Physical Modeling for Product Development and Performance Optimization in Hot Dip Galvanizing Lines

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Introduction

Processing parameters for galvanizing lines require optimization when new steel alloy systems are considered or to improve product performance. The use of well-designed and reproducible laboratory computer-controlled physical simulations provides an excellent tool where more costly trial and error techniques can be eliminated. Recently, the continuous annealing line simulator at the University of Pittsburgh was used to investigate the mechanical properties of substrates annealed through a galvanizing line with different processing conditions. The corresponding results were satisfactorily correlated to actual production results, with methodology now in regular use.

Discussion

Hot dip galvanizing lines operate continuously for the processing of flat-rolled steel coils. These lines can extend nearly 1000 feet in length from start to finish and contain up to 5000 linear feet of strip while running. While traveling over this length, the steel strip is prepared to receive the galvanize coating and subjected to temperatures that have the resulting impact of achieving desired mechanical propert

- **Entry payoff reel**
- **Welder**
- **Cleaning section**
- **Accumulator**
- **Preheat zone**
- **Direct Fire Furnace (DFF) zone**
- **Radiant Tube Furnace (RTF) zone**
- **Jet cooling zone**
- **Zinc pot**
- **Galvanneal equipment (if applicable)**
- **Cooling tower**
- **After Pot Cooling zone**
- **Accumulator**
- **Takeup reel**

Sections of metallurgical significance begin at the 'preheat zone' and run through the 'after pot cooling zone'. In these zones, the strip is exposed to elevated temperatures with the time at temperature dependent on the line speed. The DFF and RTF zones have the highest operating temperatures and are a focal point for the majority of anneal cycles. Hot dip galvanizing lines utilize a collection of anneal cycles where the temperatures in different sections are prescribed to achieve specific metallurgical outcomes. Some of the variables that influence selection of an anneal cycle include base substrate (hot rolled or cold rolled), grade/chemistry, cold reduction percentages in full-hard conditions, galvanized or galvannealed products, and final mechanical property objectives. Once an anneal cycle is selected for a given product, questions remain to define and optimize the processing window. This must take into account the temperature transitions into a product schedule and the influence of line speed on residence time at temperature. Historically, these limits would be collected over time based on empirical observations from production results or through trial-and-error methods with individual coils. In either case, the timing and costs associated with these approaches can be substantial. It would not be uncommon for days, even weeks, to transpire between test results and a subsequent trial iteration. Additionally, if results are unfavorable, significant costs can be encountered with diverting entire master coils to non-prime applications or worst-case scrap. This outcome uncertainty adds tremendous burdens and potential roadblocks to new product development or even routine material applications.

Continuous Annealing Line (CAL) Induction Simulator

A more efficient methodology to define and optimize processing windows for hot dip galvanizing lines has been developed by the Ferrous Physical Metallurgy Group at the University of Pittsburgh through physical modeling. A goal was established to design and fabricate a system for simulating CAL cycles and other heat treatments using induction heating technology.

The solution allows for samples with different geometries to be heat treated to accommodate either full-size or sub-size tensile specimens. Heating rates up to 1000 °C/s are achieved, along with cooling rates up to 300 °C/s. Simulated cycles are designed with different temperature zones to reflect the different sections of hot dip galvanized lines, and for time segments that reflect different operating line speeds. Examples of different CAL treatments performed are shown in Figure 1.

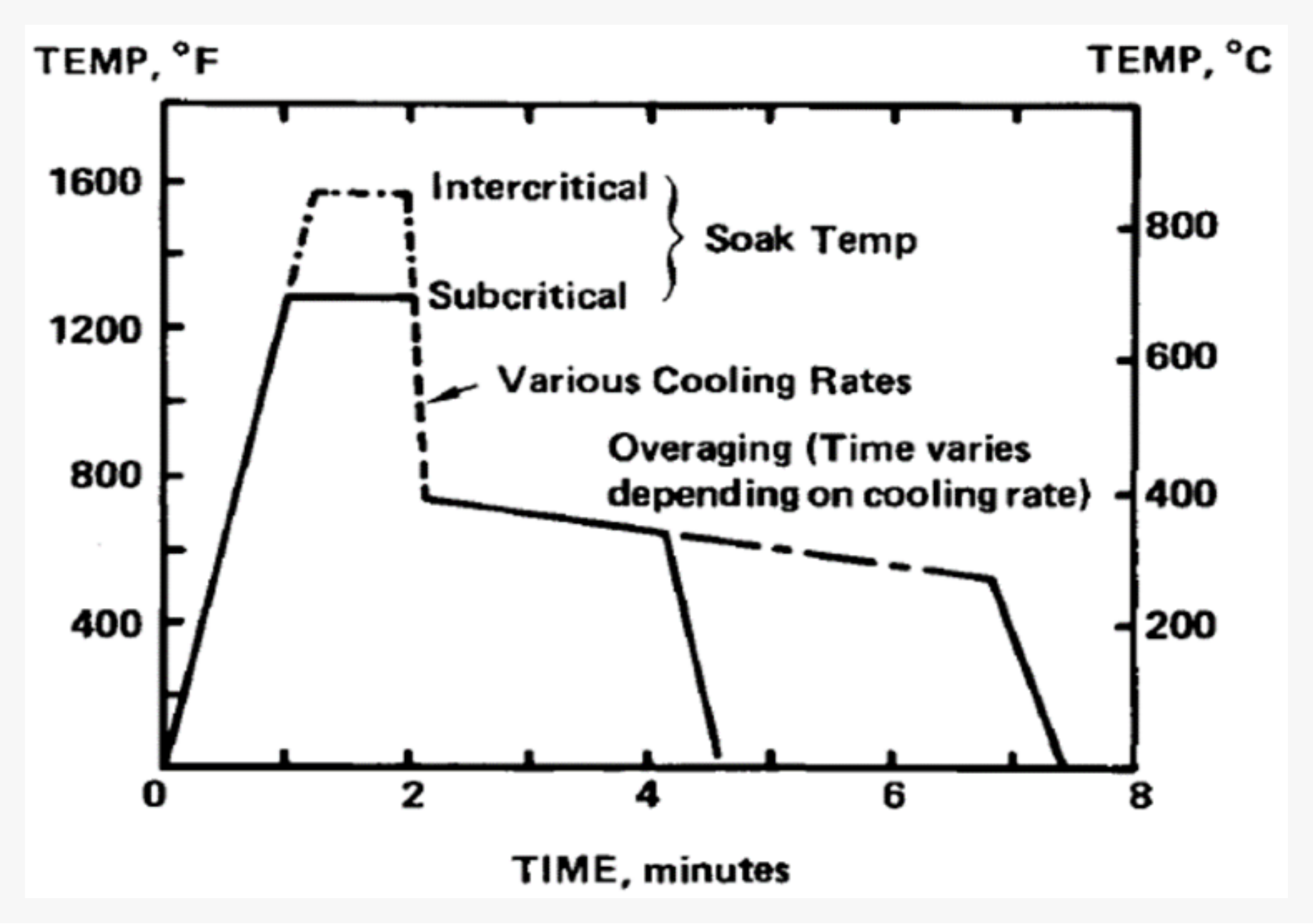


Figure 1: Continuous Annealing Line cycle schematics.[1]

The system at the University of Pittsburgh uses a 30-kWpower unit, capable of heating samples from room temperature up to 1400 °C in seconds. The system has the ability to use multiple induction coil designs. These coils can be modified in length, number of turns, and tube thickness to achieve different combinations of area treated and heating rates. The effect of coil size can be visualized in the simulations created using Ansys software (Figure 2). Different coils were designed using the same number of turns and thickness but different lengths. Shorter coils (3.5”) with smaller spacing between turns show a smaller uniform heating area and provide the ability to achieve higher temperatures in shorter times due to the concentration of the magnetic field.

