Experience from Using a New Material Model for Stainless Steels with TRIP-effect

Authors:

Daniel Hilding*, Erik Schedin**
Engineering Research Nordic AB*
Outokumpu Stainless AB, Avesta Research Centre**

Correspondence:

Daniel Hilding
Engineering Research Nordic AB
Phone +46 13 236680
Fax +46 13 214104
Email daniel.hilding@erab.se

Keywords:
Austenitic stainless steel, Sheet metal forming, Material model, Thermal analysis

ABSTRACT

This paper presents experience from using a recently developed material model for austenitic stainless steels with TRIP-effect for simulation of sheet metal forming. Results from two different forming operations are presented.

In materials with TRIP-effect, a phase transformation from austenite to martensite occurs during forming that significantly affects the hardening behavior. The effect is sensitive to the amount of straining as well as the temperature. For materials that have a strong TRIP-effect new forming techniques are possible that can lead to very light and strong components.

The material model for austenitic stainless steel sheet exhibiting the TRIP-effect has been implemented in LS-DYNA.

INTRODUCTION

This paper presents experience from using a recently developed material model for austenitic stainless steels with TRIP-effect for simulation of sheet metal forming. Results from two different forming operations are presented.

In materials with TRIP-effect, a phase transformation from austenite to martensite occurs during forming that significantly affects the hardening behavior. The effect is sensitive to the amount of straining as well as the temperature. For materials that have a strong TRIP-effect new forming processes are possible that can lead to very light and strong components. One such process is the TensForm forming process developed by Outokumpu Stainless AB for their HyTensX steel, which has an extreme TRIP-effect.

THE HÄNSEL MATERIAL MODEL FOR STAINLESS STEEL WITH TRIP-EFFECT

The material model for austenitic stainless steel with TRIP-effect used in this paper was developed by Hänsel et al. [2]. The material model will be referred to as the Hänsel model. In depth descriptions of the material model, the implementation in LS-DYNA [1], and the tests required to identify the material parameters are given in Schedin et al. [3] and Hilding and Schedin [4]. Here only a short overview of the model is given.

The model is composed of two basic equations describing the TRIP-kinetics. First the martensite rate equation, which describes the formation of martensite

$$\frac{\partial V_m}{\partial \varepsilon} = \frac{B}{A}\exp(Q/T)\left(\frac{1\text{-}V_m}{V_m}\right)^{(B+1)/B}\left(V_m\right)^p \frac{1}{2}(1-\tanh(C+DT)) .$$

(Eq. 1)

The yield stress is given by

$$\sigma_y = (B_{HS}\text{-}(B_{HS}\text{-}A_{HS})\exp(\text{-}m\varepsilon^n + \varepsilon_0))(K_1 + K_2 T) + \Delta H_{\gamma\to\alpha'} V_m ,$$

(Eq. 2)

where

ε = effective plastic strain,

V_m = martensite volume fraction $0.0 < V_m \leq$ 1.0,
T = temperature,
σ_y = yield stress.

All in all there are 14 material parameters in equations 1 and 2: *A*, *B*, *Q*, *p*, *C*, *D*, B_{HS}, A_{HS}, *m*, *n*, K_1, K_2, and $\Delta H_{\gamma\to\alpha'}$. In addition, the initial martensite fraction V_{m0} is also a parameter.

The yield surface used is Barlat's 3-parameter surface, Barlat and Lian [6]. The material parameters are identified using inverse modeling of tensile tests made with specimens at different temperatures. During the tests the martensite content is measured using a ferrite scope.

IMPLEMENTATION IN LS-DYNA 970 AS A USER-DEFINED MATERIAL

The Hänsel material model is implemented as a user-defined material in LS-DYNA 970 [1] and is written in Fortran. The material model can be run in a thermo-mechanical simulation.

FORMING EFFECTS IN CRASH

The material model can also be used for crash analysis where forming effects are taken into account. In a crash analysis the Hänsel model does not need to be run with the thermal solver activated, instead the temperatures are calculated using an adiabatic temperature calculation approach.

