La Metallurgia Italiana
International Journal of the Italian Association for Metallurgy

DOI 10.36146/2026_04_43

Relaxation and creep in hot coiled steel strip

J. Lindwall, H. Magnusson, L. Almquist Pessoa

A hot rolled steel strip that seemingly comes out as flat after the final rolling pass might potentially end up with flatness issues after it has been coiled. It is not easily understood which mechanisms in the coiling process are causing flatness issues. It is known from a material perspective that a combination of high stresses and temperatures can cause stress relaxations and creep deformations when the time in this state is long enough. A hot coiled steel strip at 600°C with a mass of 27 tonnes will take long time to cool down and it is uncertain whether stress recovery and creep behaviour have an impact on the final flatness. To investigate this, a three-dimensional thermo-mechanical finite element model with a creep material model is used to simulate the influence of creep deformations on final shape. It is, on one hand found that a relatively complex stress profiles are developed through the strip thickness when coiling, with compressive and tensile stresses beyond the yield stress, and that the tensile stresses recover unsymmetrically on one side of the strip midplane. On the other hand, is it also found that the creep deformations are only a fraction of the plastic deformations caused by the mechanical work during the coiling process. Hence, it is concluded that creep mechanisms play no, or possibly a marginal role in the shape of the final shape. Whereas stress relaxations result in a stress neutral profile in the coiled state, which may cause shape variation after uncoiling and post processing.

KEYWORDS: HOT COILING; CREEP; RELAXATION; FE-MODELLING; STRIP ROLLING; FLATNESS;

INTRODUCTION: HOT COILING AND STRESS RELAXATION

To reach the expected product quality of steel strips there is a continuous interest to understand and to predict the possible causes for flatness defects. Defects can arise during rolling, at cooling at the run-out table, or at the coiling process with cooling to room-temperature. There are different types of flatness issues that can develop during rolling, common are development of longitudinal waves, as illustrated in figure 1. Mainly, these waves arise under unfavourable rolling when the affected section becomes more processed than the rest of the cross-section of the strip. The additional work elongates the material more and the material needs to go somewhere, and the result is repeatable buckles.

In this study, interest is on the evolution of stresses and potential flatness issues that can occur when the hot steel coil is cooled to room temperature. Coiling as a process has been studied in the past by different groups.
Modelling the thermo-mechanical aspects of coiled steels is complex and many different aspects should be consid-

Johan Lindwall, Hans Magnusson
Swerim AB, Sweden

Lucas Almquist Pessoa
SSAB, Sweden

ered, as discussed in detail in [1]. Many studies in literature focus on the evolution of residual stresses for spring back analysis at decoiling such as [2]. Some few studies focus on the coiling process itself, trying to solve the complex temperature distribution in the coil during cooling, capturing variations along length and width of strip [3-8]. None of these studies have included the role of creep during slow cooling from high temperature, which can cause deformation of the coil and potential flatness issues.

The interest in this work is to investigate is to investigate if plastic deformation through creep can cause sufficient material deformation because of uneven cooling such that these defects appear by simply coiling at high temperature, even if the strip was flat beforehand. The study includes a detailed description of the stress and strain developments of the entire strip up to the coiling and models how these stresses and strains change during the hot cooling at 600°C to room temperature.

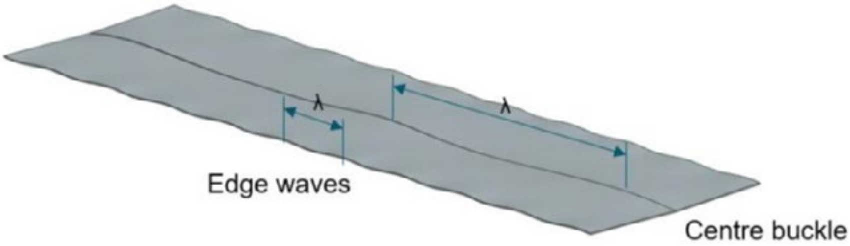

Fig.1 - Illustration of the flatness defects edge waves and centre buckle.

MATERIAL MODELING

As a starting point in the study, the so called Finbeam material model was used to fit Gleeble data, Schill et al. [9]. This model has been implemented in LS-Dyna and can capture the material response at hot-working conditions including deformation hardening and relaxation. Typical material testing parameters for hot-working conditions are 850-1250°C, and strain-rates 0.1-30 s-1. In this study, interest is at lower temperatures around 600°C, and much lower strain-rates (or creep rates), which require additional material testing but also possibly a new material model.