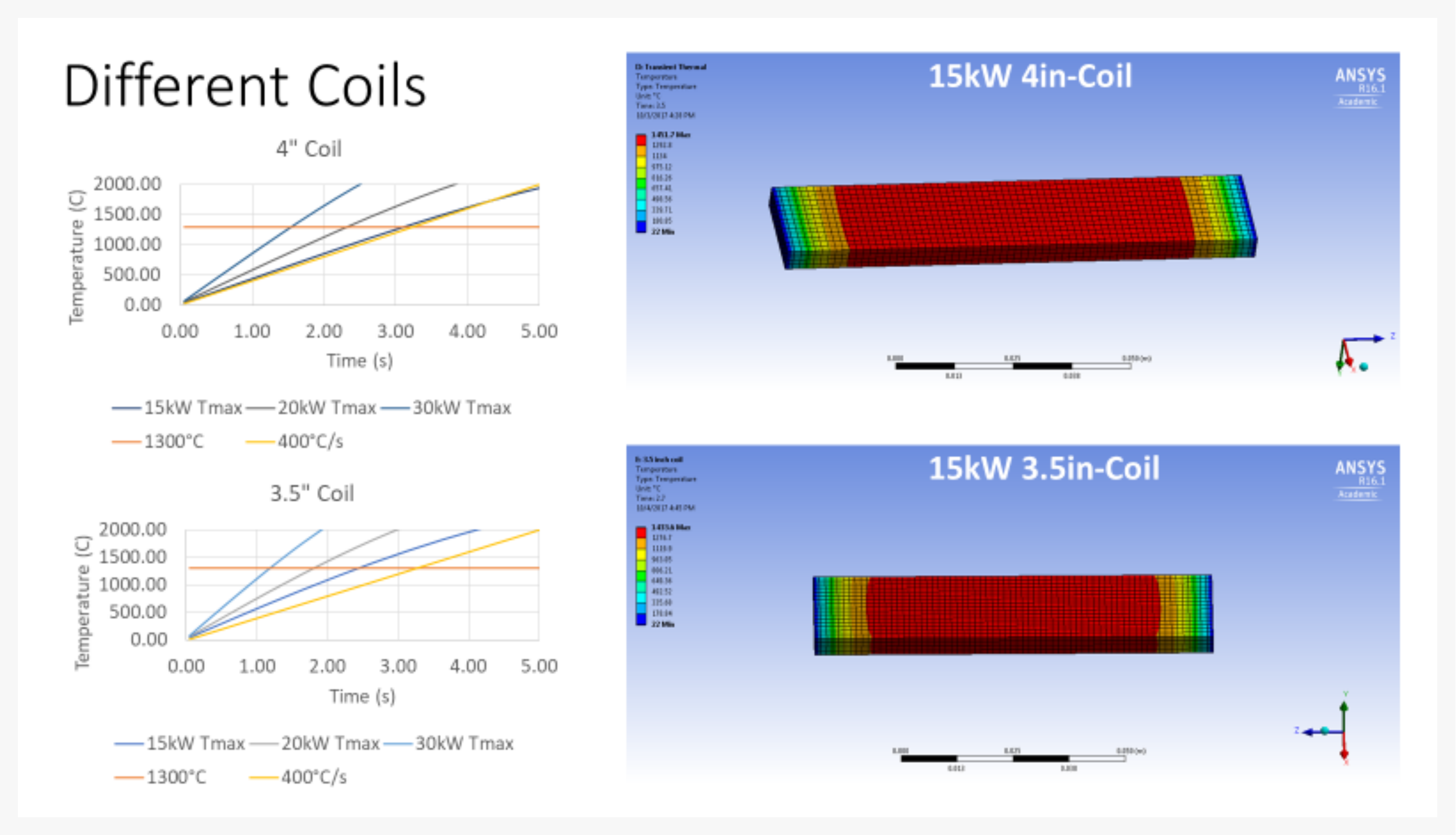


Figure 2: Effect of different coil lengths in heating behavior of samples.

The CAL simulator operates with a robust temperature control operated by infra-red (IR) sensors. The temperature control offers real-time readings of the temperature in the sample surface that are used to control the energy inputs from the power source. Cycles can be operated in the machine in multiple segments or isothermally, according to the heat treatment requirements.

Once the heating cycle is complete, the sample is moved to a cooling region by an automatic actuator where it can be submitted to different cooling media to achieve the desired cooling rate. Cooling rates can range from 0.5 °C/s (for atmosphere cooling) up to 300 °C/s (for ice baths). Figure 3 shows the range of cooling rates that can be achieved in the CAL30kW simulator.