LS-DYNA 970 LIMITATIONS

In LS-DYNA 970 not all the current state of the art analysis techniques for forming are available for a thermo-mechanical forming simulation. Most notably adaptive mesh refinement cannot be used and parallel simulations with MPP-DYNA cannot be run. At the time when the case studies were made, the new thick thermal shells could not be used successfully either. LSTC has or is planning to address these limitations in the upcoming version 971.

MODELING APPROACH

The chosen modeling approach can be outlined as follow. The Belytschko-Tsay shell element is used both for tools and blank. The tools are rigid. In short the models can be described as standard LS-DYNA 970 forming models with the following exceptions:

- Thermo-mechanical solution using the standard thermal shell (TSHELL=0).
- Thermal contacts allowing heat transfer.
- Hänsel material model.

The thermal solver in LS-DYNA is implicit and a much larger, 100 times, time-step can be used in the thermal solver than in the mechanical part of the simulation. In combination with the efficient iterative thermal solver this means that the run time is only slightly increased compared to a standard forming simulation.

GENERAL THERMO-MECHANICAL PROPERTIES

The thermo-mechanical properties of the tools are given in Table 1. The thermal heat conduction coefficient *h* between tools and blank was set to 12000 W/(m^2K), based on the estimate

$h = T_c/f,$ (Eq. 3)

where the T_c is the thermal conductivity of the lubricant, estimated to 0.12 W/(mK), and *f* is the thickness of the applied lubricant film (estimated to 0.01 mm). The thermal efficiency, the amount of plastically dissipated energy that is converted into heat, is set to 90%.

Table 1: Tool properties (Uddeholm data sheet for their Sleipner tool steel).

Thickness	10 mm
Density	7730 kg/m^3
Heat capacitivity	460 J/Kg
Thermal conductivity	20 W/m/K

STAMPING OF A PUMP COMPONENT

This report presents a verification of a finite element forming simulation for a component of a GRUNDFOS A/S pump [5]. The component, Figure 1, is formed in a single stroke operation with blank holders from a circular blank. Outokumpu Stainless AB supplied the stainless material 302XD, 1.2 mm thick, including material data, tables 1-3, and performed the measurements on the formed parts needed for the verification. GRUNDFOS A/S supplied all needed CAD data including frictional parameters as well as the punch force measurements needed for the verification. Initially the tools and blank held a temperature of 24.3ºC.

Comparisons of the simulation results with measurements are given in figures 2 and 3. The conclusion that can be drawn from the figures is that the predicted results from the simulation agree well with the experimental measurements. The strains along line L were determined with a 3D strain measuring system

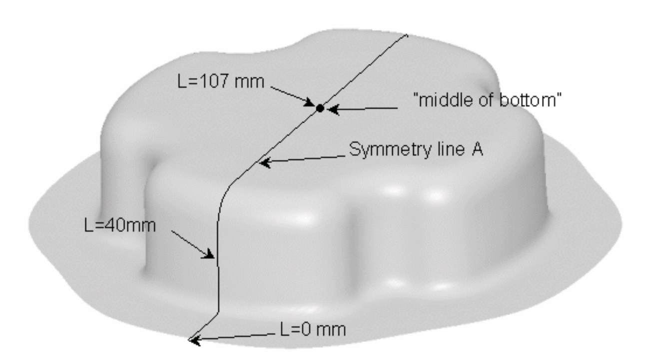


Figure 1: Pump component

Table 2: Identified 302XD material parameters.

A	B	C	D [1/K]	p	Q [K]
0.578	0.185	-6.78	0.0200	7.54	1379.
ε_0	A_{HS} [N/mm^2]	B_{HS} [N/mm^2]	m	n	$\Delta H_{\gamma\rightarrow\alpha'}$ [N/mm^2]
0.0988	-261.	9170	0.118	0.401	549.
K_1	R-value	K_2	V_{m0} [%]		
3.95	1.10	-0.00681	0.169		

Table 3: General physical properties of blank material.

