Thermomechanical forming and crash simulations

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Abstract. With increasing possibilities and demands for FEM predictions, there is a need to get each input right. For example friction modelling, press kinematics, tool deformations are issues that are addressed more and more. FEM simulations including these advanced models require that each piece of the puzzle must be right. Description of the accurate thermomechanical plasticity behaviour is important for these simulations because press and tool deformations, friction behaviour and crashworthiness are depending on having the right forces and temperatures in your system. This thermomechanical plasticity behaviour consists of strain rate and temperature dependent hardening curves and a yield locus to scale these hardening curves for the different deformation modes. An accurate and easy to use yield locus which can be determined from only three tensile tests is Vegter 2017. The hardening behaviour consists of a static part and a strain rate and temperature dependent dynamic part. The static hardening behaviour can be determined with a tensile test and a biaxial test for the extrapolation to higher strains. The dynamic hardening behaviour can be determined with high strain rate tensile tests. An additive strain rate – temperature model is used to correct the necessary plasticity tests and prepare them for hardening fitting. With a strain rate jump test the validity of the additive model is proven. Comparison between FEM simulations and measurements for several practical deformation processes show a good prediction of the forces and temperatures of the thermomechanical plasticity model.

1. Introduction

There is an increasing trend to take more information into account while simulating deformation processes. Advanced friction modelling like the Triboform model as introduced by Hol et al [1], but also press kinematics and deformations and tool deformations are addressed as shown by Pilthammar et al.[2] and the use of fracture models. The use of advanced friction models is dependent on the right tool forces (contact pressure) and temperatures during the deformation process. Therefore, it is important when using these models all the pre-conditions are right. The basis is an accurate material model. This not only means an advanced yield locus such as Vegter 2017 as introduced by Abspoel et al. [3] where parameters for the Vegter yield criterion [4] are predicted from tensile tests only, but also the use of the strain rate and temperature dependent hardening curves. The feedback of the material with the appropriate hardening for a given strain rate and temperature returns the forces on the system needed to calculate for instance the right friction factor and contact pressure. And for fracture, the right strain rate curve is needed to determine the right amount of strain when the failure occurs. Within the forming simulation community, it is not very common to calculate with strain rate let alone temperature. Within FEM programs there are several strain rate models like Johnson – Cook [5] or Cowper-Symonds [6].
When using strain rate modelling, also temperature must be considered in the right way. There is softening of the material due to the temperature generated by plastic work and friction due to forming. Krabiell and Dahl introduced an equation in 1981 for an additive term to the static hardening dependent on strain rate and temperature [7] rather than a multiplicative term as used in the other mentioned strain rate descriptions. The Krabiell & Dahl equation was added to the Bergström equation by van Liempt [8], creating a physical model incorporating strain rate and temperature. This model is used within Tata Steel to fit the hardening behaviour. But because the Krabiell & Dahl part is an additive model it can be used with any hardening law or tabulated static hardening curve. Next to what happens inside the material, thermomechanical calculations also need a representative heat transfer to the surroundings which might be important depending on the deformation speed and for instance the amount of tool contact.

2. Thermomechanical plasticity model

For the Finite element simulation, a tensile curve in rolling direction is needed. For the extrapolation of the hardening data, most often biaxial data is used. This can be a bulge test or a compression test. From the tensile test and a biaxial test, a hardening curve is fitted. Information about the strain rate behaviour can be found with the help of dynamic tensile tests. The strain rate in a regular tensile test is 0.0067/s and for the dynamic tensile tests it typically ranges from 0.001 to 200/s. Biaxial tests usually have a low strain rate typically around 0.01 to 0.1. These strain rate and temperature differences introduce a different response of the stress level in the test. Where higher strain rate will strengthen the material resulting in a higher stress level, a higher temperature will soften the material resulting in a lower stress level. Krabiell and Dahl introduced an equation to describe these effects. Equation 1 shows the description of the flow curve consisting of a static work hardening part where the hardening is not affected due to strain rate or temperature and a dynamic part where an additional stress is dependent from a given strain rate \( \dot{\varepsilon} \) (1/s) and the temperature \( T \) (K).

\[
\sigma_f = \sigma_{\text{static}} + \sigma_0^* \cdot \left(1 + \frac{kT}{\Delta G_0} \cdot \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)^{m*}
\]

Where:
- \( \sigma_0^* \) = limit dynamic flow stress
- \( k \) = Boltzmann constant = 8.617-10^-5 eV/K
- \( \Delta G_0 \) = maximum activation enthalpy
- \( \dot{\varepsilon}_0 \) = limit strain rate for thermal activated movement
- \( m^* \) = power for the strain rate behaviour

If this model is included in the FEM software it can be used directly, if not tabulated data can be generated where the FEM software will interpolate between the given conditions. Using a thermomechanical solver, requires a set of isothermal strain rate curves for each temperature. For a regular solver, only strain rate curves are used as input. In this case the temperature is not constant but a function of plastic work and can either be measured or calculated with a temperature model.