The original material model, which is based on an Estrin-Mecking type of model with some modifications [10], used a Zener expression to capture the role of strain-rates and temperatures on the dependent stresses, being yield stress, peak (tensile) stress, and steady-state stress. This allows for accurate interpolation and extrapolation in these quantities when doing simulations. Since this model was originally adapted for hot-rolling conditions with higher temperatures and deformations rates, the accuracy at low temperatures in the creep regime is to be concluded in this work. The interest is to follow how the yielding point can be reduced by potential creep. The expressions for yield stress and Zener parameter are according to below, Z is the Zener expression R as gas constant and T as temperature in Kelvin.

$$\sigma = 14.7 \cdot lnZ - 465.8 \qquad [1]$$

$$Z = \dot{\varepsilon} \exp\left(\frac{385254.4}{RT}\right) \qquad [2]$$

Models for creep are typically expressed the other way around, with strain-rate (creep rate) expressed as function of stress and temperature. Using the above two expressions, the strain-rate can be expressed as:

$$\dot{\varepsilon} = exp\left(\frac{\sigma_0 + 465.8}{14.7}\right) exp\left(-\frac{385254.4}{RT}\right) \qquad [3]$$

The parameters in the first term in equation 3 relates to the stress in MPa and the second term describes an activation energy J/mol. This model was never intended to work for creep conditions, but since its exponential relation between stress to strain-rate it is on the same form as many creep equations [11], especially for lower temperatures when creep is typically of importance for steels. In the above conversion, the yield stress has been used. Yielding is per definition the onset of deformation, and by deforming at slow deformation rates the creep stress should approach the yielding point. For faster deformation, additional work-hardening might occur, but this is not included here.

The requirements to describe creep is a model that should give a similar relation between strain-rate and stress, from relatively fast deformation down to creep conditions. The built-in material model MAT188 in LS-Dyna was selected, which uses a Garfalo-type of Sinh-expression as shown in equation below. Other possibilities are Norton-type of creep laws which have a power-law to stress, and thereby too weak relation between stress and strain-rate.

$$\dot{\varepsilon} = Asinh(B\sigma^{c})^{m}exp\left(-\frac{Q}{R}\right) \qquad [4]$$

An advantage with the above equation is that it is very similar to Eq. (3), as the Sinh-expression follows an exponential expression as long as the stresses are large, which they are at low temperatures (here defined as 600°C or lower). By comparing the two expressions, the following parameters are derived:

- m = 1 (should be exponential at low temperatures)
- $A = 1.15 \cdot 10^{14}\ s^{-1}$
- Q = 46338.0 J/mol
- $B = 0.06802\ MPa^{-1}$

Slow strain tensile testing was used to feed the creep material model with data. The material used in the study is a hot roller strip with yield stress around 350 N/mm which can be coiled at 600°C in a range of thicknesses. Slow tensile testing was applied with deformations rates of relevance for both creep and faster deformation. Testing temperatures were chosen with respect to coiling, at 400-600°C. It was assumed that even lower testing temperatures below 400°C are similar to room temperature properties.

The results from the evaluated slow-strain tensile tests are given in figure 2. Stresses are shown versus displacement measured in millimeters. The testing covers temperatures 400, 500 and 600°C, and strain-rates from 10^{-6} to $0.2s^{-1}$. The trials with slowest strain-rate were interrupted before rupture, since the material had reached a steady-state creep stress needed to feed the material model. The results are according to expectation, that stresses increase with higher strain-rate and lower temperature.

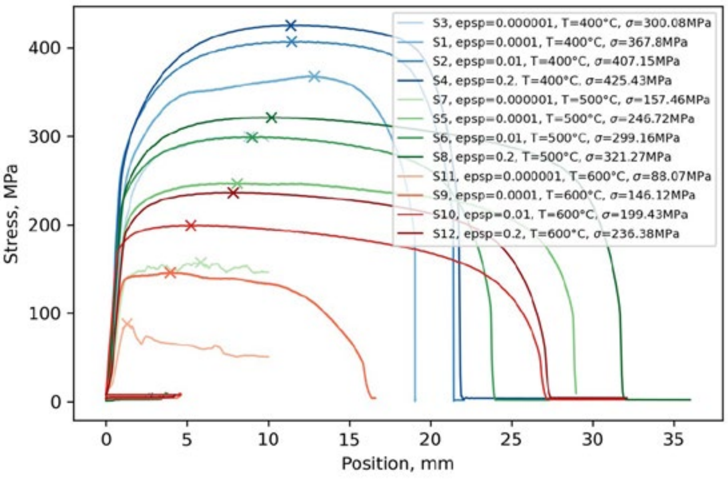

Fig.2 - Stress as function of position (in mm), for all the tests. The trials with slowest strain-rates were interrupted after steady-state conditions had been reached.

