introduction

Nowadays there are many new materials in the automotive industry. Many of these new materials are made from high strength metals, because of the environmental regulations. The new aluminium alloys have a growing potential in industrial applications. Due to their alloying they have high strength and also due to the rigid disperse precipitates they create, they have lower formability. The traditional forming technologies are not suitable for these cases, therefore new technologies have to be developed. With the Hot Forming and Quenching (HFQ®) process patented by the Imperial College London (ICL) and the Impression Technologies (ITL) aluminium parts with complex geometry can be produced. Accordingly the manufacturing process is given, but along with this, the software used to simulate the production must also keep up with these developments. They must have the new materials and must have the possibility to model the new technologies: a further problem that these high strength aluminium alloys can be successfully formed at elevated temperature. For this reason the concept of this paper is to give insight into the background of a simulation of a forming process at high temperatures. We will mainly focus on the difficulties of hot forming simulation, but it is reasonable to make an overview of the cold forming simulations too.

2. Input parameters of a cold forming simulation

The relationship of the stress and strain is the most important part of describing the mechanical behaviour of a material. For cold forming in sheet metal forming elastic-non-linear hardening material
rules are widely applied. These hardening rules describe the material that undergo elastic deformation until yield, beyond yield stress, elastic and plastic deformations occur simultaneously. The stress value needed for further plastic deformation changes, as the material deforms, i.e. it hardens.

2.1. Plastic behaviour in cold forming simulations

The yield criteria define the condition for the elastic behaviour limit, after which the material continues deforming plastically, showing a hardening behaviour. Over the years, the modelling of the sheet metal yield criteria has evolved to describe more accurately the anisotropic behaviour, based on the yield criteria proposed for isotropic materials by Tresca, Huber and Von Mises [1]. One of the first yield criteria for anisotropic materials was made by Hill, usually referred as Hill 48, which takes the anisotropy coefficients into account in several directions (0°, 45°, and 90° to the rolling direction). The deficiency of Hill classic model was already discussed in several papers, and during the last decades, new theories were published better describing the anisotropic behaviour of sheet materials: here we just mention the Barlat’89 model developed for aluminum and the BBC2005 model elaborated for steels by Banabic [2].

As the material hardens with the increasing plastic deformation, the yield surface - which was described by the yield criterion- also will change. The four types of the changing the yield surface are shown on the Figure 1.

![Figure 1. Evolution of yield locus according hardening types. [1]](image)

Isotropic hardening, which refers to the proportional expansion of the initial yield surface; (ii) kinematic hardening, if the deforming material shows a yield surface that does not change its form and size, but translates in the stress space under deformation; (iii) rotational hardening, which causes the yield locus to rotate; (iv) distortional hardening, which causes the yield locus to distort [1].

To make a forming simulation usually the yield surface and the flow curves are needed as input parameters. In a dedicated FEM code, the isotropic hardening model is the default setting, but it is possible to use another model.

2.2. The limit of forming in cold forming simulations

With the Yield surface and the flow curve the behaviour of the material can be described but can’t determine the occurrence of its failure. In sheet metal forming the limits of formability is usually defined
by the Forming Limit Diagrams (FLD). This diagram indicates the combination of the major and minor strains that can be applied to a metal sheet without failure. Prediction the failure of the sheet based on the FLD, is widespread in the industry and the finite element simulations, mainly thanks to its simplicity. Despite its prevalence, it has several drawbacks: The FLDs depend on many things, for example the sample thickness, the strain history, etc. For non-linear strain paths (Figure 2.), it changes significantly. These drawbacks (especially the dependence from the applied strain path) have pushed the development of alternative approaches for predicting the sheet failure. There are new diagrams that was designed to ignore the effect of the different strain path. The Forming Limit Stress Diagram was one of the first developments which was later improved by Stoughton [3]. The FLSD can be derived from the FLD with finite element methods, but in case of complicated strain paths the independence from strain path is still questionable.

Because of the drawbacks of the earlier mentioned models, the researcher put large effort to create another way to predict the failure, which is based on analytical formulation. These Fracture Mechanism (FM) models can use fracture criteria or can be void-growth-based. FM models like McClintock or Rice and Tracey usually has a damage indicator variable. The cracking occurs when this variable reaches a defined value.

While the dedicated fem codes based on the above described parameters are very useful tool for the industry for cold forming simulations, the simulations of forming at elevated temperature has not yet developed completely. Therefore, in the following chapter I will mainly focus on it.