3. Use of the thermomechanical model

3.1. Tensile jump test

The model is evaluated using a so-called jump test. An ISO6892-1 test piece type 2 is drawn at a constant strain rate within the parallel length \( (\dot{\varepsilon}_0) \) of 0.00025/s and during three periods of 0.5s the strain rate is increased to 0.008/s. During the periods of 0.00025/s strain rate the temperature in the sample remains constant. The temperature is measured with a thermal camera and there is a small temperature increase of approximately 2 degrees during each jump. With the Krabiell & Dahl equation it is possible to correct the jumps to the stress level at a constant speed. In Figure 1 a test at a constant strain rate of 0.00025/s and a test with strain rate jumps are shown. The jump test curve and the constant speed curve coincide.
where both tests have the 0.00025/s strain rate. Both curves are recalculated to a static curve with a strain rate of 0/s. By filling in the measured strain rate and temperature and fitting parameter \( m' \) it is possible to calculate the extra stress generated by the dynamic effects. Deducting this stress increase from both curves returns two equal curves without stress jumps. The tests were done in 0, 45 and 90 and returned an identical \( m' \) value for the three directions. Meaning there was no difference in the strain rate behaviour between the directions.

![Diagram](image-url)

**Figure 1.** Jump test (DP600)

### 3.2. Types of hardening curves

For the forming simulations three types of tabulated hardening data are evaluated. The first is thermomechanical hardening data. For 4 temperatures (20, 40, 60 and 100°C) the static work hardening and 6 strain rates are generated (0.01, 0.1, 1, 10, 100, 1000/s). In the FEM software the in-between strain rates and temperatures are linearly interpolated. If necessary, generating more in-between strain rate curves would improve the accuracy. Best would be of course to use the equation directly in the software if available. The second type of hardening curves is adiabatic curves (Figure 2). In this case the hardening curves have thermal softening included, assuming the process is quick enough to not transport heat to the surroundings. For the adiabatic curves the static work hardening and the 6 strain rates are given. In this case the temperature is not constant but is a function as described by Vegter [8]. With tabulated adiabatic hardening curves, attention must be taken for the high strain rates as it can occur that there is so much softening that the hardening curve has a negative slope at higher strains. FEM programs
are not able to cope with this. When this occurs, the stresses are manipulated such that the slope will always be positive. We call this semi-adiabatic and usually only very small corrections are necessary. The third type simulated is isothermal data. In this case it is assumed that the process has a constant temperature. Also, here the static work hardening and 6 strain rates are given for only one temperature in this case (Figure 2). The static work hardening component (σ\text{static}) from equation 1 is of course identical for both the adiabatic and isothermal hardening behaviour at 20°C.

![Figure 2. Krabiell & Dahl: adiabatic and isothermal hardening curves, start temperature 20°C (DP600).](image)

For processes with lower strain rate and strains the difference between isothermal and adiabatic data is neglectable. For processes with high strain rate and strains, it is important to use adiabatic curves. This is shown in the forming simulation of a biaxial Nakazima sample at higher speed and the simulation of crash boxes.

### 3.3. Thermomechanical material model in forming simulation

For the forming simulations, a biaxial Nakazima sample is tested and simulated to verify the model. The biaxial mode reaches high strain and that challenges the hardening curve in the strain regime where also the temperature has influenced the sample. Aramis is used to record the strains during forming which makes it easier to compare with simulations on different product height. Also, the temperature is measured during testing with a Trotec infrared camera system. The temperature was calibrated before testing with a thermocouple. The steady state temperature of the tooling and the blank in the Erichsen equipment is 27°C, as is the ambient temperature in the small chamber. The time in the press and contact with the tooling are long enough to heat up the blank to 27°C before drawing. So, in the simulation all start temperatures are set to 27°C. During forming the temperature will rise due to the plastic work and friction with the tooling. The friction is however minimised by using grease and Teflon foil. The friction coefficient is 0.01. Both the friction coefficient and the hardening behaviour influence the punch force. Only with the right friction coefficient and hardening behaviour the strains, the punch force and the temperature in the sample can be predicted. Simulations of the forming process are done in PAM stamp. For a correct representation of the anisotropy the Vegter 2017 yield locus is used [3]. The forming speed of the biaxial sample is 15mm/s. The strain rates in the dome are between 0.1 and 0.5/s. Figure 3 shows
the strain rate in the sample during drawing of a DP600. There is some fluctuation but in average the strain rate is on this level during the drawing process. Also, the temperature development during the pressing is shown. The start temperature of 27°C increases to more than 130°C.

![Figure 3](image1.png)

**Figure 3.** Strain rate in the biaxial sample (H=29mm) and temperature development during pressing

The thermomechanical simulation predicts the generated temperature well up to large dome heights. For a dome height of 35mm the strains in the section are compared for the three simulation types (Figure 4). The adiabatic and the thermomechanical strains and punch force are both quite close to the measurement while the strains with isothermal curves are too low and the punch force is too high. The softening effect in the adiabatic curves represents the reality well. The isothermal hardening is too high at higher strain levels.

