Advanced Data Acquisition for Hot Stamping and its Application

C Rouet*, G Trattnig
voestalpine Stahl GmbH, voestalpine-Straße 3, A-4020 Linz, Austria.

E-mail: christian.rouet@voestalpine.com

Abstract. Hot Stamping is a complex technology, which requires many control parameters. Some data may be measured in-situ, to be used for trigger purposes or just for protocol. Other data need to be measured in advance to act as sort of calibration data. At voestalpine Stahl GmbH, we utilize a hot forming simulator to support the product development of hot forming steels. Linking process parameters and product properties is a major key for successful product development. Advanced data acquisition and data processing is the tool for a better understanding, increased precision and reproducibility during hot forming, as well as for the generation and improvement of material cards. We present the measurement matrix and show how that data and the derived models can be used for the development of materials, processes, material cards and full Finite Element (FE) Models. Those models are validated on medium scale test components and results will be presented. Our intensive efforts lead to a stable and robust part production at our customers hot forming lines. Extending these methods to hot forming lines would assist process design, failure analysis and quality assurance.

1. Introduction
Valid metallurgical conclusions from blanks, hardened by the hot forming simulator, require the blank temperature to be known at all stages of the hot forming process [1]. Thus, a certain degree of precision during the experiment is mandatory. Consequently, voestalpine Steel has equipped a hot forming simulator with a number of pyrometers, a thermal camera and the capability to read more than 30 type-K thermocouples. The layout is shown in Figure 1, more details may be found in [2]. Most of the pyrometers are focused on different spots within the working range of the handling robot. The thermal camera is aligned to the same spot, the central located temperature measurement station, as two other two-color pyrometers. This enables a temperature measurement range of 20 - 1400 °C. The Programmable Logic Controller (PLC) can trigger a screenshot of the thermal camera at any given time, the filename is linked to the experiment.

The main emphasis of the hot forming simulator is the processing of galvanized steel blanks. In order to enable the direct hot forming process, the simulator is equipped with a contactless pre-cooling aggregate [3], [4] with a two-color pyrometer aligned right above it. The thermocouples are mainly located within our tools. Temperature information is obtained at 1.5 mm and 3 mm below the tool surface as well as in the tool’s core. Some tools can be heated to model the temperature evolution in serial production or to model tool hot spots. Roughly 250 signals are recorded simultaneously by means
of a sophisticated process data acquisition system. A summarizing set of experimental data is stored in the SQL\textsuperscript{1}-Server database for Post-processing.

![Diagram of voestalpine Steel hot forming simulator.](image)

Figure 1. voestalpine Steel hot forming simulator.

2. Data Acquisition

Data Acquisition is done in different phases for each experiment. Some data is measured prior to the hot forming, some is measured during the hot forming process itself. Some process data is not accessible during the standard hot forming routine. Therefore a discontinued process chain, a pearl string series, has to be prepared. Data obtained by tests on the formed specimens, e.g. mechanical properties, are automatically assigned and stored.

2.1. Prior to Hot Forming

In order to determine the blank’s austenitization condition, a pair of type-K thermocouples are spot welded to a blank from the investigated batch and a drag measurement is performed. Within the PLC not just the temperature information during the furnace dwell time is used. Additionally, the thermocouples (TC) are used to calibrate the pyrometers and the thermal camera. Thus, the blanks emissivity is automatically calculated for both the spectral pyrometer (Figure 2) and the thermal camera. Moreover, while the temperature is within the measurement range of the two-color pyrometers, the emissivity of the thermal camera is automatically adjusted. Below the two-color pyrometers measurement range, the simplified calculated emissivity is applied to ensure a high measurement accuracy of the thermal camera. Data integrity is kept by fading the temperature values of each system within defined regions of overlapping measurement ranges.

The spectral pyrometer cannot be accessed the same way, thus the correction of the emissivity $\varepsilon$ is done within the PLC according to the Stefan-Boltzmann Law, with $P$ being the emitted radiation power, $A$ the emitting cross section, $\sigma$ the Stefan-Boltzmann constant, and $T$ the thermodynamic temperature. For a given radiation power $P$ and constant surface $A$, a simplified relation between two states, denoted

\textsuperscript{1} Structured Query Language
1 and 2, with corresponding couples of temperature $T_i$ and emissivity $\varepsilon_i$ can be described with the following equations:

$$P = \varepsilon \cdot A \cdot \sigma \cdot T^4 \quad \Rightarrow \quad T_2 = (T_1 + 273.15) \cdot \sqrt[4]{\frac{P}{\varepsilon_2}} - 273.15$$

Up to ten drag measurements are assigned to one blank calibration data set, containing austenitization data, emissivities, a temperature dependent temperature gradient at natural convection condition, as well as for each pyrometer the necessary temperature correction data. Temperature correction data, temperature dependent emissivities and temperature dependent temperature gradients, are approximated by means of 10 point polylines. The calibration data set is stored in a SQL Server database and accessible for the planning and evaluation of tests from the same batch of blanks.