Density	7900 kg/m^3
Young's modulus	210 GPa
Poisson's ratio	0.3
Heat capacitivity	460 J/(kg K)
Thermal conductivity	25 W/(mK)

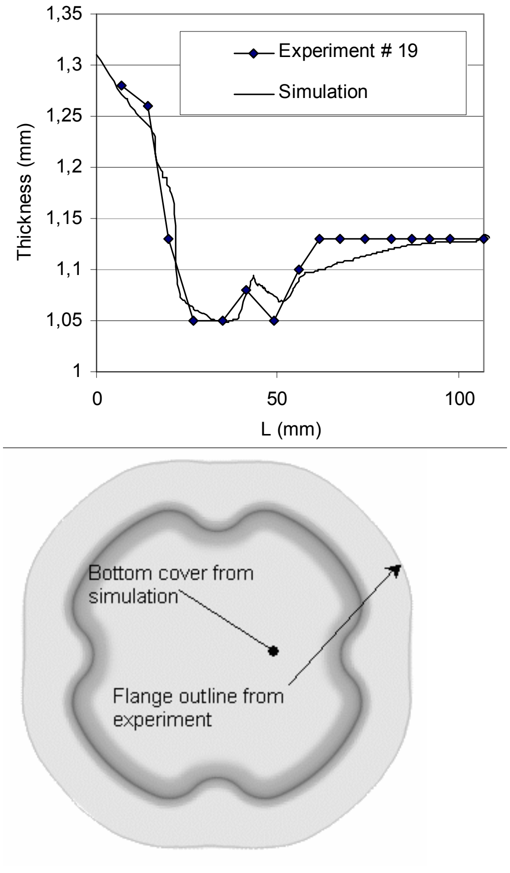
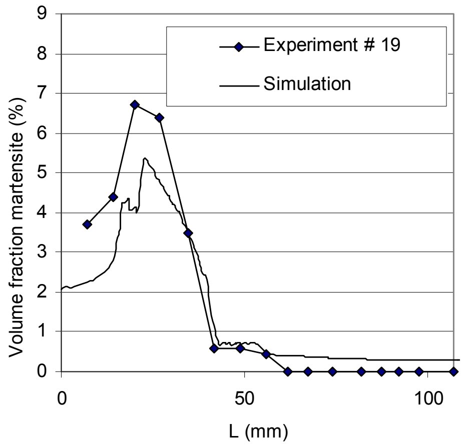


Figure 2: A comparison of the simulation results with measurements for the pump component. The line L along which some of the measurements are done is shown in Figure 1.



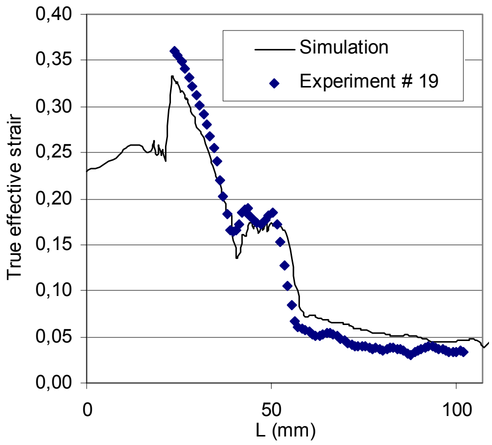


Figure 3: A comparison of the simulation results with measurements for the pump component. The line L along which some of the measurements are done is shown in Figure 1.

DEEP DRAWING OF A MUFFLER COMPONENT

The muffler component represents a fairly advanced deep drawing application and contains highly stretched areas; see Figure 4. The total draw depth is around 120 mm. Blank holding was accomplished through gas springs. Initially the tools and blank held room temperature.

Outokumpu Stainless AB supplied the stainless material HytensX, 0.8 mm thick, including material data and performed the measurements on the formed parts needed for the verification. The identified material parameters for HytensX are given in tables 3 and 4. The press forming experiments were performed at IDC, Olofström. An in depth description of this case is given in Schedin et al. [3].

The results in Figure 5 show an acceptable to good agreement between simulation and test. For the martensite content the agreement is less god than for the other responses, e.g. punch force. Some of the discrepancy between simulation and test may well be due to that there were a fairly large uncertainty in some of the experimentally determined parameters.

Table 4: Identified HytensX material parameters.

