Simulators for Product- and Process Development of New Steel Grades


* voestalpine mechatronic GmbH – vatron
** voestalpine Stahl GmbH, Linz, Austria

SUMMARY

Production parameters for advanced high strength steel grades (AHSS) are in every plant different as well as the chemical composition of the steel varies from plant to plant. The detailed specific production knowledge, the combination of the multiple influences are only applicable for the individual plant. This necessary production know-how must be gained on the own fundamental knowledge about material development and the deep understanding of the material property influences and behavior.

Every part of a continuous annealing or galvanizing line influences the strip properties. To study and understand the single and consequential impacts the process must be divided and analyzed in single steps. To perform such tests at the production plant is not economical and partly not even possible. Therefore flexible, efficient simulators for systematical parameter studies under reproducible conditions with transferability of the results to the production plant are required.

Simulators are applied for study of metallurgical reactions taking place during continuous annealing and hot dip galvanizing, in particular for development of optimum heat treatment cycles with heating, soaking, cooling, overaging and to study of surface reactions, e.g. oxidization behavior. Transformation hardening as reason for the extraordinary combination of strength and formability of modern steel grades such as dual-phase and TRIP will be the result of such simulations.

1. INTRODUCTION

Efficient product- and process development is only possible with state of the art equipment, with which industrial process steps can be simulated. One possibility is to invest in complete pilot lines which are smaller scale reproductions of the industrial processes. voestalpine Stahl follows another strategy: only the most important process steps are separately simulated in a laboratory or small scale situation. With these simulators, the most relevant process characteristics of our industrial lines are imitated. The sample size must be sufficient to allow both material characterisation and the determination of application properties. One more positive aspect of this strategy is that systematic parameter variations can be performed in a very defined way with a high level of reproducibility. Test runs can be conveniently and quickly performed with very little effort and at comparatively low cost. Measurements can be conducted that are to some extent not even possible in industrial lines. A requirement for being capable of transferring results over to the industrial situation is a very extensive knowledge of the parameters that define the process step which is being simulated.

2. PROCESS STEPS FOR HOT DIP GALVANIZING

The important process steps for hot-dip galvanizing are strip-cleaning, preannealing, annealing, galvanizing and galvannealing, skin passing and post treatment. voestalpine Stahl implemented simulation equipment according to the strategy that makes simulation of these important process steps possible. Because of the fact that this equipment is not available on the market, voestalpine Stahl developed own simulators together with the subsidiary vatron (voestalpine mechatronics). In this paper, the focus will be on our simulation equipment of the preannealing, annealing and galvanizing steps, which are possibly unique.

3. ANNEALING SIMULATION

The annealing process is a very important step in the production of cold-rolled or hot-dip galvanized steel strip. Besides determination of the microstructure and texture, which are responsible for the mechanical properties and therefore formability of the material, the strip surface is also conditioned for the galvanizing process step. For simulation the annealing process heating fixed specimen by means of quartz-lamps is often employed. Because of the inhomogeneous radiation field, it is not easy to get a homogeneous temperature
distribution on the specimen, especially, if the specimen is large. A better method is conductive heating of the specimen. We decided to develop a simulation facility fulfilling the following requirements:

- Highest flexibility and control concerning the shape of heat cycles, especially the cooling rate
- Large and different specimen sizes
- Excellent homogeneity of the temperature distribution during heating and cooling
- High productivity
- High reproducibility of the results

3.1 Multi-Purpose Annealing Simulator (MULTIPAS)

Basic idea: The specimen is connected as a resistor in the secondary circuit of a 100 kVA transformer and is directly heated by the current. Annealing is performed in air. (Fig.1)

![MULTIPAS](image)

**Figure 1: MULTIPAS**

**TECHNICAL DATA**

Specimen dimension:
550mm x 300mm x 0.4–5 mm (L x W x T)

Heating rate for reference specimen < 60 K/s
Typical soaking temperatures: 700 – 880°C

Cooling facilities cooling rate
Slow gas jet cooling 5 – 20 K/s
Rapid gas jet cooling < 120 K/s
Mist jet / spray cooling < 300 K/s
Hot / cold water quenching > 1000 K/s

Tensile force < 20 kN

The facility is equipped with various cooling modules, designed to simulate different cooling methods as used in continuous annealing technology, such as slow gas jet cooling, rapid gas jet cooling, spray cooling, water quenching (water temperature: 20–100 °C). The specimen is mounted on a carriage that can be dropped into the quench tank. An exceptionally wide range of cooling rates, from < 1 K/s to > 1000 K/s, can be covered by this device. Any physically feasible heat cycle (Fig. 2) can be programmed with the process computer.

![Different heat cycles for continuous annealing and hot-dip galvanizing lines in simulation](image)

**Figure 2: Different heat cycles for continuous annealing and hot-dip galvanizing lines in simulation**

The big advantage of this simulator is its ability to simulate a wide variety of possible heat cycles with outstanding accuracy and its flexibility regarding the specimen size. Heat cycles for continuous annealing lines as well as for hot-dip galvanizing lines can be simulated. It is also possible to "freeze" intermediate states by quenching the specimens at any point of a heat cycle to be able to investigate these intermediate conditions.