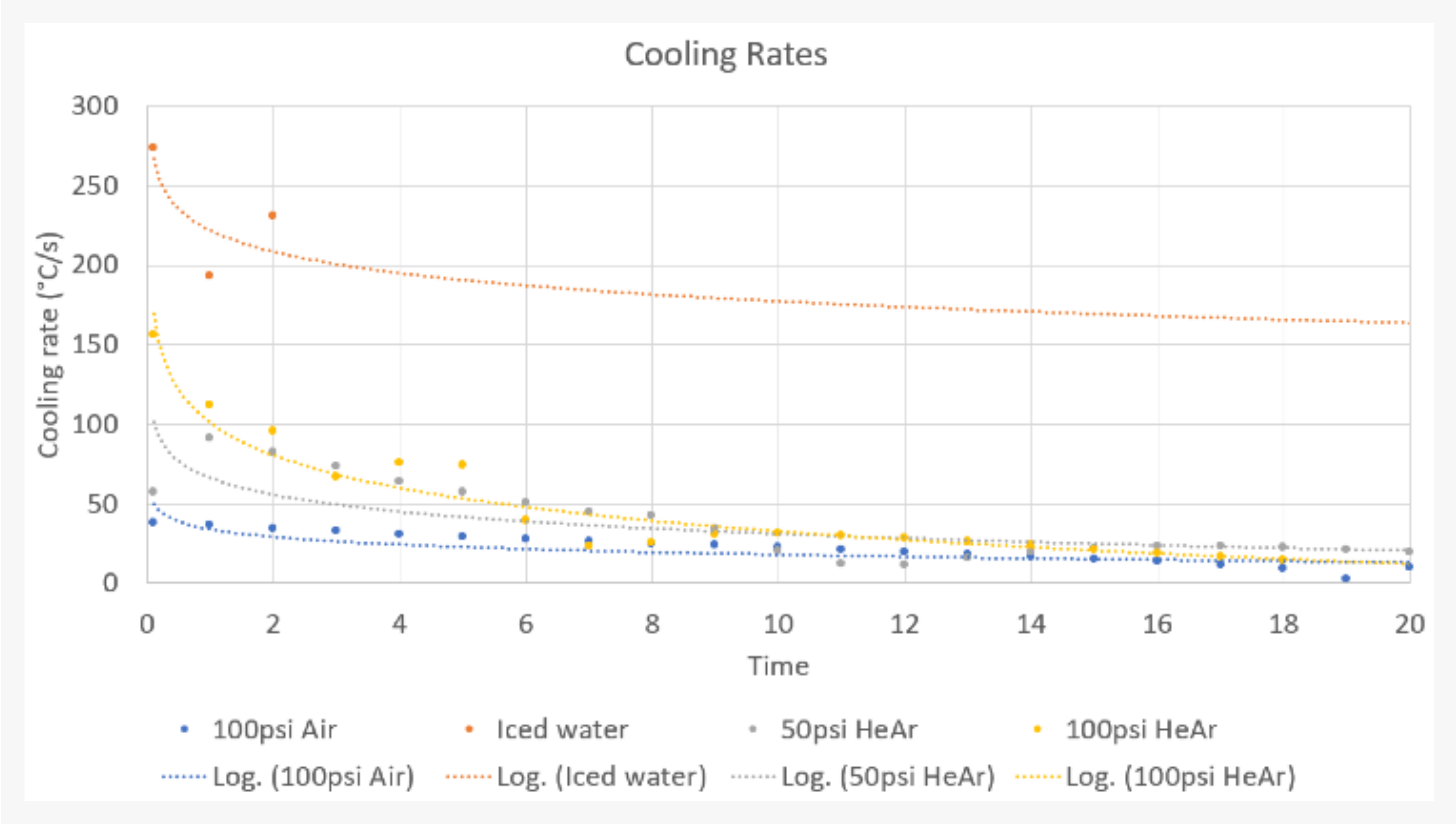


Figure 3: Different cooling rates achieved over time for varying cooling medias.

A schematic representation of the system components and organization is shown in Figure 4 and an image of the system operating is shown in Figure 5.

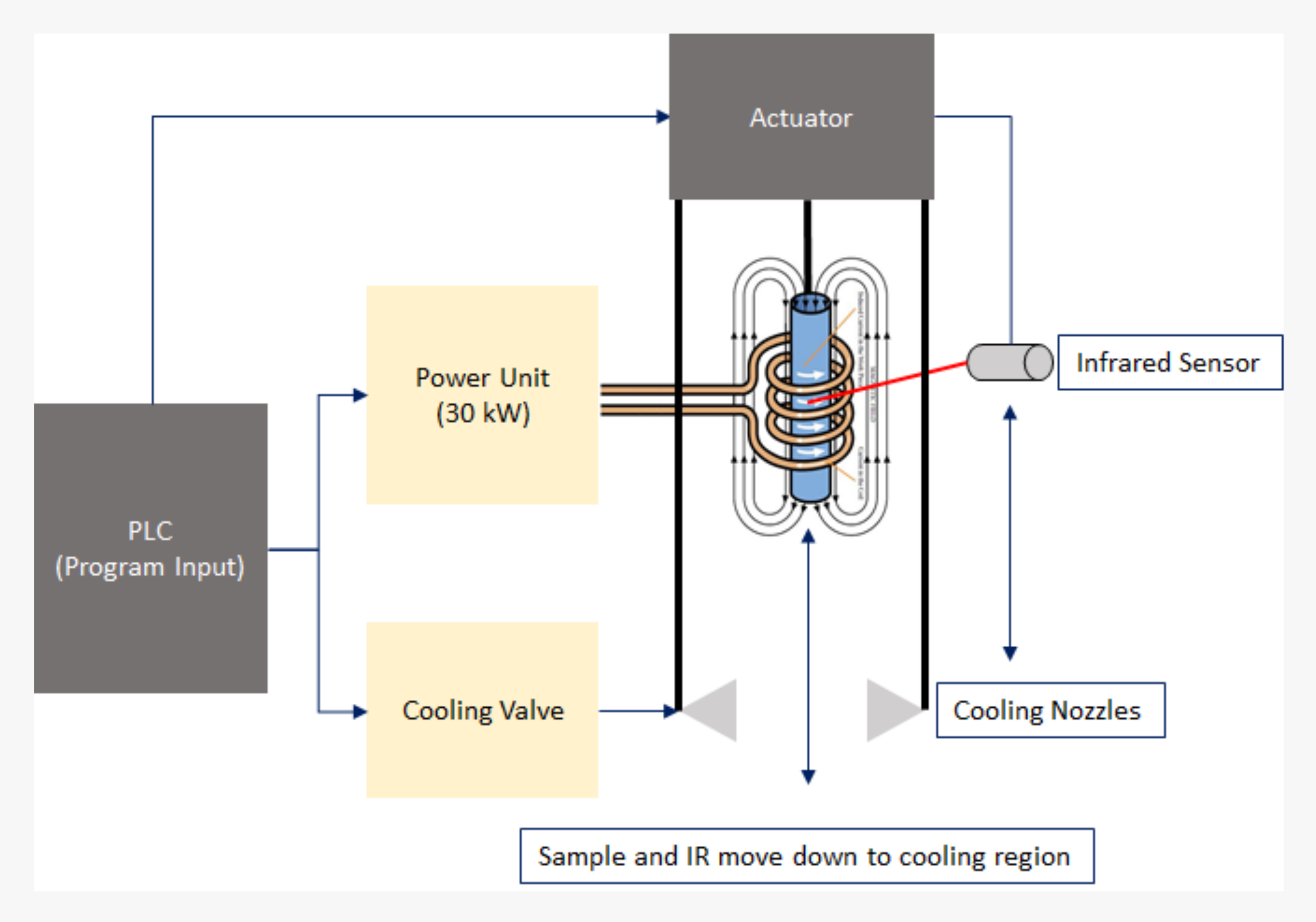


Figure 4: Concept drawing of the CAL Induction Simulator equipment.

Figure 5: CAL Induction Simulator equipment operating at the University of Pittsburgh.

CAL System Setup & Calibration

CAL System Setup & Calibration In preparation for setup of the physical modeling system, an anneal cycle is described for the hot dip galvanize line zone temperatures with a corresponding line speed (Figure 6).