A	**B**	**C**	**D [1/K]**	**p**	**Q [K]**
0.32	0.226	-2.173	0.0084	6.25	1379.4
ε_0	**A_{HS} [N/mm^2]**	**B_{HS} [N/mm^2]**	**m**	**n**	$\Delta H_{\gamma\rightarrow\alpha'}$ **[N/mm^2]**
0.002	318.2	2170	2.94	1.39	414.7
K_1	**R-value**	**K_2**	**V_{m0} [%]**		
1.0	1.10	0.0	0.01		

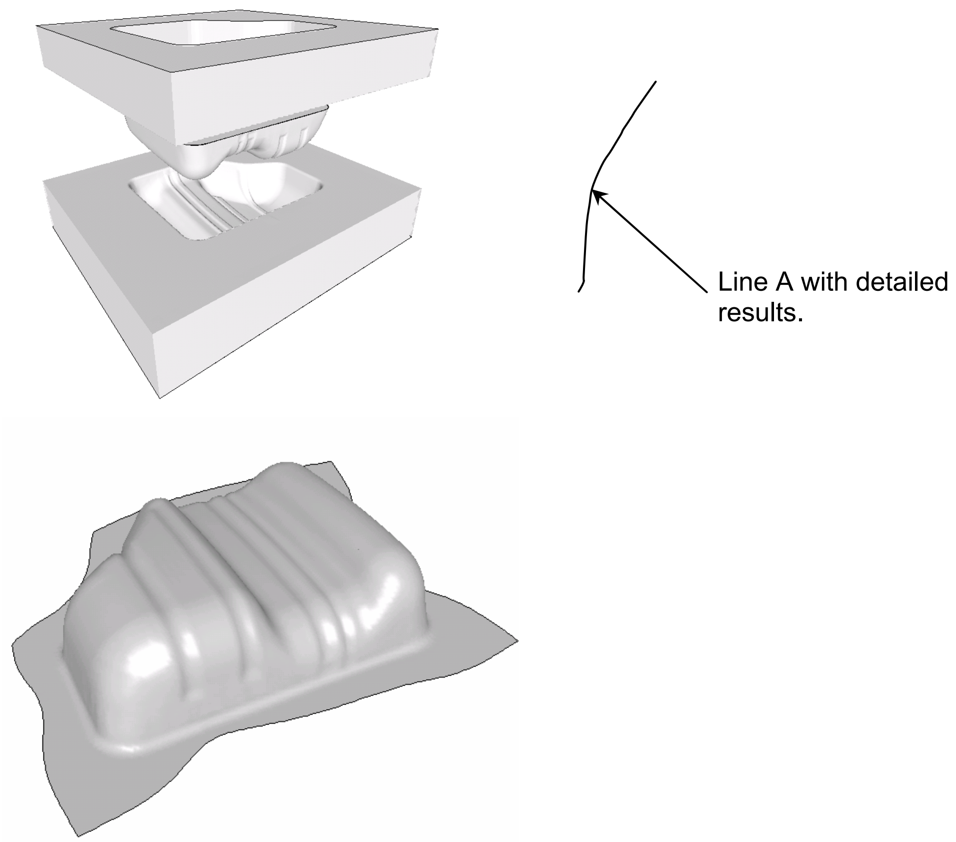


Figure 4: CAE image of the tools to the left and of stamped component to the right.

