Challenges of Simulative Consideration of Aluminium Hardening Caused by Paint-Bake

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Abstract

Local pre-straining in the forming process and thermal loading in the paint bake process have a significant effect on the further development of local material properties. In many cases it is therefore unavoidable to take such effects into account in the further course of the simulation along the part processing chain. This is particularly evident when the hardening of aluminium components during artificial ageing in the cathodic dip painting furnace is to be considered. During the precipitation processes, dislocations form between the metal lattices depending on the pre-straining and the applied temperature load, which ultimately lead to a further increase in strength.
*In the following it is shown how this strengthening can be estimated for use in subsequent CAE simulation processes and thus made accessible to crashworthiness simulations. The basis for this approach is the JMAK equation that describes the degree of local hardening phenomenologically. Tensile tests are carried out on differently pre-strained and heat-treated samples. Based on the results of the tests the parameters of the JMAK equation are derived. Using *MAT_TAILORED_PROPERTIES in LS-DYNA® allows the consideration of several locally varying state variables. Here the yield stresses are to be defined as a function of i.e. the degree of hardening and the pre-strain applied during the forming process. The corresponding quantities are mapped from the discretization of the forming simulation (i.e. equivalent plastic strains) and the thermal simulation of the paint-bake-oven (i.e. the computed degrees of hardening) onto the spatial discretization used in crashworthiness. Thus, it is possible to represent the dependence of the yield curves on the decisive influencing variables of the production and hence consider locally individual material behaviour.*

1 Introduction

In the process chain from sheet metal to the components in the car, the parts are stressed by the different process steps, which eventually may change the mechanical properties of the virgin material. Two decisive steps in this process are the forming of the sheet metal by introducing plastic deformation and the baking of the paint after coating. In particular, the combination of these two steps can have a significant influence on the properties of 6xxx aluminium. The yield strength, which is already increased by the pre-stretching, is further increased by tempering at approx. 180°C in the paint-bake oven.
The resulting local effect on the mechanical properties has a significant effect on the behaviour in a car crash and it is therefore of great interest to consider this property change in the simulation. Due to the locally different heat treatment of the components, however, the hardening of the aluminium in the furnace is inhomogeneous, which complicates a corresponding consideration of the effects in the following simulation steps.
One way to avoid this problem may be a specific heat treatment of the components after the forming process to ensure that homogeneous hardening is achieved afterwards [1]. This process, called Post Forming Heat Treatment (PFHT), in which the component is heated to 205 °C for 30 minutes at all points, however, is very cost intensive.
A second option would be to harden the material prior to the forming process, but clearly this considerably reduces the formability, which not only renders this option comparatively expensive, but also unnecessarily complicates the forming process. This set of possible processes is summarized in Fig. 1.