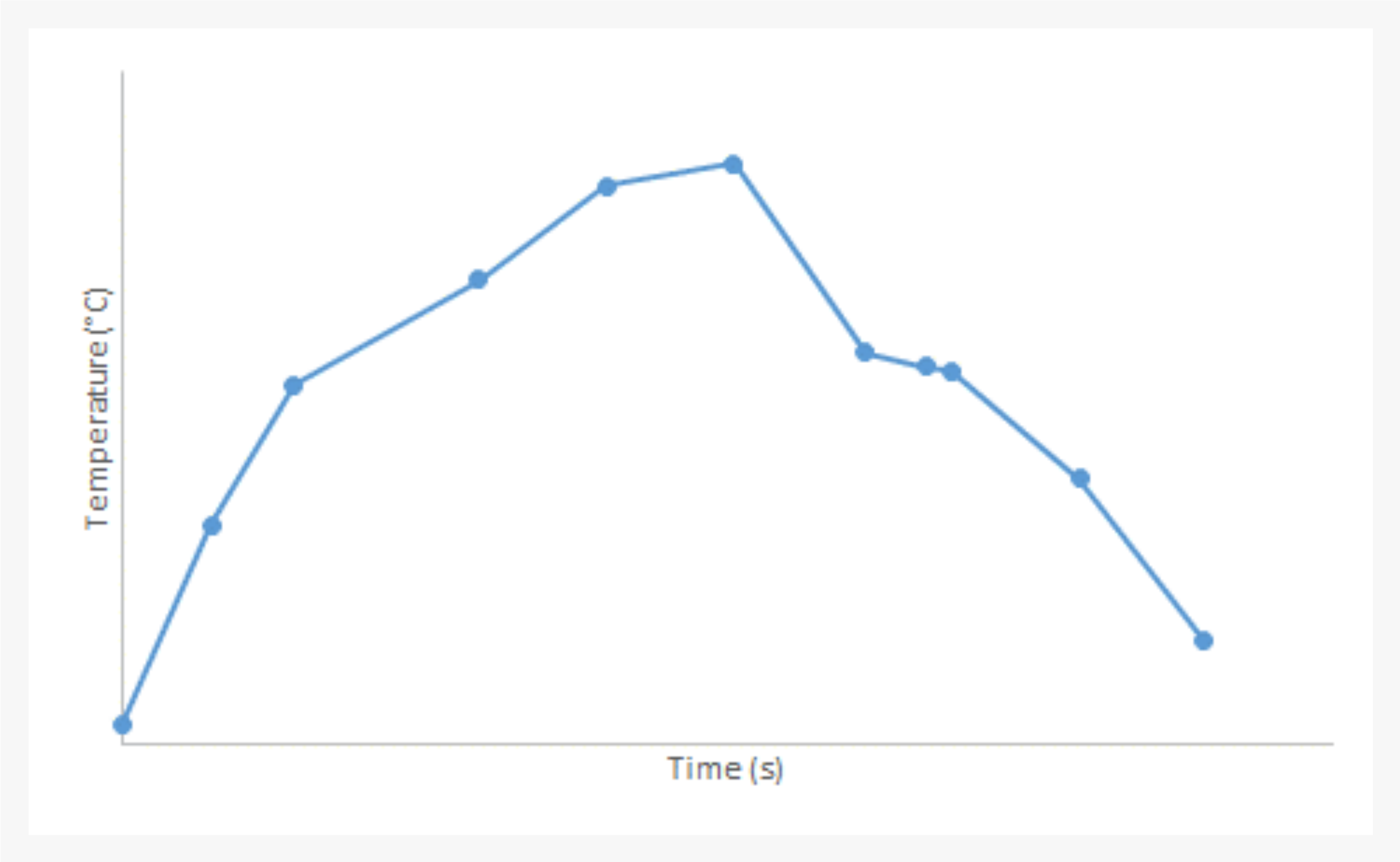


Figure 6: Example anneal cycle defined for simulation work.

The simulation is comprised of multiple segments with variable heating and cooling rates which are loaded into the PLC box of the CAL simulator system. The software interface is backed up by a program developed in the CScape Programming software where considerations for heating rate and peak temperatures are set. For a specific heat treatment, up to ten different steps can be set up in the machine to obtain the adequate cycle rates and temperatures.

With the cycle loaded into the system, a test specimen is used to calibrate the heating profiles. Once the desired profile is achieved, the set number of test specimens are subjected to that given anneal cycle with temperature results recorded for each specimen (Figure 7). Generally, sample temperature control has been within +/-5°C of targets.

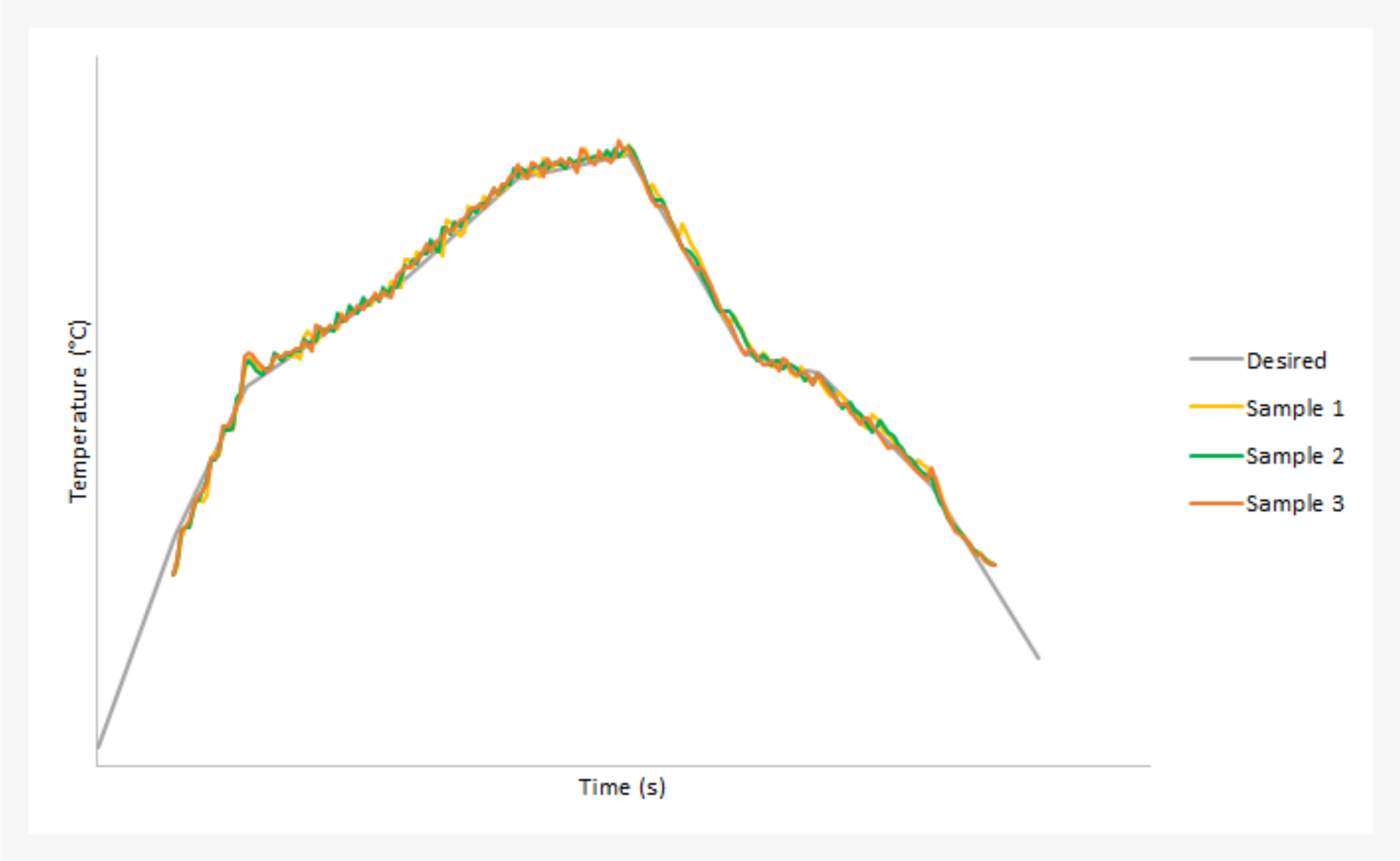


Figure 7: Anneal cycle results for test specimens compared to the desired anneal cycle.