Figure 2. Part of calibration data for pyrometer 4 (P4, Keller PA 28): (left) drag measurement of P4 compared with the averaged thermocouples and calculated emissivity $\varepsilon$, (right) calculated and approximated emissivities and the effect on the temperature deviation of P4 compared to the averaged thermocouples before and after emissivity correction.

2.2. During Hot Forming

The main data during the hot forming process are blank and tool temperatures, tool position and forces, and corresponding time. A typical requirement for direct hot forming of galvanized blanks is a blank temperature of approximately 535 °C at the beginning of the forming process itself, regardless of the pre-cooling strategy chosen.

Other typical required data is the final blank temperature at tool opening. Both temperatures can’t be measured directly, but their value can be extrapolated if the temperature gradient for the measured temperature is known or measured. With a known transfer time from pre-cooling to tool contact (tool dependent) and the calibration data for natural convection (as described in section 2.1.) the PLC is able to calculate a pre-cooling end temperature. The robot is then able to transfer the blank to the press at the right time. In Figure 3 left, a comparison between calibration data at natural convection and the linear extrapolation is shown for a target temperature of 535 °C. For the linear extrapolation the average temperature gradient of target and cooling end temperature is used. In case of short transfer times from pre-cooling to press the linear extrapolation gives accurate results.

After the stamping cycle the blank is transferred to a measurement location, where the temperature is measured by means of a pyrometer and thermal camera. A linear regression is calculated and a backward-extrapolation is done to obtain e.g. an actual mean cooling rate (Figure 3, right). For more complex hot forming processes featuring more than one forming step, like the multistep process [6], the same linear regression can be used to extrapolate the temperature into the subsequent forming tool.

In case of a desired exact time of initial tool contact, the PLC has to deal with at least eight different tool-sets and therefore different robot target positions, causing different transfer times. Therefore, the
PLC recognizes the installed tool, knows the robots transfer time and adjusts wait times automatically. If the robot program is optimized, a self-learning PLC program adjust to deviations in the range of about one second within probably ten strokes to regain a time precision of 0.1 s. The results of the effort can be seen in Figure 4.

A new aggregate at the hot forming simulator, not available at the time of the prior publication [2], is a laser distance sensor, which can be used to measure the blanks curvature (due to excessive pre cooling or weak geometric stability at high temperatures) and adjusts the robots movement on the fly to avoid crashing the blank into the tool, while trying to insert the blank into the tooling. The same calculation is done when returning the blank to the stock.

![Figure 3](image1.png)  
**Figure 3.** Comparison of blank temperature extrapolation into the press starting from the pre cooling end temperature of pyrometer 5 (P5, Keller PA60) by means of linear extrapolation (left). Blank temperature backwards extrapolation out of the tool by means of linear regression of a subsequent pyrometer measurement P4 (right).

![Figure 4](image2.png)  
**Figure 4.** Results of the adaption process of waiting time after a change of e.g. robot transfer time or press speed to meet the designated forming start temperature again.

2.3. Data acquisition by means of experimental setup
Within the previous chapter it was shown how e.g. a mean cooling rate of a tool could be obtained. Unfortunately, knowing a mean cooling rate is not always sufficient during the development of a new steel grade. Sometimes, actual time depending blank temperatures are required, but a pyrometer cannot measure within the closed tool. Therefore, discontinued processes are put together to form a pearl string
series or staircase series to get intermediate data even after short quenching times. The same principle is applicable to other difficult to measure process data. A similar method is described in [9] to get a crack propagation versus intrusion.

2.4. Postprocessing data after hot forming

Typically, press hardened blanks are investigated for mechanical properties by means of tensile and bending angle tests. As we have a highly automatized test facility, the results from these tests are fed into another database and the PLC searches on daily basis for those test results. In the case of new data the PLC inserts them into the SQL Server database with a link to the performed experiment. Standard database tools or Excel macros may be used to do further desk research on the measured data. Other results from surface depending tests can also be fed into the SQL database and linked to the corresponding experiment.

3. Application in Finite Element Model Development for Heat Transfer Analysis

The main benefit of the hot forming simulator is the experimental determination of the process parameters and final material properties of the hot formed components. Additionally it is necessary to develop and validate FE-Models for the forming tools and process design. One important feature of the FE-Models is the accurate description of the heat transfer between blank and tools to determine the blank temperature during the forming process. The development of the blank temperature depends on the heat capacity and conductivity of the blank, the heat transfer between the blank and the tools, and the tools thermal properties [7]. The heat transfer itself depends on the coating of the blank, the contact pressure and also contact gap width [5]. After modelling all these parameters in the FE-Model, it finally depends on the FE-Solvers implementation of these heat transfer mechanisms.