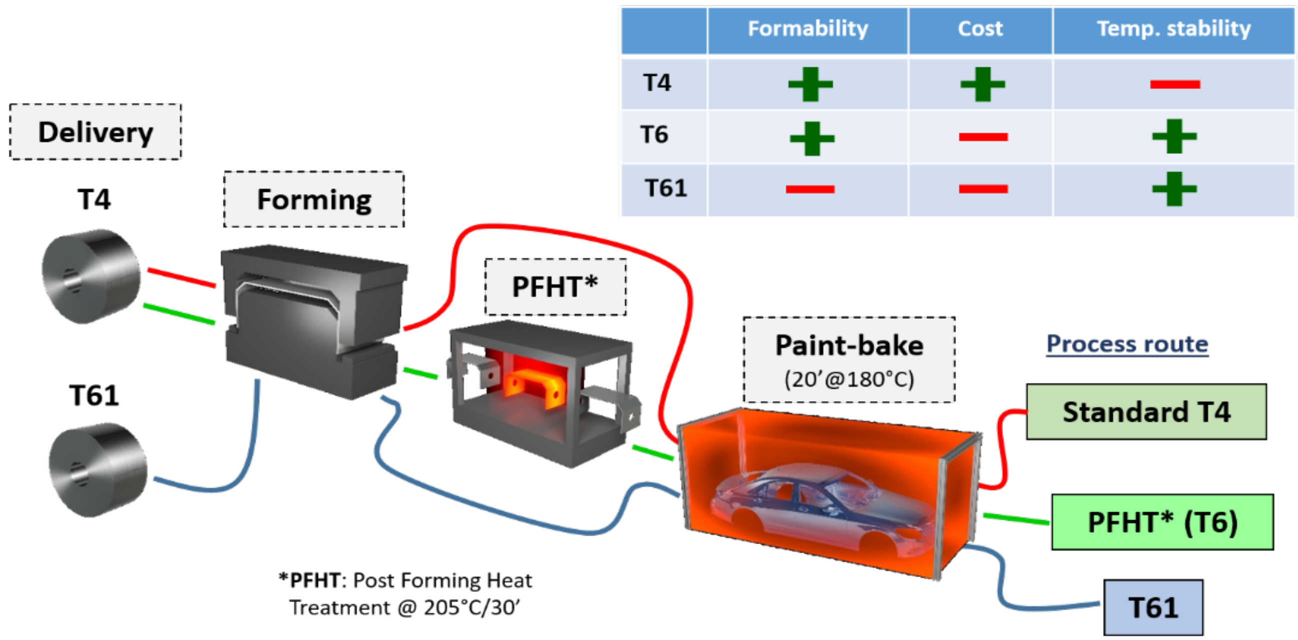

Figure 1: Typical manufacturing process chain.

Obviously, the optimal case would be to consider the inhomogeneous hardening in all subsequent simulation models. This would allow to avoid the expensive PFHT and also no additional problems could arise in the forming process. Therefore, in the following it will be discussed how such an inhomogeneous hardening can be determined and made accessible in simulation models.

1.1 The JMAK-equation

The Johnson-Mehl-Avrami-Kolmogorov, or JMAK, equation also known as the Avrami equation is able to describe the process of phase transformation between two states at constant temperature [2, 3, 4, 5 & 6] and can therefore also be used to describe the hardening of aluminium as a result of heat treatment. In its classical form, the JMAK equation is given as:

$$\frac{f_{rel} - f_{rel0}}{1 - f_{rel0}} = 1 - \exp\left(-\left(\frac{t}{\tau}\right)^n\right), \qquad \tau = t_0 \exp\left(\frac{Q}{R \cdot T}\right)$$

Therein are:

f_{rel} $\rightarrow$ Relative volume fraction of precipitates $[0, 1]$
f_{rel0} $\rightarrow$ Initial, relative volume fraction of precipitates $[0, 1]$
T $\rightarrow$ Temperature in K
t $\rightarrow$ Time
R $\rightarrow$ Gas constant
Q $\rightarrow$ Aktivation energy
t_0 $\rightarrow$ Time constant
n $\rightarrow$ Avrami-exponent

The parameters f_{rel0}, Q, t_0 and n must be fitted by appropriate tests.

The JMAK equation can also be represented more generally as a differential equation:

$$\frac{\mathrm{d}f_{rel}}{\mathrm{d}t} = (1 - f_{rel}) \frac{n}{t_0 \exp\left(-\frac{Q}{R\,T(t)}\right)} \left(\ln\left(\frac{1 - f_{rel0}}{1 - f_{rel}}\right)\right)^{\frac{n-1}{n}}$$

The solution of the differential equation allows the consideration of non-constant temperature profiles:

$$\frac{f_{rel} - f_{rel0}}{1 - f_{rel0}} = 1 - \exp\left(-\left(\int_0^t \frac{1}{t_0 \exp\left(\frac{Q}{R\,T(\xi)}\right)} \mathrm{d}\xi\right)^n\right)$$

It is assumed that the relative volume fraction of the precipitates corresponds to the degree of hardening. Hence $f_{rel} = 0$ corresponds to non-hardened, $f_{rel} = 1$ to fully hardened material. As an indicator of the degree of hardening, the yield strength $R_{p0.2}$ of classical tension tests is typically chosen. The yield strength of the untreated material shall correspond to a degree of hardening of 0, whereas the yield strength of the fully hardened material is assigned a degree of hardening of 1. This allows the degree of hardening of partially hardened material to be determined as follows:

$$f_{rel} = \frac{R_{p0.2} - R_{p0.2,\boldsymbol{f_{rel}=0}}}{R_{p0.2,\boldsymbol{f_{rel}=1}} - R_{p0.2,\boldsymbol{f_{rel}=0}}}$$

A suitable series of measurements can be used to identify the unknown quantities of the JMAK equation as described by Esmaeili & Lloyd [7].