Worthington Industries Case Example

A cold rolled full-hard 1010 substrate was selected for simulation work to assist with material application. The substrate received a predetermined amount of cold reduction (>50%) and possessed the chemistry described in Table I.

Carbon	Manganese	Phosphorous	Sulfur	Silicon	Aluminum
0.09	0.33	0.011	0.009	0.01	0.036

Table I: Chemistry (wt%) of simulation specimens.

In order to define the operating window in the broadest sense, seven anneal cycles were outlined for simulation. Specimens were provided to The Ferrous Metallurgy Group at the University of Pittsburgh from which to calibrate each profile and then heat treat three samples per anneal cycle. The samples were returned to Worthington Industries for mechanical property and microstructural evaluation. Subsize tensile specimens were prepared based on the size of the heat treated regions.

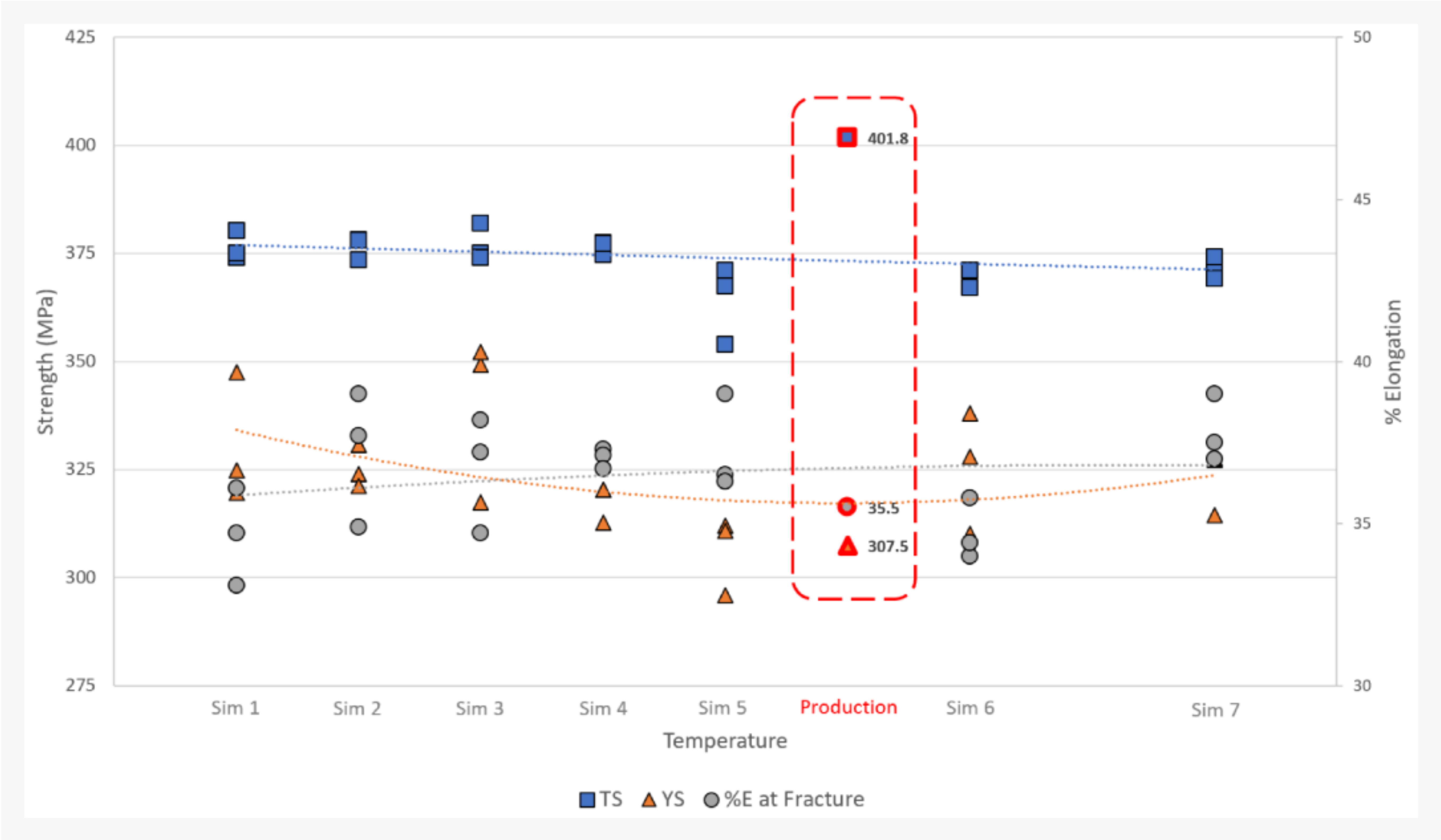


Figure 8: Simulation and production mechanical property results.

Mechanical property results from the simulation work are depicted in Figure 8. Based on this information, an anneal cycle with a peak metal temperature falling between two of the simulated results was selected for the production process. Data points representing the average production results for this material after processing through the hot dip galvanized line are also included in Figure 8. Simulation work did an excellent job of predicting the Yield Strength and % Elongation. The Tensile Strength was ~6% higher in production compared to simulated data, possibly attributable to actual production parameter differences compared to plan.

Optical microstructural examination was performed to follow the evolution of features across the range of anneal cycles tested. Example results of this evaluation are shown in Figures 9 and 10. Despite performing the simulation in air, no appreciable surface decarburization was observed due to the relatively short heating cycle.