Further MULTIPAS is useful for studying galvannealing by performing experiments on galvanized samples from the plant.

3.2 Continuous Annealing Line Simulator (CALSIM)

CALSIM has been specially designed for the simulation of a continuous annealing line equipped with a rapid gas jet cooling system or for simulating annealing at hot-dip galvanizing lines. This simulator is mainly aimed for simulating surface properties as well as the recrystallization process. Therefore the annealed samples are suitable for studying surface properties like phosphatibility, surface cleanliness or electrogalvanizability. Because of the size of the samples, forming experiments in dependence of annealing parameters are also possible. The surface properties are primarily determined by reactions of the strip surface with the annealing atmosphere. Therefore, it is essential to control and, if necessary, to influence the time-temperature cycle as well as the chemical composition of the annealing gas and its dew point during the simulation of the annealing process.

In order to achieve the above goals, a completely new design has been developed and implemented, which has the following main features:

- Specimen dimension 340mm x 100mm x 0.2–2.0 mm (L x W x T)
- Heating rates ≤ 30 K/s and
- Cooling rates ≤ 100 K/s (for a specimen thickness of 0.8 mm)

The simulation system has a lock to charge the specimen, three heating elements and a cooling zone (Fig. 3).

Figure 3: a) Design of a heating element  
   b) CALSIM, schematic diagram

The heating tubes are made of heat-resistant steel and act as resistors and are directly heated by current fed by three transformers with an electrical power of 10 kVA. Atmosphere and walls are hot like in the production plant. No refractories are used. Therefore, after having inserted the specimen, the desired atmosphere can be adjusted in a very short time. The composition of the atmosphere and the dew point can be accurately adjusted. Mixtures between 100% nitrogen and 100% hydrogen can be used, and the dew point can range from −50 °C to +30 °C. Analogously to the real plant, at low temperatures the specimen is heated in the heating tube by convection, but consequently primarily by heat radiation.

To analyze the process gas a mass spectrometer is used. Thus, real-time measurements can be carried out and the gas reactions of the sample covered with emulsion oil and the process gas can be studied directly during annealing by analyzing the process gas as well as the annealing atmosphere from each zone.

The process control system consists of four PC’s and one PLC. For the access to the process control system the laboratory LAN is used.

Sequence of an experiment:

Apart from the simulation of continuous annealing and hot-dip galvanizing cycles, CALSIM also allows determination of the emissivity of, e.g., steel strip by simultaneous measurement of the specimen temperature with thermocouples and a pyrometer. The control models of continuous annealing lines and the accuracy of temperature determination and, thus, the quality of the product can be improved by using the specific emissivity data of the relevant steel grade in addition to the calibration of the pyrometers with a black body.

### 3.3 Performance and Exemplary Results

The homogeneity of the temperature in the useful area of the specimen is excellent in all phases of the heat cycle and, thus, also during rapid cooling (Fig. 4). This allows studying the influence of the heat-cycle parameters on the mechanical properties of cold-rolled strip in detail with high accuracy. Easy handling of CALSIM guarantees high working efficiency. Up to 30 specimen can be treated in a shift of 12 hours.

![Figure 4: Heat cycle and temperature](image)

Before selecting the first continuous annealing plant supplier and its technology, voestalpine Stahl carried out intensive studies on the relationship between the chemical composition, heat cycle and properties of Al-killed CQ, DQ and DDQ. For example, the impact of the cooling rate and start quench temperature on C in solid solution, $C_{\text{sol}}$, and the aging behavior is shown in Fig. 5.

![Figure 5: Influence of cooling rate ($v_Q$) and start quench temperature ($T_Q$) on carbon in solid solution ($C_{\text{sol}}$) and aging index (AI)](image)

$C_{\text{sol}}$ was determined through internal friction measurements by means of an inverted pendulum also constructed by vatron. The results show that lowest $C_{\text{sol}}$ values and therefore high aging resistance can be achieved when rather high cooling rates and high start quench temperatures are used. They also prove that the density of carbide nuclei can be increased by supercooling. As a result, the diffusion distances become shorter, and lower $C_{\text{sol}}$-values and higher aging resistance can be achieved.

To meet the demand of the automotive industry the development of hot-dip galvanized bake hardening steel grades is a very important task. It is well ac-
accepted that the BH effect is based on a controlled carbon aging mechanism.

4. PREANNEALING SIMULATION

Based on the experience of the CALSIM voestalpine Stahl decided to develop a preannealing simulator with the characteristics of a direct-fired furnace (DFF) with the development partner vatron.

The DFF is a very important step in the hotdip galvanizing process. In combination with the annealing section it is possible to influence the surface chemistry of the steel surface concerning wettability and reactivity with the Zn-bath.

The research was concentrated on oxidation kinetics of different steel grades in respect to oven-parameters such as lambda, temperature and oven residence-time.