TEMPERATURE MODELING IN STEEL COIL

A coil was recorded with a thermal camera directly after coiling and continued for 33 hours while it was left to cool. The recording was then analysed in a software where markers were placed strategically on the frame as shown in figure 3. Markers 1-12 was placed on one side of the coil, mark 13-15 on the outer layer and mark 16-18 on the inside. These markers were later used to calibrate a model to simulate the temperature evolution in a representative solid body.

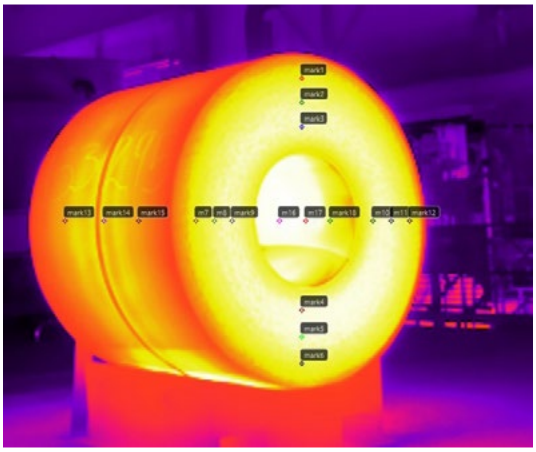

Fig.3 - Temperature measurement using thermal camera.

The temperature evolution was modelled using a 2-dimensional axis-symmetric model with anisotropic thermal conductivity in the radial and axial direction. The modelling domain is shown in figure 4. Material data was estimated using JMatPro. The radial conductivity is highly limited due to the small gap between each layer, consisting of oxide scales and air gap, and was modelled by applying a factor that reduced the values. The factor could not easily be estimated as it depends on the thermal conductivity and thickness of the oxide and gap between each layer, contact pressure, thermal shrinkage, etc. [7]. Ultimately, this depends on the elastic material properties and the contact pressure because of tensioning during coiling. The factor then becomes a unique value for each position in the coil and changes over time. A simplification was done by calibrating a constant value to provide a good fit to the measured temperature histories. The resulting value used in the simulations was 0.3, meaning that the thermal conductivity in the radial direction was 30% of the values in the solid material. The material density was assumed constant and equal to 7758.79 kg/m^3.

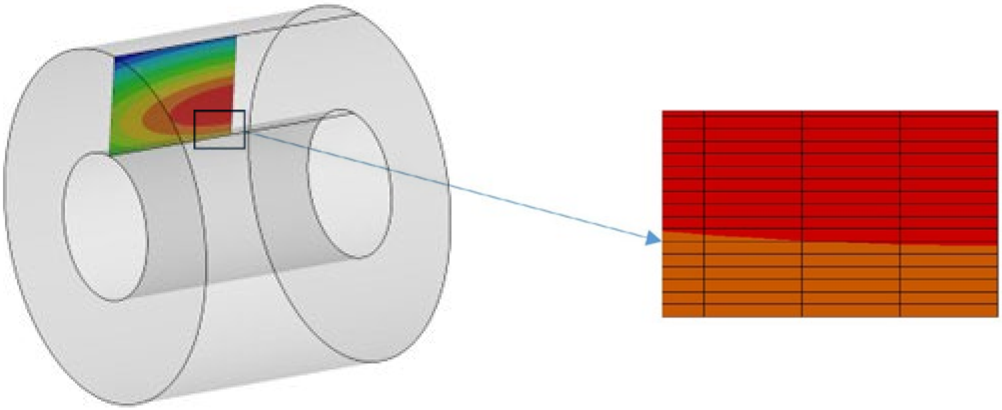

Fig.4 - Coil model for temperature simulation and mesh resolution.