2 Experimental program

The investigated material is a 6xxx aluminium that exhibits a high hardening potential. First, A80 specimens were pre-stretched to a defined elongation in a universal testing machine. In the next step the samples were exposed to a defined, constant temperature for a certain period of time. Finally, the samples were mechanically tested again in tensile loading until fracture failure.

	100°C	140°C	160°C	180°C	200°C
30 min	X	X	X	X	X
60 min	X	X	X	X	X
120 min			X	X	X
180 min				X	X
240 min	X	X	X	X	X
360 min				X	X
480 min	X	X	X	X	X
600 min				X	X
900 min			X		
1440 min	X	X	X		

Figure 2: Examined duration-temperature combinations for heat treatment.

2.1 Pre-treatment of the samples

The parameters degree of pre-strain, temperature and duration of heat treatment were varied. Values between 0% and 15% in steps of 3% were examined as degrees of pre-strain. The temperature was chosen to values between 100 and 200 °C. The duration of the heat treatment lasted from 30 minutes to 24 hours. Fig. 2 shows the test matrix, whereby all 6 degrees of pre-strain (0%, 3%, 6%, 9%, 12%, 15%) were examined for all marked duration-temperature combinations.

2.2 Test evaluation and parameter identification

For all tests $R_{p0.2}$ was evaluated and initially plotted logarithmically against the duration of the heat treatment, see Fig 3. Apart from the heat treatment at 200 °C it can be concluded that the longer the treatment lasts, the more the material hardens. At the highest examined temperature of 200 °C a contrary effect is seen which is attributed to the so-called over-aging of the material where after an initial rise the value of $R_{p0.2}$ decreases with increasing duration of heat treatment.

