IOB Department for Industrial Furnaces and Heat Engineering | RWTH AACHEN UNIVERSITY

Simulation Model for Quenching of Ultra-Thin Precision Strips

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Introduction

The heat treatment process is a crucial step in producing ultra-thin precision strips as it determines both their mechanical properties and the required flatness. Current research focuses therefore on the development of an innovative annealing line with a new cooling concept (see **Figure 1**) which has the goal of improving the product quality of precision strips. During this heat treatment process, rapid cooling from the austenitizing temperature to room temperature induces martensitic transformation in the strip. This study presents a simulation method using the FEM Solver Abaqus/CAE to analyze the quenching step during the heat treatment of ultra-thin precision strips. The focus is on computing stresses, strains, and flatness effects that arise during martensitic transformation within the steel strip. Simulation results provide insight into the deformation behavior of the strip and facilitate the evaluation of flatness effects.

Analyzing stress and strain distributions is crucial for evaluating flatness effects and ensuring dimensional accuracy and surface quality of precision strips. This study combines thermo-mechanical analysis with flatness evaluations to provide a comprehensive understanding of the impact of the quenching process on the strip flatness. In order to achieve this, a thermal simulation model for calculating the quenching step during heat treatment is coupled with the model for calculating the deformation.

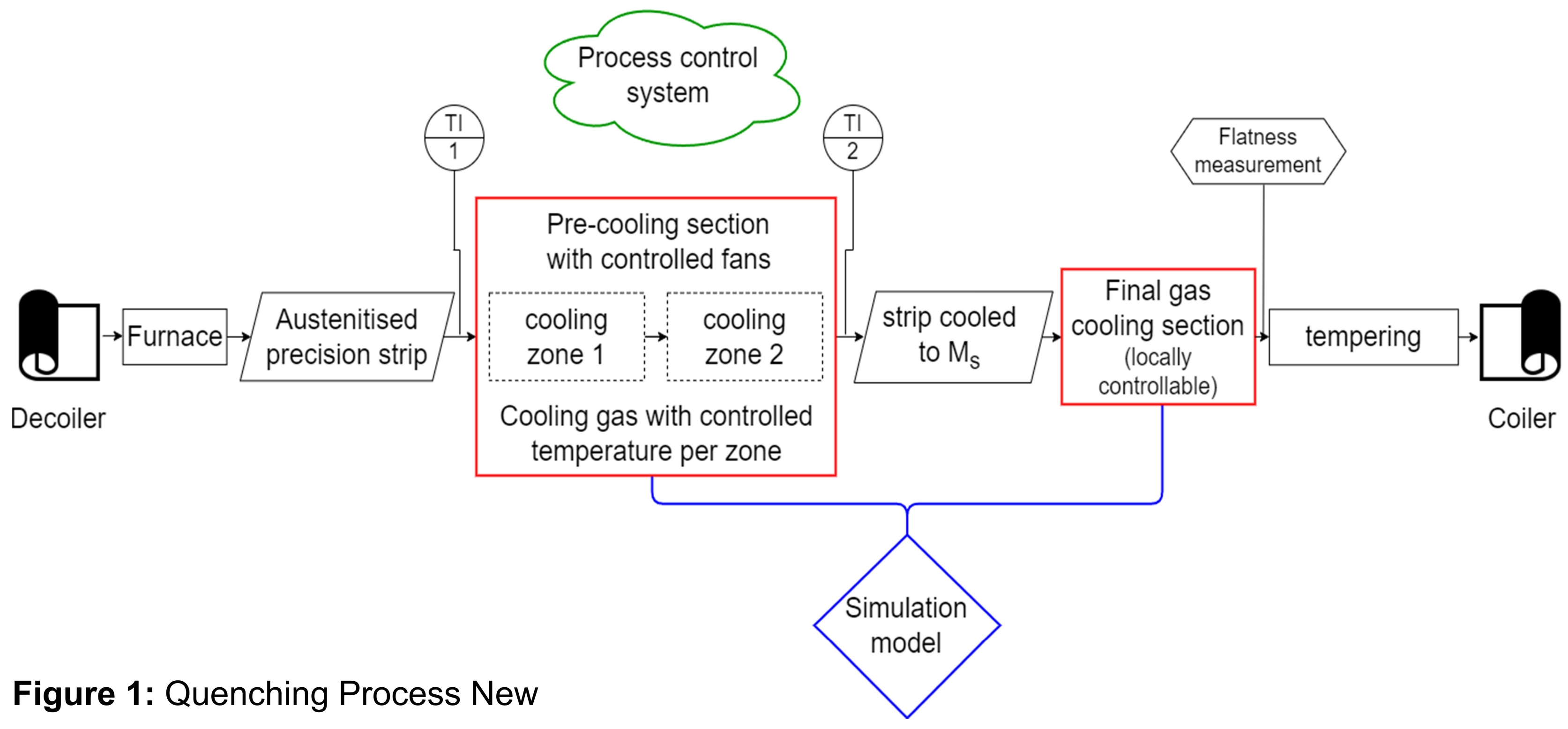

Figure 1: Quenching Process New

Coupled finite difference model for calculating the strip temperature during quenching