MODELING OF COILING WITH PRE-TENSION

The stresses and plastic deformation developed during the coiling process was modelled in two separate models: one model for the stretching in the length direction together with bending over the pinch rolls, and another model for the coiling with bending on the increasing coil radius. The stress state from the first model was used as initial state to the second model using the interface_springback keyword in LS-Dyna. The final stress state after coiling was later used as an initial state for the creep simulation. Symmetry conditions made in possible to only model one half of the strip/coil, from the centreline to one edge. This simplification was done in all models.

The strip was modelled with shell elements with a thickness of 4 mm having five integration points in the thickness direction. Meaning that there will be a resolution of the stress through the thickness as there will be compressive and tensile stresses in the strip.

Pre-tensioning (pinch rolls)

An initially stress-free strip segment was pre-tensioned with a coiling force and bent over a rigid cylinder, shown in figure 5. The rigid cylinder represents the lower pinch roll with a diameter of 235 mm. The strip tension of 75794 N (half because of symmetry) was applied to the front of the strip at an angle that represented the increasing coil radius. The tail was constrained with a strip velocity of 5.0 m/s, which is an assumed mean value of the rolling speed in the final pass. The bending naturally causes compressive stresses on the bottom surface and tensile stresses on the top surface. The tension causes and average tensile stress in the length direction. The sum of these stresses gives the actual stress state in any position in the 3D space.

Coiling

The final stress state from the pre-tensioning was applied as an initial state in the coiling simulation. The front elements were fixed to a rigid spiral-shaped body at its smallest radius. The spiral was rotated with an angular velocity that corresponded to the coiling velocity of 5.0 m/s, see figure 5. Hence, the rotation velocity gradually decreased as the radius increased to maintain a periphery velocity of 5.0 m/s. When the strip elements and the spiral elements came into contact, they were permanently tied, assuming no slipping between the two parts. The tail was constrained with a point load equal the strip tension 75794 N (half because of symmetry) and constrained to a horizontal plane to limit additional bending (simulating firm alignment with the pinch rolls).

When the simulation was completed, a dynain file was automatically created using the interface_springback keyword. This creates a part file with the deformed geometry and the current stress and strain state. This file was later used as input to the stress recovery and creep simulation with the temperature history simulated earlier as an external load.

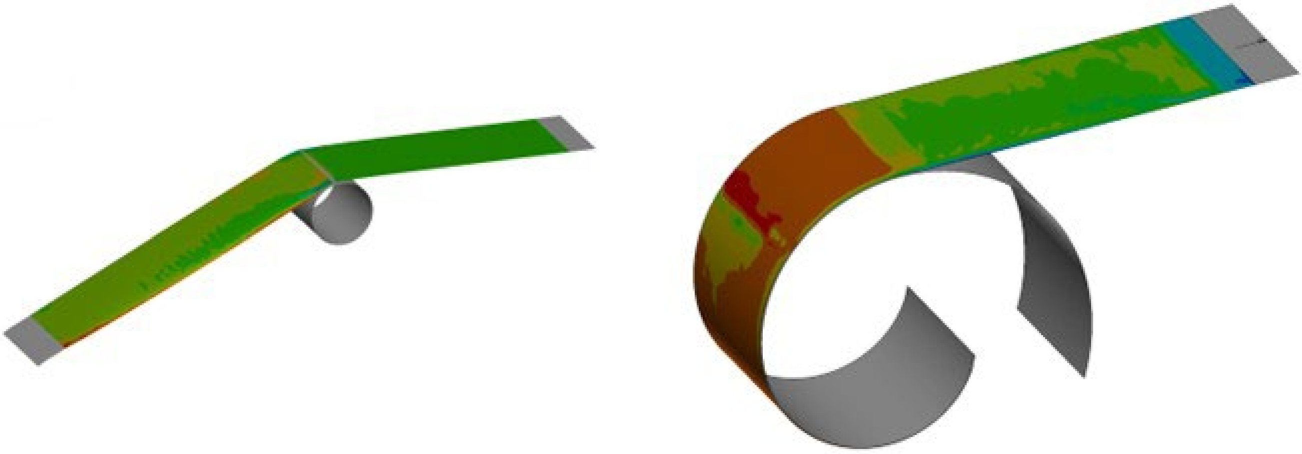

Fig.5 - Pinch roll bending with pre-tension (left), and mechanical coiling model with bending over a rigid body with linearly increasing radius (right).