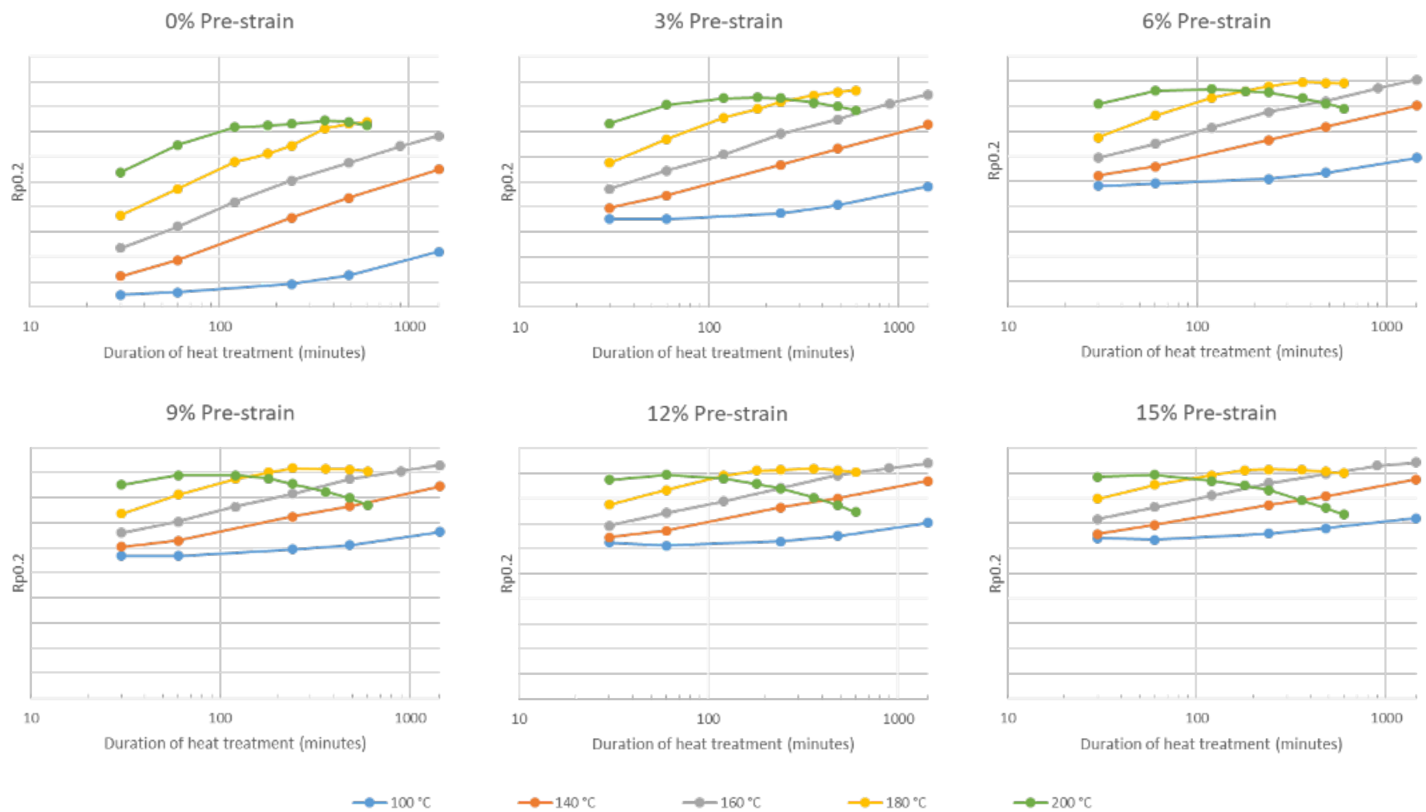

Figure 3: Evaluation of the yield strength.

It is assumed that the maximal occurring value of $R_{p0.2}$ of the non-pre-stretched but heat-treated specimens can be assigned to a fully hardened material. To determine the yield strength for uncured material, a completely untreated material is tested. Now, if a proportional relationship between $R_{p0.2}$ and the computed hardening value is assumed, the unknown parameters of the JMAK equation can be approximated on the basis of the specific values of $R_{p0.2}$ from the remaining experiments with non-pre-strained material.

For each characteristic test within the given test matrix in Fig.2 the corresponding yield curves have to be identified by a suitable approximation method. Typically, this is done by a combination of Hockett-Sherby, Swift or Ludwik extrapolation methods. However, in the present case a reverse engineering strategy to identify each single point in the yield curve was applied. The generated multi-dimensional yield definition tables are applied within the constitutive model in crashworthiness as described in Chapter 3.2.

3 Mapping and constitutive model

3.1 Mapping and collection of relevant data

Before the aforementioned calibrated model can be used in the proposed process chain, the corresponding data needs to be captured from the forming simulation of each part; this is to get the pre-straining information i.e. the equivalent plastic strain in each integration point. Furthermore, the thermal loading in each integration point needs to be captured as well to compute the local hardening of the aluminium alloy. For this a transient, thermal CFD-simulation of the oven-process is performed. This simulation models the whole body-in-white running through the corresponding e-coat-oven. To determine the heat-up, holding and cooling of the body, convection, radiation and heat-conduction are regarded. At this stage it is also necessary to emphasize the fact that both simulations are typically done on a different spatial discretization compared to the targeted crashworthiness simulation. This in turn enforces to application of mapping software to carry over, smooth, interpolate and extrapolate the collected data to the new target mesh. In the present case the computation of the hardening value is done within the applied mapping software ENVYO® [8].

Fig. 4 shows exemplarily two points of the hardening evolution due to a given temperature profile taken from of a full body-in-white. The values of the local plastic pre-strain are obtained from the corresponding forming simulation and subsequently combined with the hardening degree computed within ENVYO based on the thermal simulation. Both results are made available on a new spatial discretization as local information with the keyword *INITIAL_STRESS for the subsequent crashworthiness simulation in LS-DYNA. ENVYO allows to execute both steps simultaneously in one tool [9 & 10].