The coupled finite difference simulation model (FD model) for calculation the strip temperature during quenching, which is implemented in the MATLAB® environment, was developed at the IOB. The model calculates the temperatures over the entire strip width during the quenching of precision strips based on the new cooling concept. For this purpose, all necessary boundary conditions of the line, such as the material properties (strip width, thickness), the input temperature distribution after austenitizing across the strip width, the cooling rates of the convective impingement gas jets and the strip speed can be adjusted in the model. The model calculates the temperature distribution, as shown in **Figure 2**, over the entire strip width based on experimental measurements of the convective heat transfer distribution, see **Figure 3** and **4**. This allows conclusions to be drawn about the uniformity of the quenching and about temperature gradients, which directly indicate the expected flatness of the strip. The result of the quenching calculation is used in the deformation model to calculate the temperature and quenching-induced deformations over the strip width. The model is further described in [1].

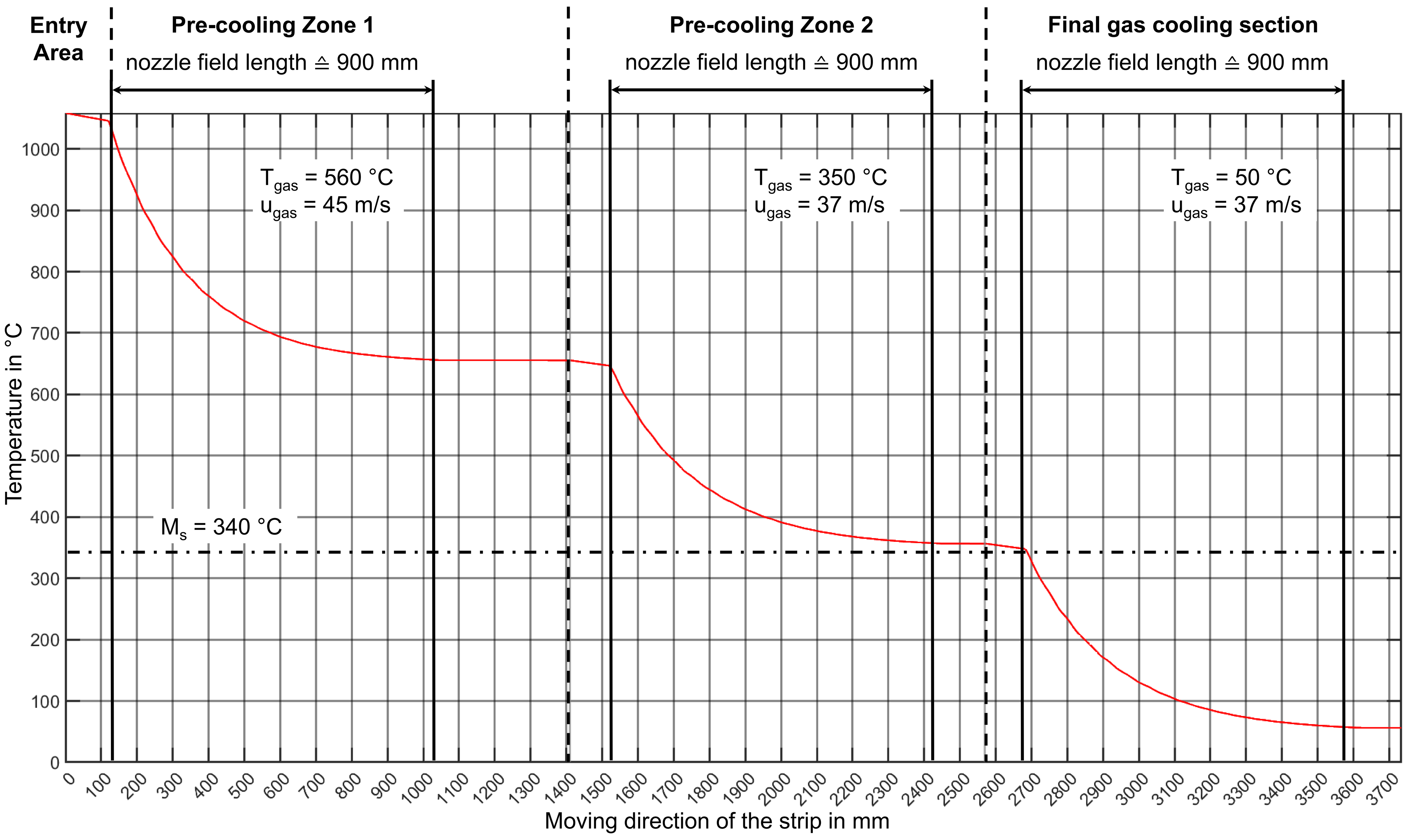

Figure 2: Temperature distribution (averaged over the strip width) for the quenching of precision strips at a strip speed of v_{strip} = 12 m/s

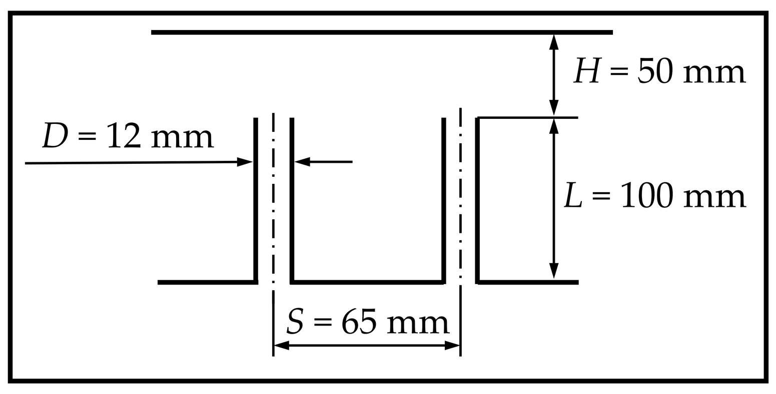

Figure 3: Scheme of the round nozzle system used in the pre cooling section

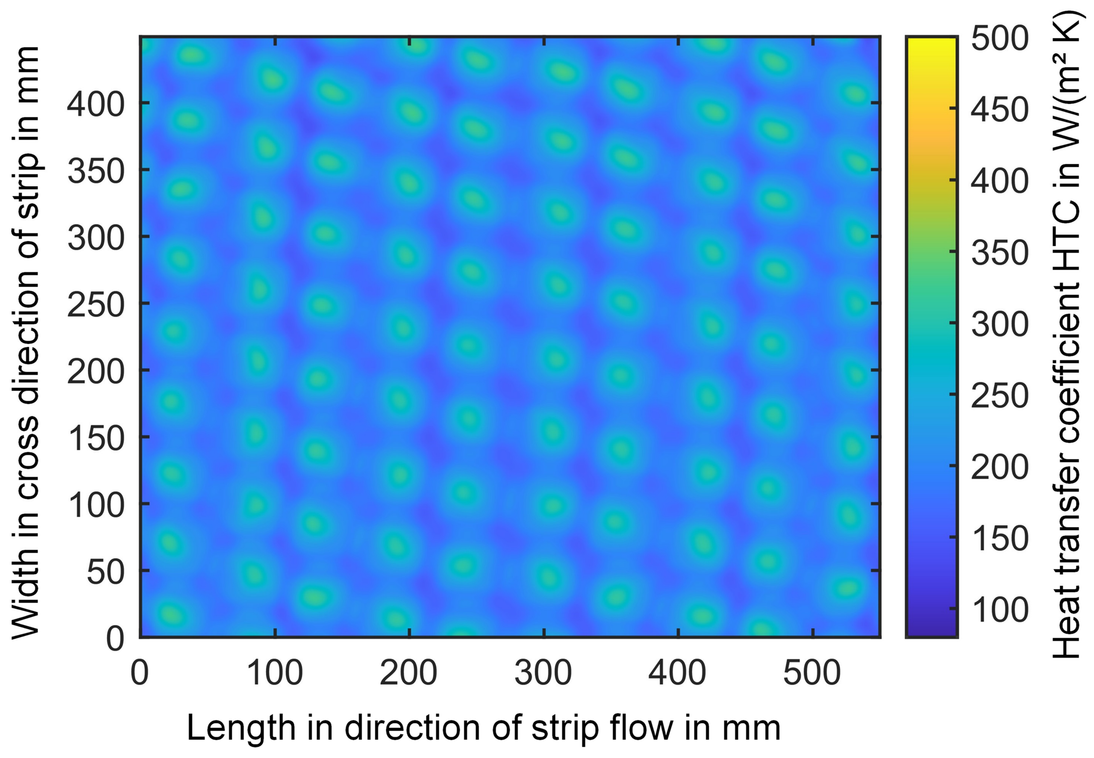

Figure 4: Experimental measurement results of convective heat transfer distribution from round nozzle system in pre-cooling section