4.1 DFF-Simulator

The DFF-Simulator has been designed to simulate the direct-fired preannealing section of a CGL or CAL. The DFF has the big advantage of implementing “preoxidation” by just changing the air/gas ratio (lambda) towards more oxidising conditions 7, 8, 9.

The detailed investigation of oxidation kinetics to implement preoxidation on the industrial line was therefore our first goal. However, because on some CGLs the DFF is also the only precleaning instrument (as in our CGL1), the cleaning effect of a DFF is also a topic for investigation.

Figure 6: Sketch of our DFF-Simulator

A global sketch of the DFF-simulator built by voestalpine Stahl in cooperation with vatron is shown in figure 6.

4.2 Exemplary Results

The first aim of the DFF-trials was to investigate oxidation kinetics for a rephosphorised IF-steel grade. To obtain the desired values several samples were driven through the simulator at varying Lambdas and keeping a constant final sample-temperature. Oxide thickness was determined either by pickling in inhibited HCl or galvanostatic stripping (for samples with less than about 0.5g/m² of oxide).

Some of these samples were then annealed in the CALSIM. Figure 7 shows the effect of preoxidation on the manganese surface-enrichment for the investigated steel grade, indicating the effect to suppress surface enrichments and improving galvanizability by preoxidation.

Figure 7: GDOS Profile showing the effect of preoxidation on the Mn-Surface enrichment of a rephosphorised IF-steel.

5. GALVANIZING SIMULATION

In continuous hot-dip galvanizing lines the heat treatment and surface refinement of the strip are carried out in one pass.

In order to be able to adjust the optimum thermal treatment for the cold-rolled material to be annealed and galvanized, it is imperative initially to precisely analyze the effects of temperature and annealing gas on the mechanical material characteristics as well as on the surface qualities. Because this is very costly and time-consuming during the production process voestalpine Stahl developed again together with vatron a galvanizing simulator, called GALVASIM to analyze the relationship between heat treatment, gas atmosphere and zinc bath, surface and material characteristics.

5.1 GALVASIM

The galvanizing simulator serves primarily to simulate heat-treatment cycles in defined gas atmospheres with the subsequent galvanizing of the sample.

BENEFITS

Simulation facilities help to lower development costs, since industrial-scale experiments consume hundreds of tons of materials with the risk of scrapping or downgrading and can be replaced by laboratory trials just needing some kilograms of specimen yielding the same results. The investment of such simulators pays back within a few months comparing the high costs of experiments on the production plant and their risks for
disturbance or damage of the production plant against the low costs of simulator trials.

GALVASIM has a modular configuration (Fig. 9). The sample is moved back and forth between the individual zones by means of a driving mechanism that runs according to the specific requirements. The specimen temperature is measured with two thermo-couples directly welded to the specimen. The temperature signal is used to control the heat cycle.

The system allows rapid infrared and/or inductive heating of the samples and a subsequent soaking in an electrically heated radiation pipe furnace. In this zone atmosphere and walls are hot like in the production plant. No refractories are used. Therefore, after having inserted the specimen, the desired atmosphere can be adjusted in a very short time.

The composition of the gas atmosphere can be selected according to individual requirements. Inert gases as well as reactive gases may be used for annealing. The dew point of the annealing gas can be adjusted in wide ranges by means of direct humidification.

To analyze the process gas a mass spectrometer in combination with a dew-point mirror system is used.

Controlled cooling is performed with a cooling system that employs gas-jet nozzles, so that high cooling rates are achieved.

The zinc bath is equipped with a stirring device. This allows the simulation of the movement of the strip in the pot of the industrial line. Additionally top dross can be removed with a bath surface skimming device.

Bath heating and pot material are capable for processing Z, ZA, AZ and aluminium coatings.

The coating thickness of the zinc layer is adjusted by air-knives. The wiping pressure, the distance of the air knives to the sample and the sample speed during passing the wiping system can be varied.

Final solidification of the coating layer by defined cooling is done in the cooling section. Wiping and final cooling for zinc solidification can be done with N2, HNx (max. 5% H2) or air.

GALVASIM at voestalpine

![Figure 8: GALVASIM at voestalpine](image)

Figure 8: GALVASIM at voestalpine

The galvanizing simulator is controlled by two personal computers and a PLC.

After processing the sample is taken out of the simulator and used for further process steps or analysis like:
- wet chemical coating analysis
- tensile testing
- coating adhesion testing (e.g. ball impact test)

**TECHNICAL DATA**

- Specimen dimension 200 mm x 130 mm x 0.3–3.0 mm (L x W x T)
- Heating rates ≤ 75 K/s and
- Cooling rates ≤ 100 K/s (for a specimen thickness of 0.8 mm)
- Annealing atmosphere: HNx (0-100% H2)
- Dew point: -55 - +10°C
- Wiping gas: N2, HNx (0-5% H2), air
- Cooling gas: N2, HNx (0-5% H2), air
- sample moving speed: max. 1000 mm/s
References:

10) Harald Deinhammer, "Charakterisierung und Simulation der aufheizzonen von kontinuierlichen Feuerverzinkkungsanlagen“, TU-Graz 2001