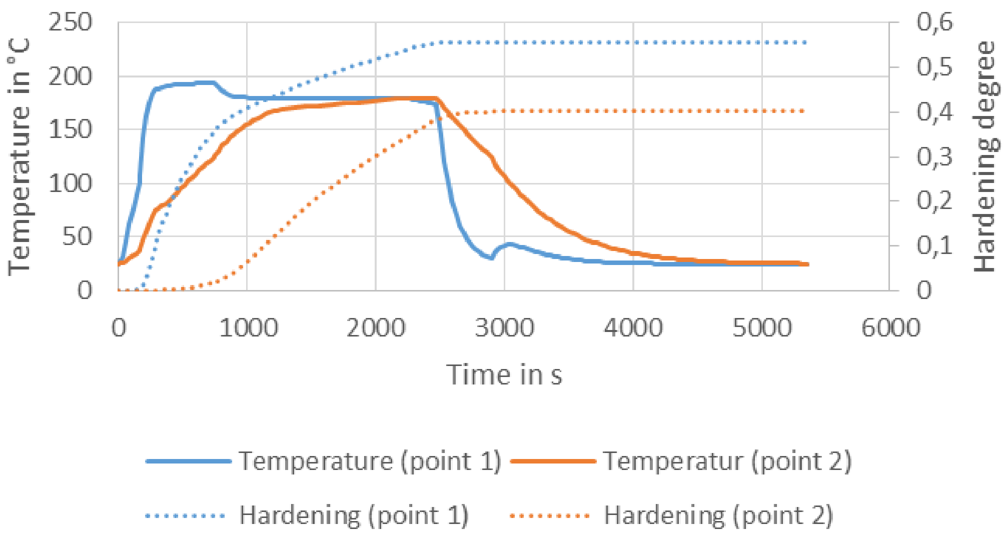

Figure 4: Exemplary evolution of the hardening for two points based on a given temperature profile.

3.2 Mapping and collection of relevant data

To consider the effect of locally varying hardening in crashworthiness simulations with LS-DYNA, the material model *MAT_TAILORED_PROPERTIES (*MAT_251) can be applied. This model is based on classical strain rate dependent von Mises plasticity (i.e. *MAT_PIECEWISE_LINEAR_PLASTICITY or *MAT_024) but additionally allows the consideration of further state (or history) variables in the stress integration algorithm [11].

For this purpose, yield curves are to be defined for various value combinations of the additional history variables, which are then interpolated accordingly in each cycle of the simulation run. In the present case, both the pre-strain as well as the degree of hardening resulting from the heat treatment can be taken into account. Depending on the nonlinearity of the dependencies on these state variables more or less yield curves shall be defined. In the following a minimal material card and table definition for *MAT_251 is given:

```
*MAT_TAILORED_PROPERTIES
$      MID        RO         E        PR                          FAIL      TDEL

         1   2.70E-6      70.0      0.33
$                         LCSS                  VP     HISVN     PHASE
                             1                 1.0         6
$     EPS1      EPS2      EPS3      EPS4      EPS5      EPS6      EPS7      EPS8

$      ES1       ES2       ES3       ES4       ES5       ES6       ES7       ES8

$ ================================================================================
*DEFINE_TABLE_4D_TITLE
history hardening degree
$     TBID
         1
$   hardening degree         TABLE_3D_ID
              0.00                    10
              1.00                    11
$ ================================================================================
*DEFINE_TABLE_3D_TITLE
hardening=0.0: history variable prestrain
$     TBID
        10
$          prestrain         TABLE_2D_ID
              0.00                   100
              0.10                   101
$ ================================================================================
*DEFINE_TABLE_2D_TITLE
hardening=0.0/prestrain=0.0: yield curves vs strrate
$     TBID
       100
$        strain rate      yield_curve_ID
           0.000100                 1000
           0.000200                 1001
$ ================================================================================
*DEFINE_TABLE_2D_TITLE
hardening=0.0/prestrain=0.1: yield curves vs strrate
$     TBID
       101
$        strain rate      yield_curve_ID
           0.000100                 1010
           0.000200                 1011
$ ================================================================================
*DEFINE_TABLE_3D_TITLE
hardening=1.0: history variable prestrain
$     TBID
        11
$          prestrain         TABLE_2D_ID
              0.00                   110
              0.10                   111
$ ================================================================================
*DEFINE_TABLE_2D_TITLE
hardening=1.0/prestrain=0.0: yield curves vs strrate
$     TBID
       110
$        strain rate      yield_curve_ID
           0.000100                 1100
           0.000200                 1101
$ ================================================================================
*DEFINE_TABLE_2D_TITLE
hardening=1.0/prestrain=0.1: yield curves vs strrate
$     TBID
       111
$        strain rate      yield_curve_ID
           0.000100                 1110
           0.000200                 1111
```