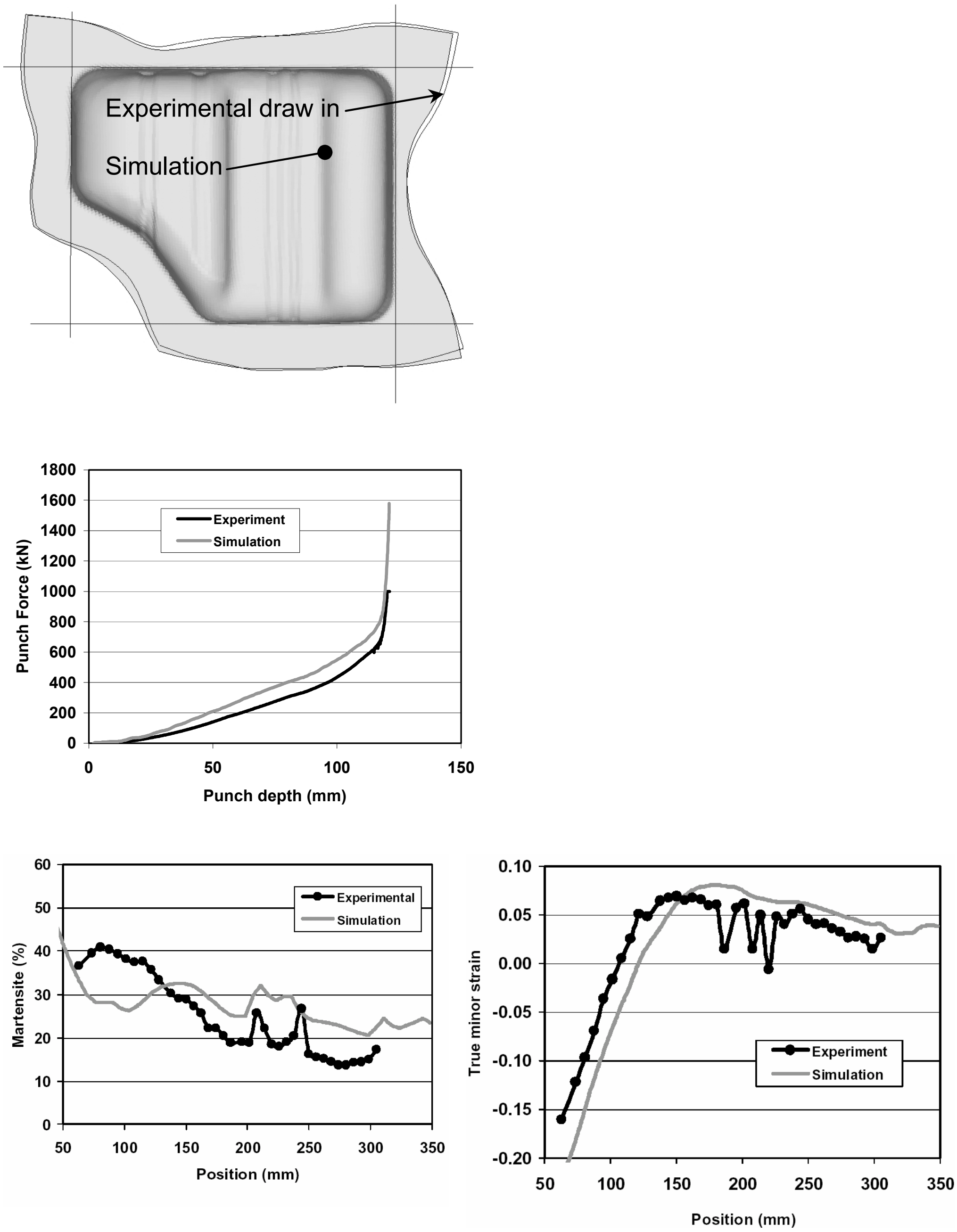


Figure 5: A comparison of the simulation results with measurements for the muffler component. The line A along which some of the measurements are done is shown in Figure 4.

ASPECTS ON THE THERMAL MODELING

An area where there is room for improvement is the thermal modeling. In the case studies the tools and blank are modeled using the standard thermal shell element (about 10 mm thick). The latter means that a uniform temperature is assumed through the thickness of the tools. This is of course not correct. Ideally the tools should be modeled using solid elements. Using solid elements to model the tools has the drawback that it significantly increases the time to create the models of the tools, i.e. it disrupts the normal workflow for forming simulations.

IDEALIZED FORMING OPERATION

To quantify the error introduced by modeling the tools and blank by thin thermal elements the following idealized forming operation is simulated using several different modeling approaches.

The forming operation consists of a uniform stretching of a thin sheet resting on a 10 mm thick tool. The blank is stretched uniaxially about 37% more or less instantaneously and then immediately placed onto the tool, see Figure 6 and tables 1, 5, and 6. Tool and blank are initially at room temperature (293 K). Thermal loss to the surrounding air is not taken into account.