MODELING OF RELAXATION AND CREEP

Simulation of the stress relaxation was done by combining the thermal simulation of the temperature history and the final state of the coiling simulation. The creep model was a transient implicit structural model only and the temperature history was applied with the keyword load_thermal_binout. The temperature was mapped to the geometry by the nodal ID's. Thus, it was absolutely necessary that the radial and axial position of each node in the deformed body corresponded to the exact same position of the same node ID's in the thermal model, that was rotationally symmetrical. This was achieved by modelling with the same number of elements in the radial direction in the thermal model as the number of elements in the length direction in the mechanical model. The spiral shaped body increase the radius linearly such that all elements land on the designated radial position.

The simulation was completed when the temperature reached values well below 200°C, which took about 24 hours. The time steps were automatically adopted but never longer than 100 seconds or such that the maximum temperature change was no higher than 0.01°C/time step. The stresses, effective creep strain etc. were computed every time step and stored to a data file in a frequency of 120 seconds for external postprocessing.

SIMULATION RESULTS

Temperature history

The temperature history by the thermo-camera recording and the simulation are shown in figure 6. Solid lines belong to the side of the coil where one edge of the strip is seen layer by layer. The dashed lines belong to the side where the tail of the strip is seen. The model parameters calibrated to fit the measurement on the firsts (mark 1-3). The temperature readings by mark14 and mark15 drops more quickly than other values, assumed because of a looser contact on the last lap, and therefore with poor thermal conductivity in the radial direction.

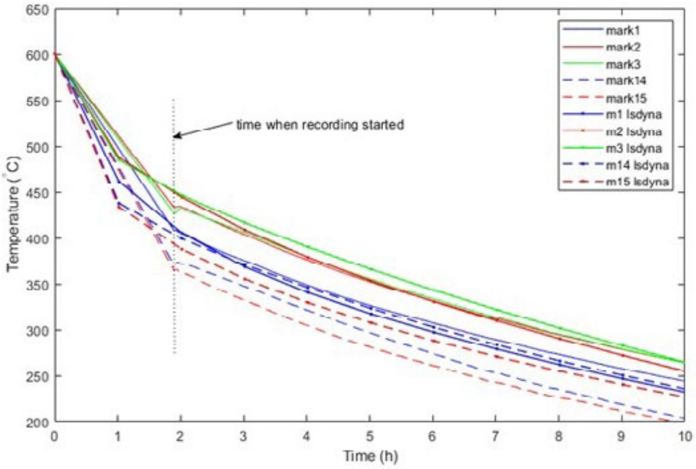

Fig.6 - Temperature history at selected position of the coil; measured and simulated.

Stress and strain evolution during coiling

When the strip is under tension and bent in the pinch rolls, it experiences compressive stresses and plastic deformation on the underside and tensile stresses end plastic deformations on the upper side as presented by the blue curves in figure 7. The mean stress and the stress at the neutral plane are positive as expected by the pulling force in the length direction. Much of the stresses swich between compressive and tensile when it is coiled, as seen by the red lines in the same figure. The radius of the coil is much larger than the radius of the pinch roll and therefor, the strip is "bent back" to a straighter state, yet curved. The stresses reach the yield stress, and the strip becomes plastically deformed in tension and compression, right graph in figure 7. Because of the limited hardening at the coiling temperature, the stress doesn't increase much beyond the yield stress.