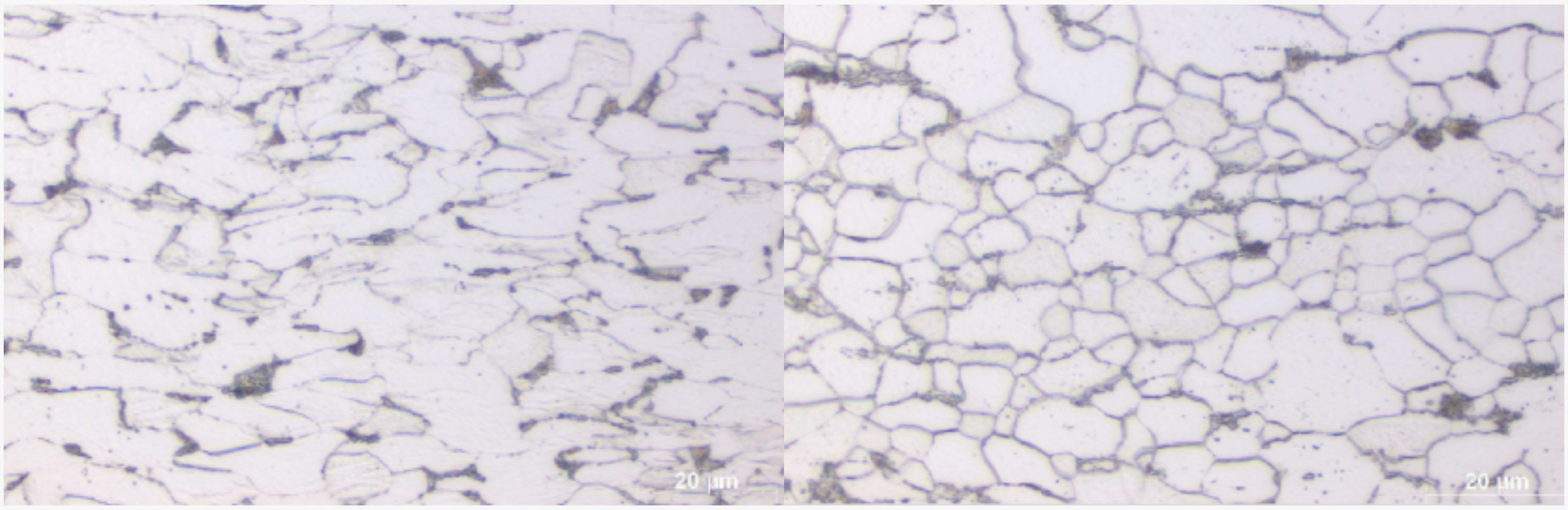


Figure 9: Grain structure of the cold rolled full-hard substrate (left), and recrystallized structure (right) from a simulation similar to the production cycle (1000X, 5% nital).

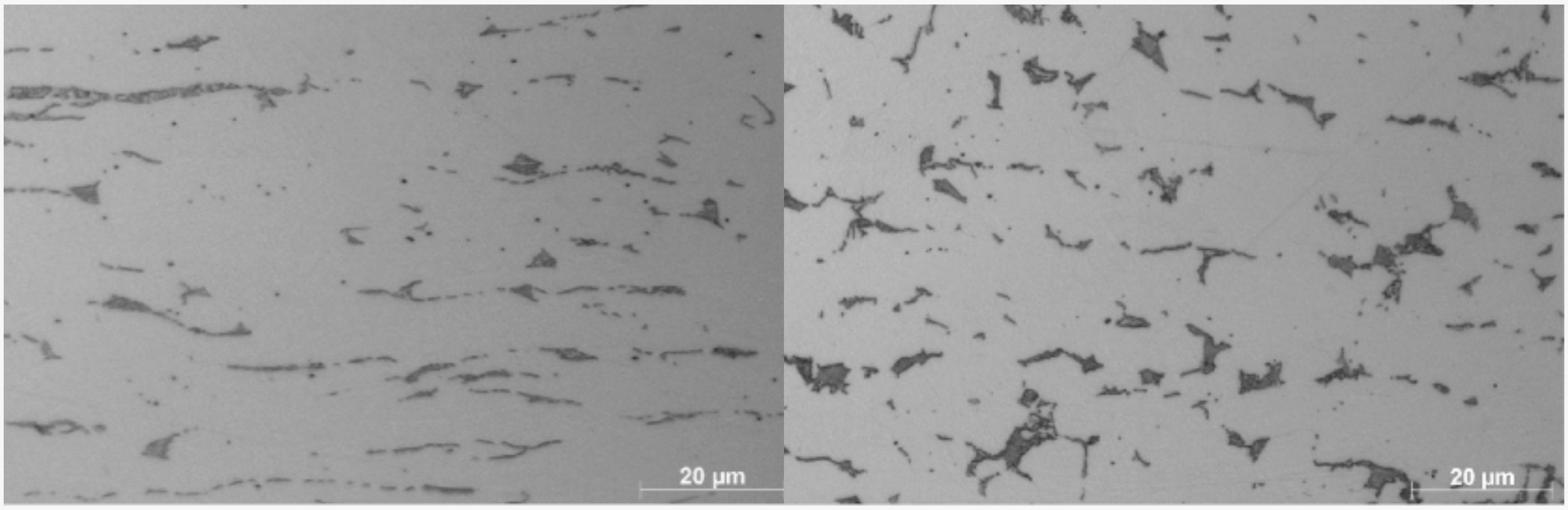


Figure 10: Carbide structure of the cold rolled full-hard substrate (left), and resulting structure (right) from a simulation similar to the production cycle (1000X, 4% picral).

Electron Backscattered Diffraction (EBSD-IQ) analyses were used to assess the microstructural condition of the samples prior to and after annealing simulations. The results are presented in Figure 11. This figure presents the Inverse Pole Figures (IPF) for different conditions, clearly showing the changes in the microstructure with annealing. As expected, the full hard condition exhibited a preferred crystallographic orientation and highly deformed grains. The annealed samples showed substantial recrystallization and a random texture. The higher temperature anneal (Simulation 5) produced substantial recrystallization with an average grain size of 12.4 µm, compared with the lower temperature anneal (Simulation 1) with an average diameter of 10.0 µm.