One approach to validate the heat transfer FE-Model is the use of a pearl string test.

3.1. Pearl String Test Series and derived Models

Pearl string tests provide deep insight into complex processes and provide the possibility to fit models into obtained technological data. This knowledge can be used to improve today’s processes or to develop new ones, as well as to validate FE models.

One rather easy pearl string test is mentioned in subsection 2.3. , where a series of increasing press times during quenching is suggested. Several dimensions may be added, such as tool temperature, pressure, or sheet thickness. Here we limit ourselves to sheet thicknesses as a second dimension. A model for an expected sheet start and removal temperature was used, as described in subsection 2.2. .

The pearl string test series was conducted using HX340LAD+GI90/90 blanks in three different sheet thicknesses of 1.20, 1.48 and 1.98 mm. The tooling is made of Böhler S600 tool steel with a rather low thermal conductivity [7] at room temperature compared to special steels optimized for hot forming tools. The tools were heated to a temperature of 200 °C and a contact pressure of 3 MPa was applied. The quenching time was varied from 0.5 to 10 s. Figure 5 shows the extrapolated quenching end temperature for all three sheet thicknesses.

The quenching end temperatures can be fit. The fit’s quality is significantly improved if the datapoint for 0.5 s is not used. This is justifiable, since the data point density is much higher at lower quenching times and measurement problems increase significantly for lower quenching times. While 10 s quenching time is quite long compared to industrial quenching times, it’s still rather short compared to the tooling cycle time with the given cooling. Thus, a typical approach for a thermal fit of the temperature $T = a \cdot e^{-b \cdot t} + c$ with $a$, $b$, $c$ being the fit parameter, and $t$ as the time, doesn’t work well. Quenching end temperatures at industrial important quenching times are predicted too low, for longer quenching times the temperatures are expected too high. The fit quality is improved significantly, at least in the investigated region, if a linear term is added. The new fit using $T = a \cdot e^{-b \cdot t} + c + d \cdot t$ is compared to the classical fit and measurement data in Figure 5 for 1.48 mm sheet thickness. The correlation coefficient improves from 0.75 to 0.83 for 1.48 mm and by at least 6 percentage points for the other two investigated sheet thicknesses. The newly introduced term $d \cdot t$ can be explained by the
influence of the rather low thermal conductivity of S600, resulting in higher temperature differences with rising sheet thicknesses. $d$ also represents the limit for the resulting blank cooling rate for longer quenching times.

![Figure 5](image-url) (left) Quenching end temperature for different sheet thickness and (right) fit results for a sheet thickness 1.48 mm.

In theory, the tools thermostat temperature should be the asymptotic limit for the blank quenching end temperature, but the active temperature management of the tooling is not accounted in the simulation. Therefore, regardless of the used fit, it is only valid in the observed timespan. The fit parameter for the four parameter $a$ to $d$ are shown in Figure 6, together in the resulting fit parameters of the three investigated sheet thicknesses. Parameters $a$, $c$ and $d$ are aligned almost perfectly linear depending on the sheet thickness, parameters $b$ seems to be rather constant. Since $b$ describes mainly the influence of the heat transfer coefficient and the tool’s thermal conductivity, it is reasonable to expect $b$ to be constant. As a result, $a$, $c$ and $d$ may be approximated linearly to form a general purpose fit for good estimation for the quenching end temperature depending on sheet thickness and quenching time. Finally, the quenching end temperature $T$ for the given tool of a temperature of 200 °C can be estimated by

$$T(s, t) = (120s + 41.9) \cdot e^{-1.10t} + (54.0s + 175) + (-3.66s + 1.79) \cdot t,$$

with the sheet thickness $s$ and the quenching time $t$.

![Figure 6](image-url) Fit parameter for all three sheet thicknesses. Graphical representation, with the linear thickness dependency of the parameters, (left) and fitted parameter values (right).
The comparison of the experimental (Figure 5 left) and numerical (Figure 7) temperature versus closing time curves show similar behavior. Still, the temperatures at low quenching times in the simulation are higher than in the experiments.

For the 1.48 mm sheet thickness two variations are shown in Figure 7. The dashed green line shows the influence of the tools thermal conductivity $\lambda$, an increase of 50 % leads to slightly lower blank temperatures, since the increased thermal conductivity leads to lower temperatures at the tool’s surface. A stronger influence on the result has the heat transfer coefficient between blank and tool $\alpha$. Here the dashed green line shows the increased temperature, when decreasing the coefficient by 50%.

3.2. FE Model Validation

For the FE-Analysis a purely thermal model was used, since thermal stresses and thermal deformation have shown no significant influence on the final temperature of the blank in the simulation.