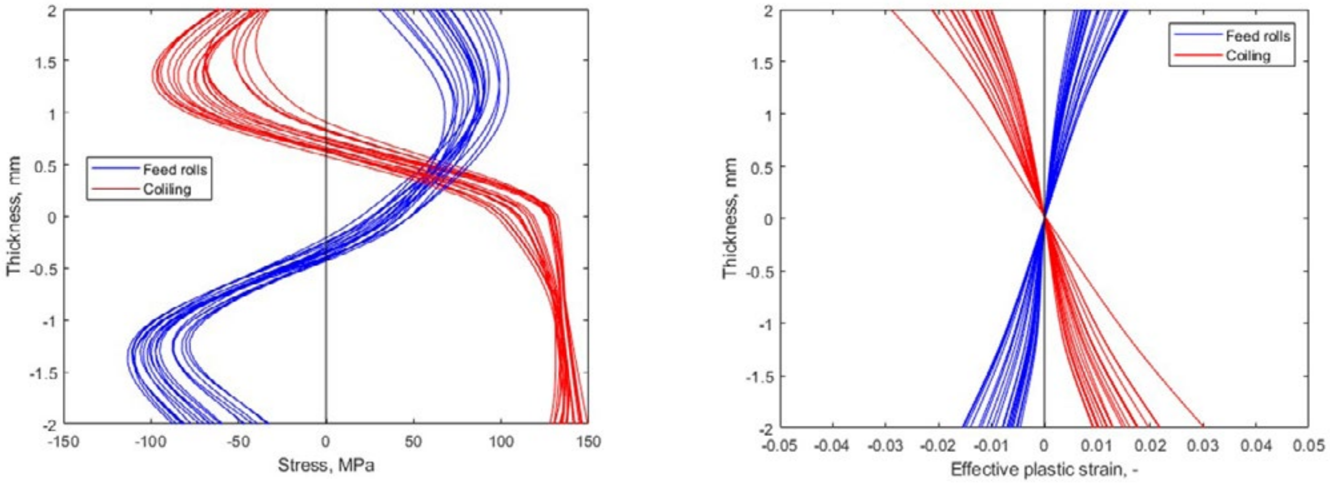

Fig.7 - Stress (left) and effective plastic strain (right) development during tensioning in pinch rolls and coiling. Each line represents the value through thickness at a location along the centreline of the strip. Values go from blue to red.

Stress and strain recovery during coil cooling

The built-in stress relaxes during the time when the coil cools down from the coiling temperature. Figure 8 shows the stresses and effective plastic strains at a low temperature, as they change from the initial coiling state shown in Figure 7. The potential/driving force for stress relaxation is high in the beginning when both the stresses and temperatures are high. Eventually, the rate reduces, and the stress stabilizes at roughly ± 50 MPa. Even with the reduced stress state, the change in plastic strain is only marginal as shown in the right graph in figure 8.

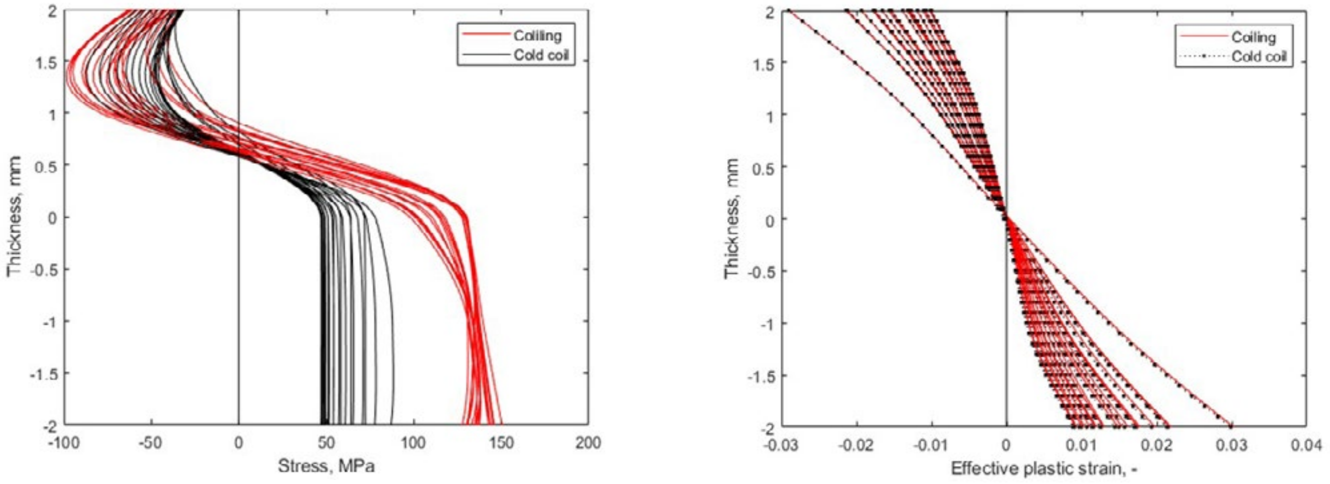

Fig.8 - Stress (left) and effective plastic strain (right) evolution during cooling of the hot coil. Each line represents the value through thickness at a location along the centreline of the strip. Values go from red to black.