![Figure 4](image2.png)

**Figure 4.** Comparison of results for thermomechanical, adiabatic and isothermal simulations.

Using a thermomechanical solver should always result in the best approximation of the reality providing the heat transfer coefficient is taken properly. When using a regular solver, it is important to consider if the process is adiabatic or isothermal. In this case the punch force for the isothermal simulation is too high because the isothermal hardening curves at the high strains are stronger compared to the adiabatic ones for the same strain rate. The punch force is important in friction modelling because advanced friction models are dependent on the correct contact pressures.
3.4. Adiabatic material model in crash simulation

For the crash simulations, a 500mm long closed top hat as shown in Figure 5 is tested and simulated to verify the model. For crash simulations in PAM crash 2018 only strain rate dependent hardening curves are possible and no temperature dependency, so a thermomechanical simulation is not possible. Adiabatic hardening curves are used in combination with a Vegter 2017 yield locus. The rolling direction in the closed top hat is perpendicular to the length of the closed top hat. The backing plate is welded to the top hat with 17 spot welds on each flange. There are three triggers applied: one in the backing plate and one on each side of the omega profile to ensure a correct start of the deformation process. A DP600 was tested and simulated by dropping a mass of 138.9kg with a speed of 13.69m/s. In the folding areas of the profiles corners the strain rates can go up to 800/s.

![Figure 5. Closed top hat dimensions and model.](image)

Figure 5. Closed top hat dimensions and model.

![Figure 6. Closed top hat, crash simulation and tested sample](image)

Figure 6. Closed top hat, crash simulation and tested sample

Figure 6 shows the deformed closed top hat of the simulation and experiment. The number of folds found in the simulation is the same as for the experiment. In Figure 7 two signals are shown: the force-displacement and the displacement-time. The force signal of the experiment contains an oscillation (caused by the loadcell) which introduces the differences between the experiment and simulated forces. It is also extremely difficult to measure a force without oscillations at such high impactor speeds. The displacement of the impactor as function of time is a very stable signal. For the displacement of the impactor a small difference of 2mm is found between the experiment and the simulation.
4. Discussion
The tensile jump test shows that the strain rate behaves additive and not multiplicative. Krabiell and Dahl describe an additional term to the hardening where an increase in strain rate adds stress to the static curve whereas an increase in temperature reduces the amount of added stress. The amount of cooling to the surroundings determines the temperature increase during the deformation of the material. When no thermomechanical simulations are done, one must estimate if the process is adiabatic, isothermal or
something in between. For fast deformations an adiabatic process can be assumed. Slow deformations might be closer to an isothermal process. The simulations on the Nakazima sample give a good insight in the validity of the thermomechanical model. All aspects can be measured: force, temperature and strains. The thermomechanical and adiabatic simulations show a good similarity with the measured properties. Where the isothermal simulation deviates for the higher strains because at these high strains softening is playing a large role. For the crash test on the closed top hat the adiabatic simulation shows a very good similarity with the measured crash length and deceleration of the impactor weight. The folds in the tested and simulated sample are similar. The adiabatic hardening curves are a good representation of the materials behaviour.

5. Conclusions

- The Krabiell & Dahl additive strain rate – temperature model can be added to any static hardening fit.
- It was possible to extract the strain rate behaviour from the tensile jump test.
- The strain rate parameters found with the tensile jump test were used in forming and crash simulations and showed a good similarity between measurements and simulations which indicates that this additive hardening model is a good representation of reality.

References

[1] Hol J 2013 Multi-scale friction modeling for sheet metal forming PhD Thesis University of Twente, the Netherlands
[2] Pilthammar J Sigvant M Kao-Walter S 2016 Including die and press deformations in sheet metal forming simulations journal of physics: conference series 734 032036
[3] Abspoel M, Scholting M E, Lansbergen M, An Y and Vegter H 2017 A new method for predicting advanced yield criteria input parameters from mechanical properties Journal of Materials Processing Technology 248 pp 161-177
[4] Vegter H and Van den Boogaard A H 2006 A plane stress yield function for anisotropic sheet material by interpolation of biaxial stress states International Journal of Plasticity 22.3 pp 557-580
[5] Johnson G R and Cook W H 1983 A constitutive model and data for metals subjected to large strains, high strain rates and high strain rates and high temperatures Proceedings of the 7th International Symposium on Ballistics: pp 541–547, retrieved 2009-05-13
[6] Cowper G R and Symonds P S 1958 Strain hardening and strain rate effects in the impact loading of cantilever beams Applied Mathematics Report Brown University
[7] Krabiell A and Dahl W 1981 Zum Einfluss von Temperatur und Dehngeschwindigkeit auf die Streckgrenze von Baustählen unterschiedlicher Festigkeit Archiv für das Eisenhüttenwesen 52 pp 429-436
[8] van Liempt P 1994 Workhardening and substructural geometry of metals Journal of Materials Processing Technology 45 (1-4) pp 459-464
[9] Vegter H 1991 On the plastic behaviour of steel during sheet forming PhD thesis University of Twente, the Netherlands