The following modeling approaches are examined both for tool and blank:

App. 1: Thermal solid elements, characteristic element size 0.1 mm.
App. 2: Standard thermal shell elements, TSHELL=0 on *CONTROL_SHELL.
App. 3: Thick thermal shell elements, TSHELL=1 on *CONTROL_SHELL.

The results show that the temperature through the thickness of the blank is almost uniform (only a few percent deviation). The temperature time history for the blank is shown in Figure 7.

The idealized model gives some insight into the question at hand and supports the following conclusions:

- Modeling the sheet with standard thermal shell elements (TSHELL=0) gives acceptable errors.
- The temperature distribution in the tools can be important. The tools should be modeled using thick thermal shell elements (TSHELL=1) or using solid elements.

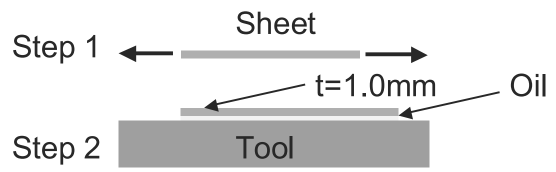


Figure 6: Idealized forming operation.

Table 5: Blank properties, low alloy carbon steel.

Thickness	1.0 mm
Density	7800 kg/m^3
Heat capacitivity	470 J/Kg
Thermal conductivity	50 W/m/K
Yield stress	300 N/mm^2
Hardening	No hardening

Table 6: Oil film properties.

Thickness	0.01
Heat transfer coefficient	12 000 W/m^2/K
Thermal conductivity	0.12 W/m/K

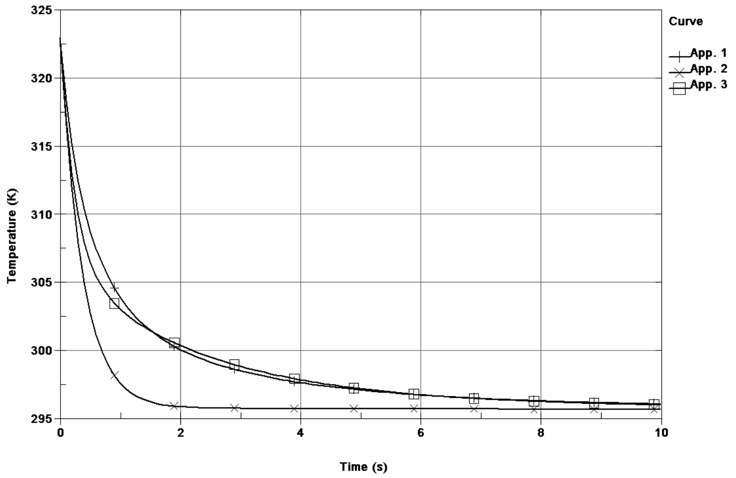


Figure 7: Temperature time history for blank.

SUMMARY AND CONCLUSIONS

Simulation of forming of TRIP-effect materials may require a thermo-mechanical simulation and a more complicated material model than usually employed. The latter leads to a more complicated work flow compared to standard forming simulation, i.e. of low alloy cold forming steels. The case studies reported in this paper show however that high-quality simulations of forming operations involving stainless steel with TRIP-effect are indeed possible also in practice.

Note that forming simulation of TRIP-effect materials for some applications can be done with satisfying accuracy using the standard method, i.e. without thermo-mechanical simulation and using a standard material model. However, for forming processes that take advantage of the temperature dependent hardening of these materials a thermo-mechanical simulations and/or special material model such as the Hänsel model may be required to get acceptably accurate predictions from the simulations.

FUTURE WORK

Ongoing and planed future work in this area includes the incorporation of the Hänsel model in LS-DYNA 971 as well as additional validations of the model for several industrial forming operations. The validations will possibly also include springback prediction accuracy. A better understanding of the heat transfer between tools and blank would also be welcome.

The Hänsel model for the TRIP-effect is planed to be part of the official LS-DYNA 971 release. LS-DYNA 971 will also have new improved thermal analysis functionality and performance that will be beneficial to thermo-mechanical forming simulations.

ACKNOWLEDGEMENT

We thank Ole Schøler Sørensen at GRUNDFOS A/S for his support.

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