Creep strain during coiling

The material changed shape to a very small amount during cooling due to creep, as shown in three layers in the strip thickness in figure 9. The total creep strain acts as a plastic deformation and could potentially lead to flatness issues. However, the maximum creep strain was computed to 4.9×10^{-4} which is very low as compared to the effective plastic strain by the mechanical deformation during coiling. As a reference, the effective plastic strains by mechanical work were around to 2×10^{-2} at most.

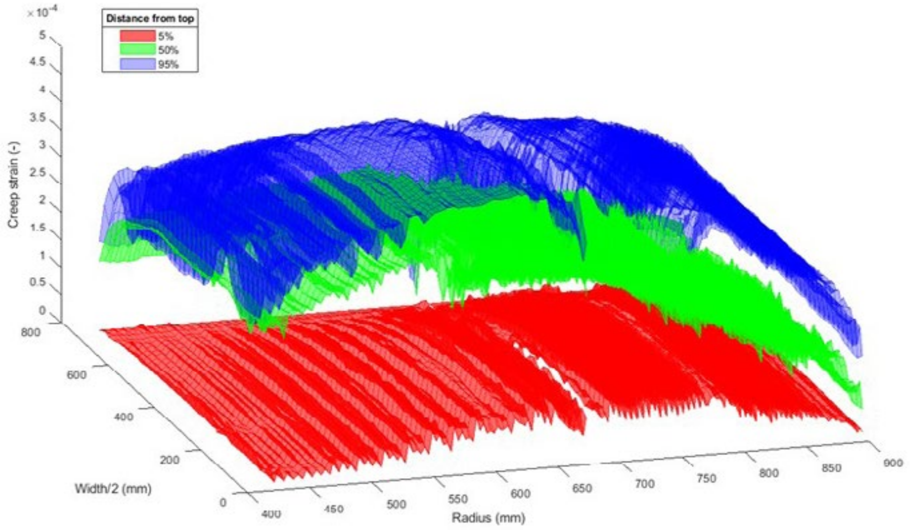

Fig.9 - Total creep strain during cooling of the hot coiled strip. Each plane represents a cross section along the thickness, i.e. 5% from the top is the outer surface (convex side) and 95% from the top is the inner surface (concave side), 50% is the centrum plane through thickness.

The rate at which the plastic strains recovers is shown in figure 10. As indicated by the scale, the rate is low, about 1.0×10^{-7} at most, and decreases quickly because of the decreasing temperature and stresses.

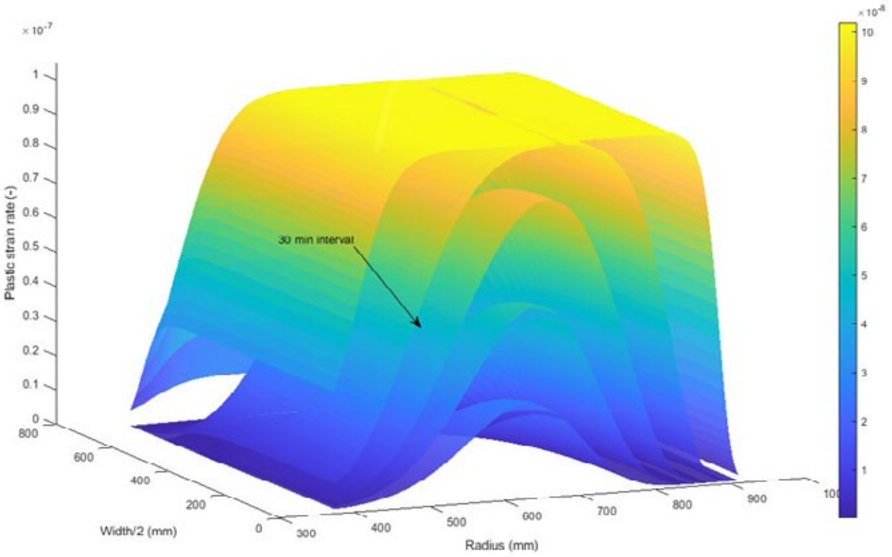

Fig.10 - Plastic strain rate in strip in steps of 30 min directly after coiling.