Finite element model for calculating stresses, strains and deformation

The finite element simulation model (FE model), which is build in Abaqus/CAE, is based on the dimensions of the strip, including a maximum length of 3700 mm, a strip width of 380 mm and a strip thickness of 0.125 mm. The width and thickness are based on production parameters and can be changed. The length of the modelled strip can vary between 1400 and 3700 mm. This depends on whether individual sections or the entire quenching unit of the heat treatment process is being considered for calculation. The strip is meshed with a maximum number of 1.4 million shell elements. The model incorporates temperature-dependent material properties and employs a calculation method that couples temperature and displacement for problem resolution. The cooling process from austenite temperature to room temperature has been pre-simulated using the FD model.

The temperature distribution is used as a boundary condition within the FE model. A moving strip is simulated by assuming the temperature distribution for every time step during quenching. To calculate the stresses, strain and deformation, the strip needs fixed boundary points. For this purpose the strip edges are used as bearings. One edge is used as a fixed bearing while the other corners allow a strip displacement in different room directions, see **Figure 5**. Strip movement in Z-Direction is not allowed at all four edges of the strip but the deformation in Z-direction can occour at any other point of the model. A tensile force F_N is exerted on one wide side of the strip, which is intended to represent the strip tension occurring during the process.

To simulate the martensitic transformation during quenching two user subroutines are added to the model. The UMAT (user Material) and the USDFLD (user defined field) subroutine. The variation of martensitic volume fraction with the temperature during quenching is calculated using the Koistinen-Marburger equation (K-M model) [2].

$$f(T) = 1 - exp[\alpha(M_s - T)]$$

The K-M model calculates the fraction of transformed martensite f, dependent from the martensite start temperature M_s and the actual quenching temperature T. In the model the fraction of transformed martensite is recalculated for every element during every time step. Based on the subroutines and the K-M model the FE model calculates the deformation of the strip during quenching.

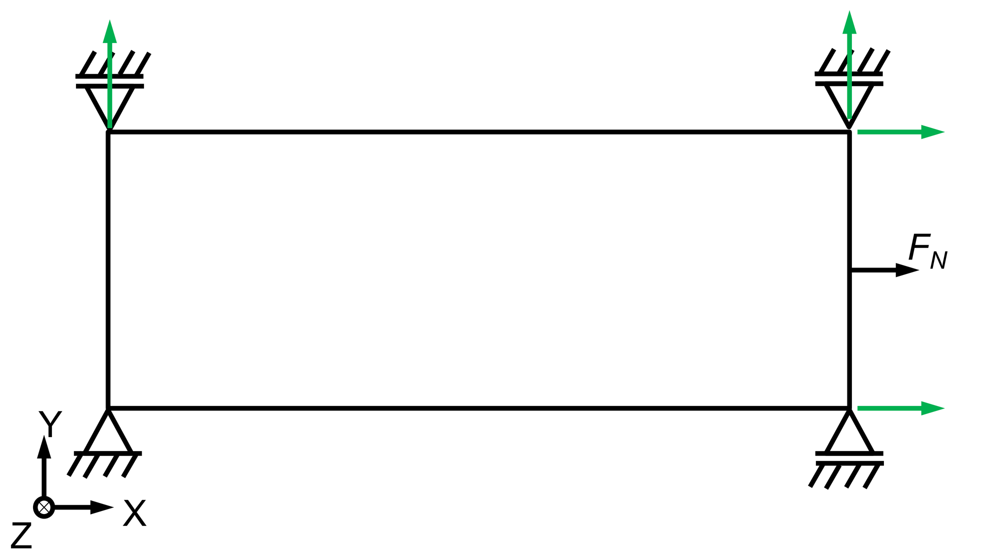

Figure 5: Boundary Conditions for strip movement, permitted displacement directions indicated by green arrows

Conclusion

In conclusion, the Abaqus simulation model presented, is a tool for examining the quenching process of ultra-thin precision strips. It analyses stresses, strains and flatness effects resulting from martensitic transformation during quenching. Residual stresses and strains can cause local deformations and distortions that affect the flatness of the strip, so within the model the varying temperature gradients across the strip due to cooling rates are considered. As of today, first simulations of the quenching is running. Therefore **Figure 6** shows a first result of the occouring deformation U due to martensitic transformation in the final quenching section. From the deformation result, statements can be made regarding the flatness of the strip after cooling. The direct effects of temperature gradients across the strip width, which can be caused by disparate cooling processes, are also evident.