3. The problems in hot forming simulations

In hot forming, the material properties and relationships should be known as a function of temperature, as well. For the description of material behaviour for hot conditions besides the temperature dependence of basic physical properties we have to know the material relationships between the stress and strain components (usually given by the hardening rule)[2].

Higher strain rates at the same temperature lead to greater stress, however the higher the temperature is the lower the reached stress level is. Along with this, the yield surface and the flow curves changes as the function of temperature. Because the temperature and the strain rate are usually not constant during the forming process, describing the material behaviour becomes more complex. Most of the dedicated FEM packages are not able to handle the complexity of the above described process, even though it is well suited for simulation of cold forming process.
3.1. Plastic behaviour in hot forming simulations

As it was mentioned earlier, modelling of hot forming processes is more complicated from the viewpoint of flow curves, since in this case, the visco-plastic material model should be used. Therefore, the dependence of flow curves on the temperature and strain rate should be taken into account which requires the flow curves determination at different temperatures and strain rates. Describing the yield surfaces are also difficult tasks, because the temperature dependence of anisotropy coefficients has to be taken into consideration, as well [2].

Based on the different temperature and strain rates for a correct simulation more flow curves and Yield surfaces are required. It can be easily performed in FEM codes with a flow curve matrix that have temperature and forming velocity axes (Figure 3).

![Flow curve matrix and Yield surfaces](image)

Figure 3. a.) Flow curve matrix and b.) Yield surfaces

The two input parameters that I show on the Figure 3. are not independent. The Yield surface - based on the Yield criteria - can be derived from the flow curve. Due to this reason the flow-curve-matrix is enough to describe the behaviour of the material while it deforms.

3.2. Problems with predicting the failure in hot forming simulations

The limits of formability can be regarded as one of the most important input parameters in any forming simulation. In the viewpoint of failure, the Forming Limit Diagrams are not suitable in hot forming simulations. On the one hand because of its drawbacks, on the other hand, because their strain rate and temperature dependence. In hot forming simulation, where the temperature of sheet and also the strain rate can change from point to point, which means that different Forming Limit Curves should be applied theoretically from point to point too, which is obviously impossible and also the FLC determined for a fixed temperature and strain rate may be used with acceptable accuracy in a limited range of parameters [2]. It is possible to add the strain rate or the temperature to the FLD as a third axis but not at the same time. Maybe this model might be inserted to a dedicated FEM code, but usually the temperature and strain rate are not constant during production.

Due to this reason researches want to create another way to predict the failure of the sheet. The FLSD is based on the forming limit diagram and its independence from strain path is also questionable cannot be applied either, accordingly this model also not appropriate. The Fracture Mechanism model works with a constant damage variable, however this variable changes significantly while the material deforms at elevated temperature.
3.3. New damage model

Most of the works on damage mechanics uses state variables to represent the effects of damage on the structural stiffness, remaining life and failure of the material, but damage evolution does not progress spontaneously after initiation, thus requiring a damage evolution model. Lin, Liu and Dean (2005) introduced continuum damage mechanics theories to model damage evolution in a wide range of metal forming processes, particularly for hot metal forming. One of the newest models based on the aggregation of the damage, which means that under plastic deformation discreet voids or cracks may nucleate and grow within the material and eventually these defects would coalesce to form macro cracks, leading to material failure. The effective stress forms the basis of the Continuum Damage Model (CDM):

\[ \sigma_{eff} = \frac{\sigma}{1-D} \]  

(1)

Where \( \sigma \) is nominal stress, and D is material damage variable. This model connects the strain with an inner damage variable, which is zero before the deformation, and one in the moment of failure. It can be seen, that this damage variable changes as the deformation progresses. As the deformation correlate the temperature, and the changing of the stress level, the CDM model is currently the best option to modelling a hot forming simulation like the HFQ™. Along with the positives the CDM also have some drawbacks. It can’t be yet applied in dedicated FEM codes, and need many complicated measurements to define.

4. Conclusions

In this paper we have shortly summarized the present situation of the numerical simulations and modelling. We have made an overview over the parameters of the cold forming simulations. Based on this, easy to ascertain about the excellent applicability of the dedicated FEM codes in supporting the cold forming production. The parameters that are needed by the simulations should be available and easy to define. Despite nowadays we can usefully apply these parameters to the numerical prediction of the limit of forming it needed to be upgraded in the future.

Based on the example of cold forming simulation we have made an overview about the current state of hot forming simulations. The most disadvantages of this kind of simulations come from the difficulty to defining the limit of forming. We have shown the new models that can meet the expectation, but they applicability in dedicated FEM codes is questionable.

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