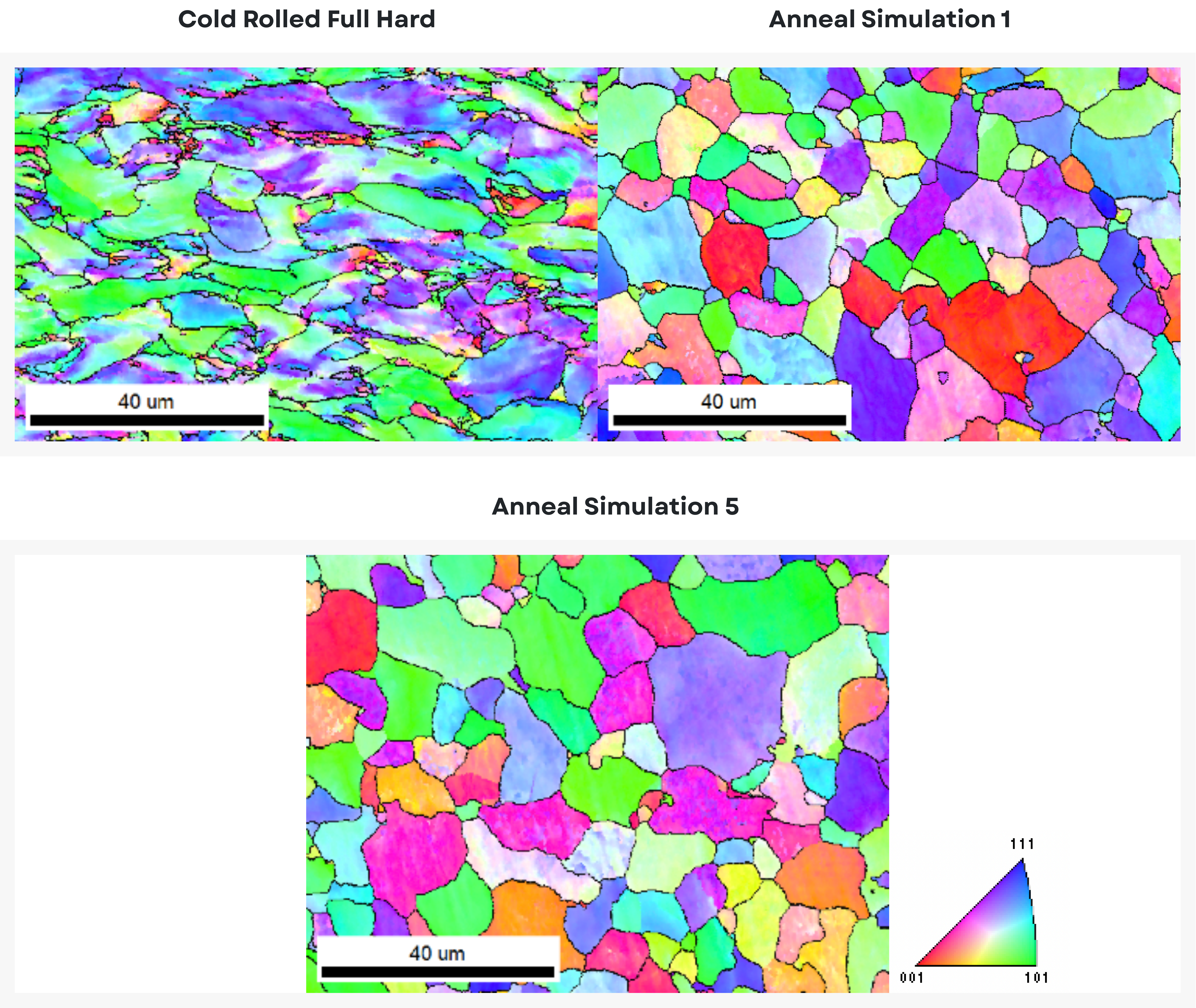
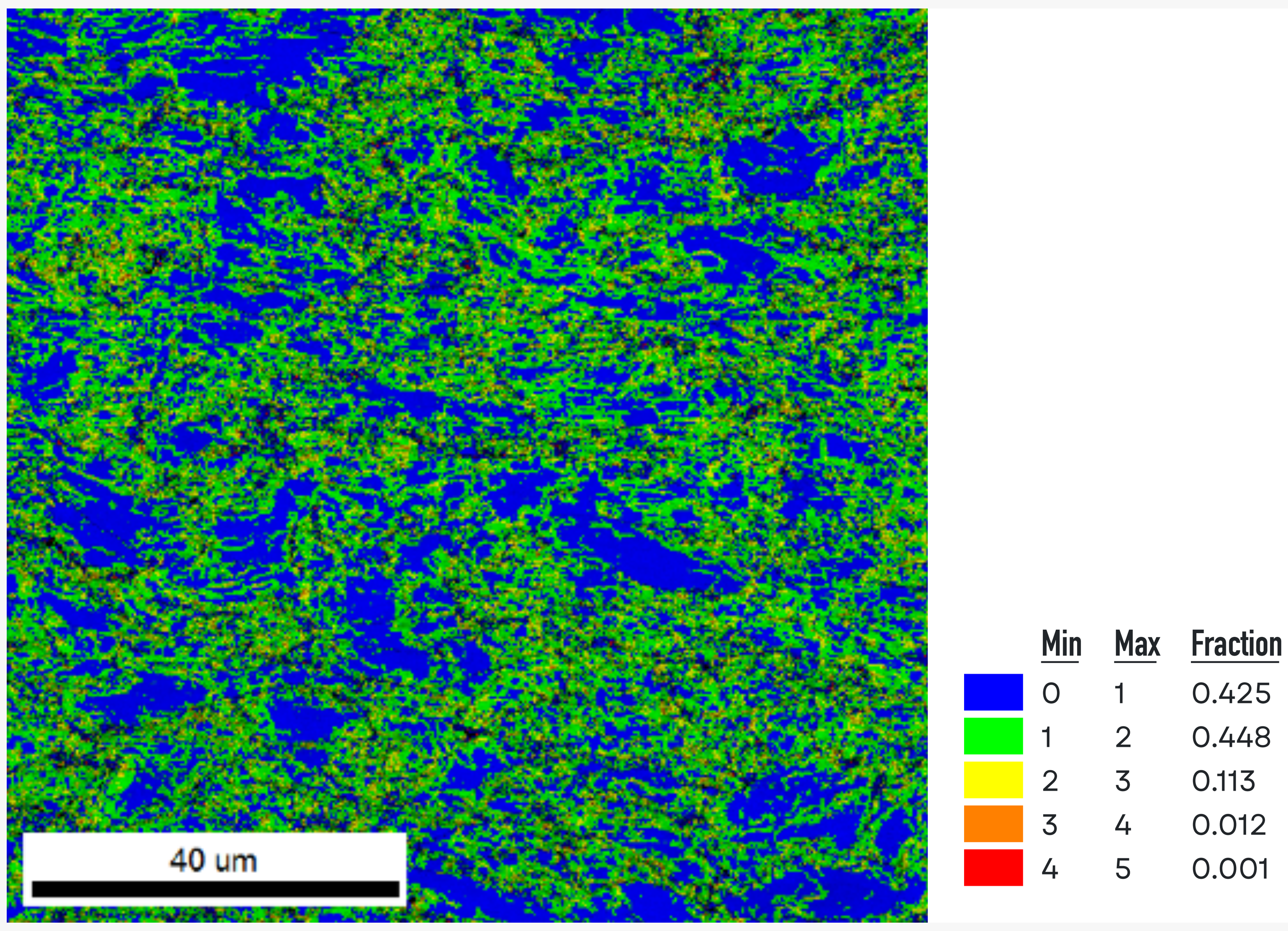


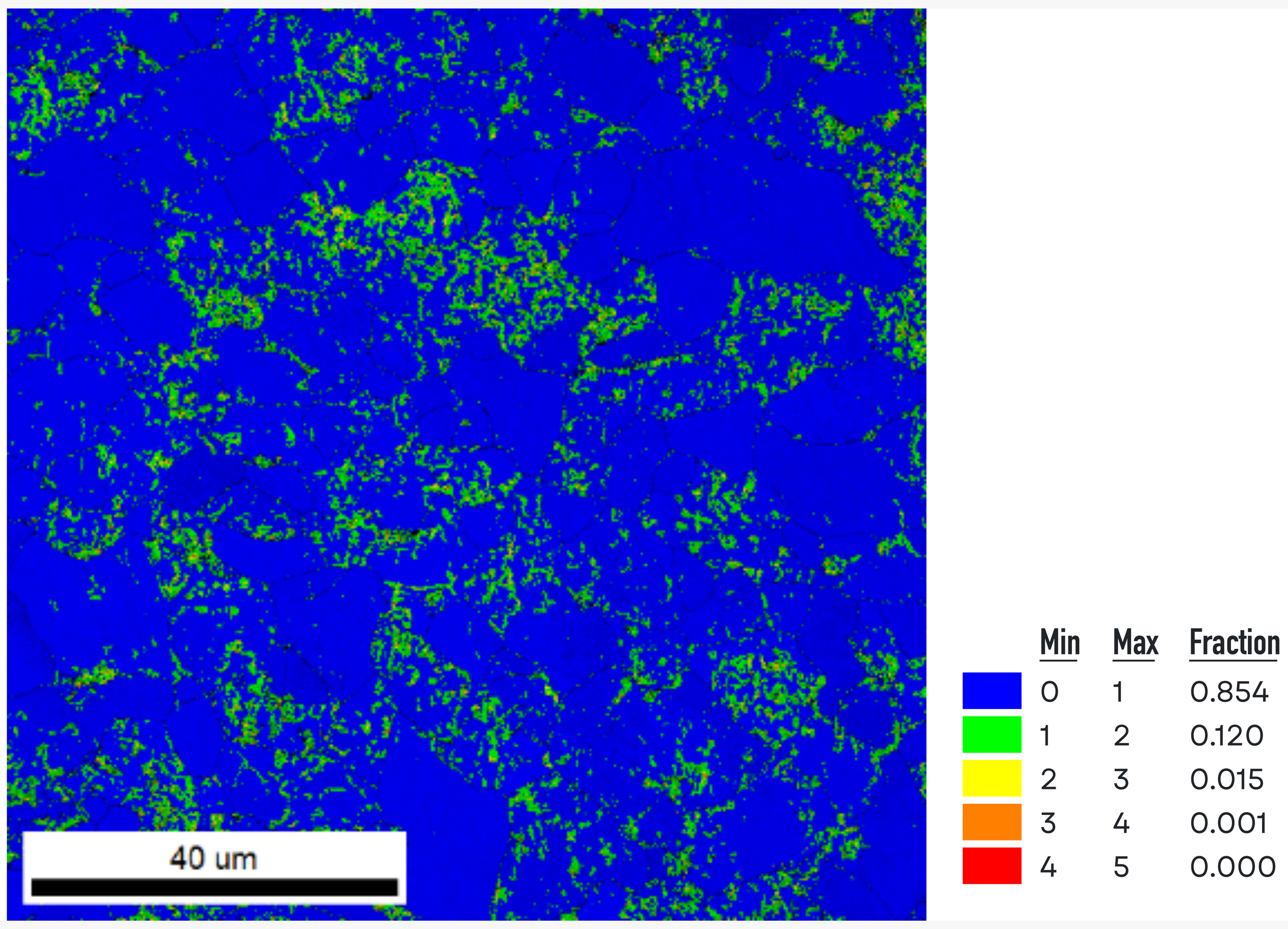
Figure 11: Inverse Pole Figure (IPF) as function of processing.