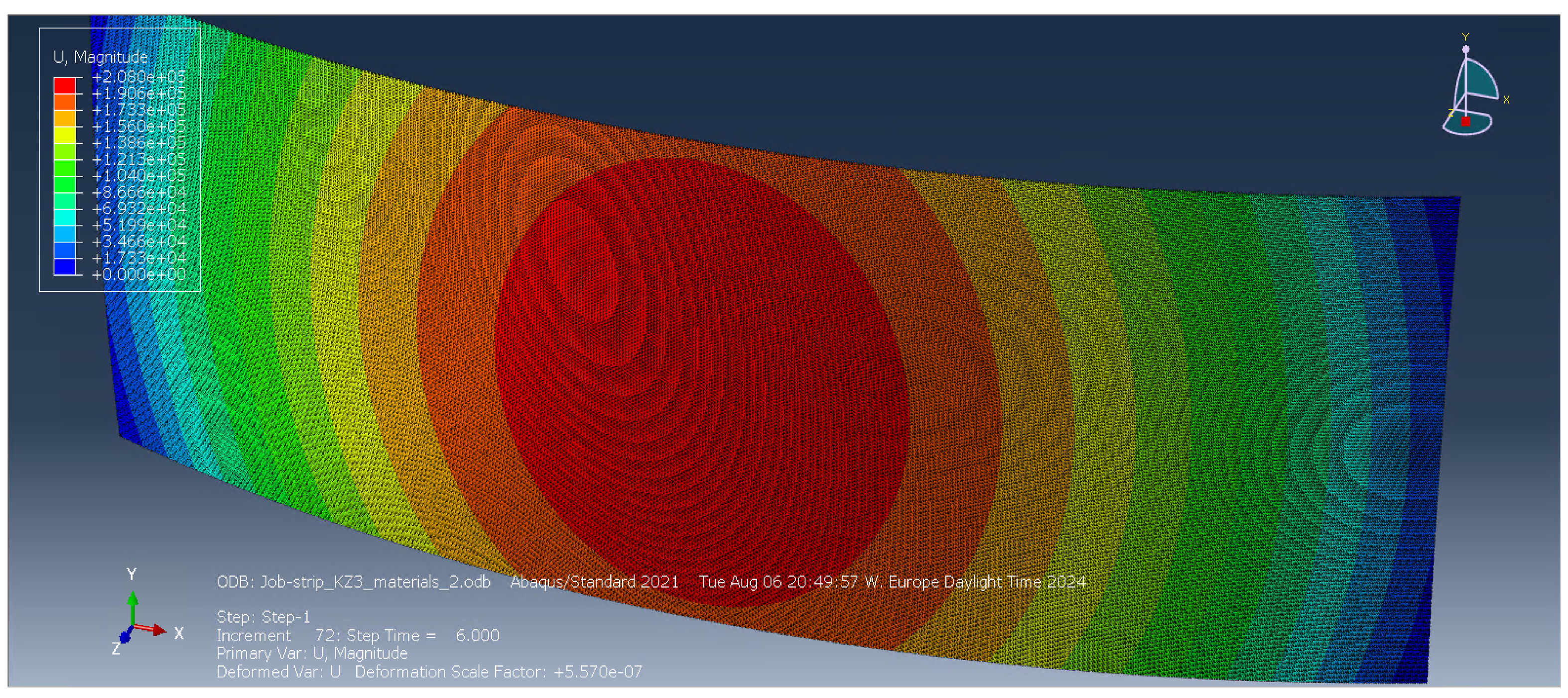

Figure 6: Result of the deformation U of the strip in the final quenching section

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[1] N. Rademacher, C. Kühnert, D. Büschgens, M. Eickhoff, H. Pfeifer, T. Bernard, Simulation model of a strip annealing line to improve product quality in precision strip production, presented at. 14th European Conference on Industrial Furnaces and Boilers (INFUB-14), 2-5 April 2024, Algarve, Portugal, ISBN: 978-989-35683-0-9

[2] D.P. Koistinen, R.E. Marburger, A general equation prescribing the extent of the austenite-martensite trans-formation in pure iron-carbon alloys and plain carbon steels, Acta-metallurgica, 1959, 7, pp. 50-60

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