It can be seen that there is an additional variable HISVN on card 2 of the constitutive model that has to be specified (marked in red colour). Here the position of the first additional history variable in the keyword *INITIAL_STRESS is to be given. In the present case the dependence of the stresses on four history variables (in total) is defined: Namely the plastic strain, the plastic strain rate and the given position in HISVN+1, which refers to the constant values of the hardening degree, and furthermore the HISVN, which refers to the value of pre-straining. Both latter values are given in the stress initialization card. LCSS therefore refers to a 4D table, where again 3D table-IDs are listed for different hardening degrees. In these 3D tables, here ID=10 and ID=11, reference is again made to the classical 2D tables where the dependence on the strain rate can be considered (here: 100, 101, 110 and 111). Here the connection to the yield curves is defined where the plastic behaviour, i.e. the yield stress as a function of the plastic equivalent strain is specified.

4 Example

The method of calculating the hardening using the JMAK equation was applied to a vehicle in production. The result, i.e. the local distribution of the hardening, was transferred to the components using ENVYO. Fig. 5 shows an example of the hardening distribution for 3 components. On this basis, and in conjunction with the results of the forming simulation, even more detailed crash simulations can now be performed.

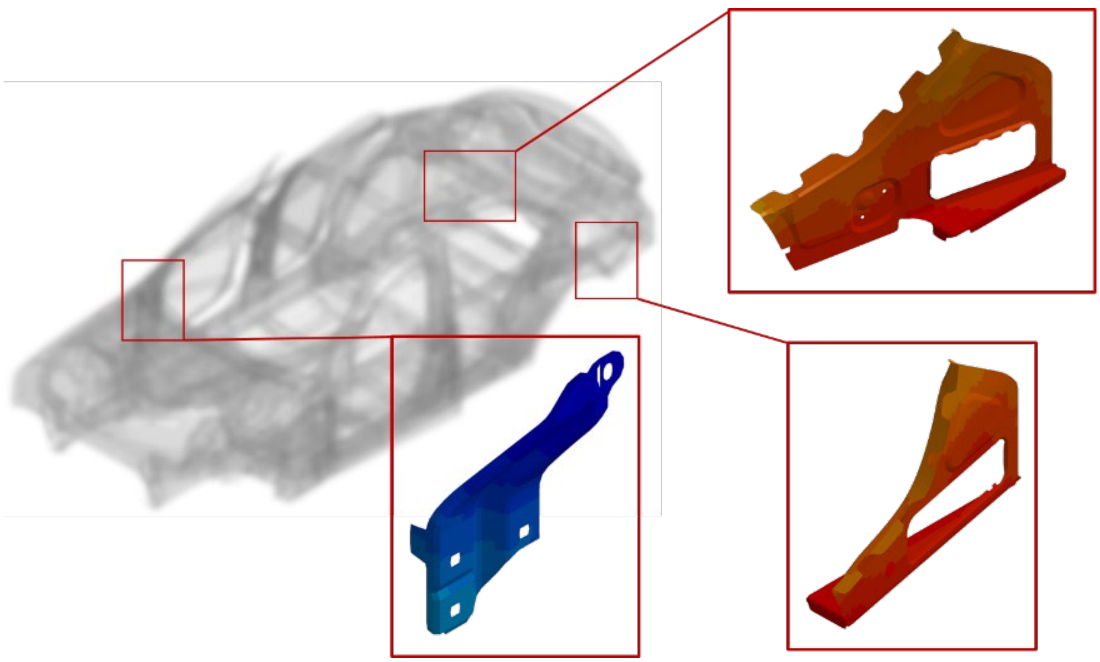

Figure 5: Exemplary representation of the local hardening distribution for selected components of a production vehicle.

5 Conclusion

In LS-DYNA it is indeed possible to consider the local properties of aluminium components hardened by pre-stretching and subsequent heating during the paint-bake. The presented strategy shows a convenient way to aggregate and use the relevant data from previous simulations by applying the mapping suite ENVYO. Of course, when using this method, it must also be kept in mind that effects such as ageing can generally not be considered with a JMAK equation. A large number of experiments were carried out for the present study. However, future investigations will concentrate on methods to reduce the number of physical experiments necessary in order to determine the JMAK parameters for other alloys.

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