The blank was heated and austenitized in the furnace, temperature measurements shows the phase transformation to ferrite takes place before placing the sheets in the press. So the material model only has to model the thermal properties of the ferritic phase, including the temperature dependent density, heat capacity and heat conductivity [7]. The tool steels thermal properties where available for a temperature of 200 °C, since only an increase of about 50 °C at the tools surface was measured, no temperature dependency of these parameters was used.

For the heat transfer between blank and tool, a constant heat transfer coefficient was assumed. The value was derived from previous heat transfer measurements [5] with the used steel type, coating and contact pressure. Due to the number of thermocouples installed in the tool, the tool temperature can be compared as well. In order to do that, the simulated temperatures need to be recalculated to compensate the relatively long response time of the sheathed type-K thermocouple compared to a maximum quenching time of 10 s. Welded sheathed thermocouples of 1.5 mm diameter typically show an $t_{90}$ time in moved water of approximately 0.4 s and in moved air of 25 s [8], resulting in a thermal response time of 0.17 s and 10.86 s respectively. An increased response time of 1.5 s is assumed to correspond to a rather weak thermal contact within the drilled TC hole compared to the moved water response time. Figure 7 right shows the effect of the response time to the simulated temperature and compares it to the measured values of the experiments. 1.5 s response time seems to be a good choice to perform the required peak temperature time shift to match the measurement.

3.3. Validation Results

Figure 7: Simulation Results. Blank temperature versus time from the FE-simulation for different sheet thickness and variations with modified tool thermal conductivity $\lambda$, and heat transfer coefficient $\alpha$ between blank and tools (left), tool temperature for three depths of simulated, filtered (response time = 1.5 s) simulated (Sim) and measured (Meas.) data (right).
It would therefore be possible to achieve the experimental curves in the simulation e.g. by increasing the heat transfer coefficient \( \alpha \) to higher values. Therefore experimental evaluations on the heat transfer coefficient are in progress, in order to validate the used \( \alpha \)-values.

Another possibility to further decrease deviations between the simulation and experiment is the modification of the tool’s heat capacity, which would both decrease the simulated tool temperature and blank temperature.

4. Summary
The knowledge of the temperature evolution during the hot forming process is of essential for a steel manufacturer, since we focus in the steel development on the time and temperature dependent phase transformations – which enables the production of martensitic high strength steel components.

Therefore the use of temperature evolution models in the PLC is crucial in the analysis of the forming process, test design and test control. The models enable tests with accurate non-contact temperature measurement with batch specific emissivity values and predetermined start and end test temperatures.

As for the numerical FEM simulation, there is still work to do to close the gap between measured and simulated blank and tool temperatures. This work will proceed by adding other press hardening steels and multiple tool temperatures.

The hot forming simulator is a powerful tool for our product and FE model development. Being able to define process parameters with good accuracy in combination with pearl string test procedures helps identifying process parameter limits, which must be kept to meet the required specifications of the material properties.

References
[1] Karbasian H, Tekkaya A E, A Review on Hot Stamping. In Journal of Material Processing Technology 210, No 15, pp. 2103-2118, 19 11 10.
[2] Rouet C, Kurz T, Trattnig G, Wagner C (2020) Physikalische Warmumformsimulation und ihr Einsatz in der Produktentwicklung eines Stahlherstellers. Proceedings of 15. Erlanger Workshop Warmblechumformung, p47
[3] Schwinghammer H, Luckeneder G, Manzenreiter T, Rosner M, Tsipouridis P, Kurz T (2013) Zinc Coated Press Hardening Steel for the Direct Process. 4th Int. Conf. Hot sheet metal forming of high performance steel CHS2, Lulea, Sweden, pp. 525-536
[4] Kurz T, Schwinghammer H, Luckeneder G, Manzenreiter T and Sommer A (2015) Zinc Coated Press-hardening Steel – Challenges and Solutions. 5th Int. Conf. Hot sheet metal forming of high performance steel CHS2 (Toronto, Canada) pp 345-354
[5] Schachinger E D, Kohnberger S, Faderl J (2017) Evolution of phases and formation of oxides on different galvanized hot formed steel grades. In: 6th International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Atlanta, USA, pp. 111–119
[6] Belanger, P, et al (2017) New Zn Multistep Hot Stamping Innovation at Gestamp, In: 6th International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Atlanta, USA, pp. 327–335
[7] S600 Datasheet by voestalpine BÖHLER Edelstahl GmbH & Co KG
[8] E.g.: Brochure “MIT R9 DE GB” by Reckmann GmbH, “Downloads” section of www.reckmann.de, from April 7th, 2021
[9] Wagner L, Larour P, Lackner J, Schauer H and Berger E (2019) Characterizing axial crash foldability of AHSS & UHSS sheets by means of L-profile compression tests. In: Proc. of the 38th IDDRG Int. Conf. (Twente, Netherlands, June 3-7)