The effect of the different annealing temperatures can also be assessed by examining the different amounts of recrystallization obtained using the Kernel Average Misorientation (KAM) factor. This factor can provide an estimation of the total recrystallization in each sample, as shown in Figure 12. The recrystallization percentage increases with annealing temperature, reaching 86% recrystallization for Simulation 1 and 88% for Simulation 5 in this example. From the EBSD information, it is also possible to calculate the Stored Energy (SE) associated with each sample to review changes as a function of annealing. For example, the full hard sample exhibited an approximate SE value of 1.51 J/cm^3, while the annealed samples had SE values of 0.56 and 0.42 J/cm^3, respectively. The SE changes support the impact of annealing temperatures on the microstructural changes observed in this study.

Cold Rolled Full Hard



Anneal Simulation 1



Anneal Simulation 5

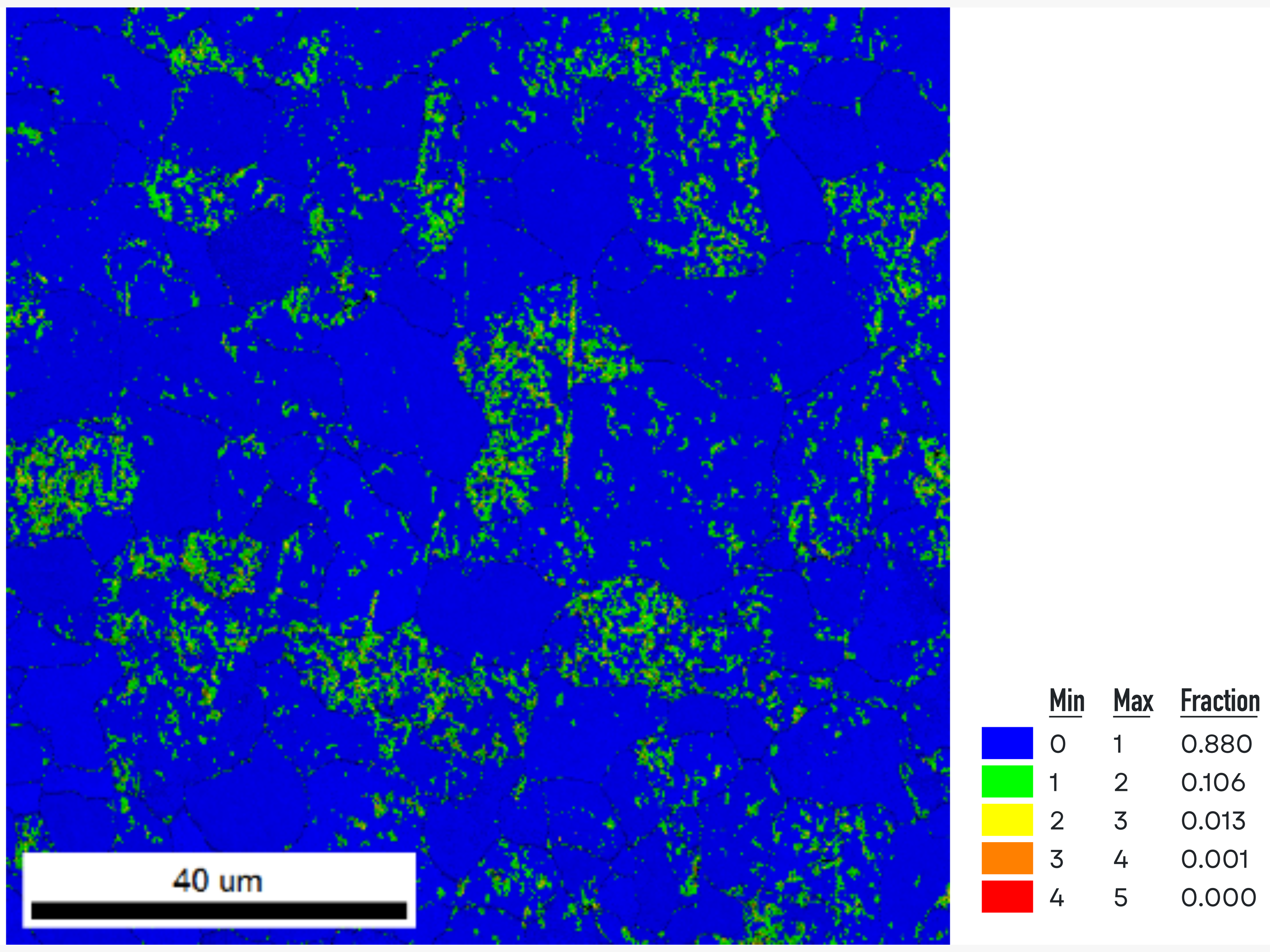


Figure 12: Kernel Average Misorientation (KAM) of multiple conditions.

Conclusions

The University of Pittsburgh's CAL Induction Simulator has proven to be an effective tool for physical modeling of hot dip galvanizing processes. Mechanical property and microstructural results produced in this manner have provided reasonable estimates on results from which to make informed processing decisions. Use of this methodology has reduced the time associated with grade development cycles, has reduced risks associated with uncertain outcomes, and has resulted in improved operational efficiency with lower costs. The modeling has been successfully used to evaluate both hot rolled and cold rolled substrates, both galvanized and galvannealed products, and a wide range of grades including low carbon, HSLA, and AHSS.

Acknowledgements

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