CONCLUSIONS

The resulting total creep strain during cooling is only a fraction of the effective plastic strain developed during coiling. This suggests that the creep strain will have no, or potentially a very little effect on the shape of the strip. Thus, creep is no factor to consider when it comes to flatness issues during coiling. In other words, all shape changing deformations are caused by the mechanical work during the coiling process. Nevertheless, the stresses within the strip that are close to the flow stress have recovered during the cooling. It was only on the bottom half of the strip that the stresses recovered from values around 150 MPa to about 50 MPa. The upper half did not recover much at all as the initial stress state in compression was already low. The noticed stress recovery is not expected to have additional effects on the flatness as the values are well below the yield stress in cold conditions.

Additional plastic deformations are applied during uncoiling to straighten the strip. The stresses required to unfold the strip, and make it flat, would have to be higher than the yield stress to have any permanent effects. Therefore, it is not possible to predict if the residual stress from the coiling has any effect at all on the final product. Likely, the uncoiling process itself will act as a levelling process.

FUTURE WORK

We suggest that the simulation results conclude that creep has not effective impact on the flatness of the strip during coiling. The stress variations along the width of the strip on the other hand, caused by the mechanical deformation during coiling, indicate that there might be variation of residual stresses after uncoiling. It is uncertain whether this relatively small stress variations can have an impact on the final flatness. If this mechanism is of interest to investigate, it is suggested that the complete coiling and uncoiling is simulated with flow stress data at relevant temperatures and strain rates at coiling and room temperatures.

REFERENCES

[1] V. Sattinger, A. Kainz, K. Schörkhuber, L. Aigner, K. Zeman. (2013). "Calculation of mechanical and thermal influences during coiling of hot strip", XII International conference on computational plasticity - Fundamentals and applications. COMPLAX XII. E. Oñate, D.R.J Owen, D. Peric, B. Suárez (Eds.). https://www.researchgate.net/publication/296680155_Calculation_of_Mechanical_and_Thermal_Influences_During_Coiling_of_Hot_Strip

[2] F. P. Amado, T. Gurova. (2025). "Prediction of residual stress after cold rolling and coiling process", The Journal of Strain Analysis for Engineering Design, 60(1), 49-58. https://doi.org/10.1177/03093247241273805

[3] B. Yang, J. Scholler, E Montazerozohour, S. Grosseiber, A. Seyr, B, Linzer. (2025). "Advanced coil cooling model incorporating layering and interface effects of strip windings", ISIJ International 65(11), 1717-1724.

[4] M. Dai, Y. Hu, Y. Hao, P. Qiu, H. Xiao. (2025). "Analysis of temperature and stress fields in the process of hot-rolled strip coiling", Metals 2025, 15(2), 111. https://doi.org/10.3390/met15020111

[5] R. Raj, J. B. Wiskel, M. J. Gaudet, D. G. Ivey, H. Henein. (2024). The effect of non-uniform skelp temperature on X70 steel coil cooling. Ironmaking & Steelmaking: Processes, Products and Applications. 2024;0(0). doi:10.1177/03019233241291653

[6] M. Karlberg. (2011). "Modelling of the temperature distribution of coiled hot strip products", ISIJ International 51(3), 416-422. DOI:10.2355/isijinternational.51.416

[7] M. Karlberg. (2016). "Thermo-mechanically coupled isotropic analysis of temperatures and stresses in cooling of coils", ISIJ International 56(10), 1808-1814. DOI:10.2355/isijinternational.ISIJINT-2016-073

[8] S. Witek, A. Milenin. (2018). "Numerical analysis of temperature and residual stresses in hot-rolled steel strip during cooling in coils", Archives of civil and mechanical engineering 18, 659-668. https://doi.org/10.1016/j.acme.2017.11.002

[9] M. Schill, J. Karlsson, H. Magnusson, F. Huyan, N. Safara, J. Lagergren, T. Narström, F. Johansson. "Simulation of hot plate rolling using LS-Dyna". Presented at the 13th European LS-Dyna conference 2021, Germany.

[10] N. Haghdadi, D. Martin, P. Hodgson. (2016). "Physically-based constitutive modelling of hot deformation behavior in a LDX 2101 duplex stainless steel". Materials & Design 15, 420-427. https://doi.org/10.1016/j.matdes.2016.05.118

[11] S. R. Holdsworth, M. Askins, A. Baker, E. Garboldi, S. Holmström, A. Klenk, M. Ringel, G. Merckling, R. Sandström, M. Schwienheer, S. Spigarelli. (2008). "Factors influencing creep model equation selection", International journal of pressure vessels and piping 85(1-2), 80-88. https://doi.org/10.1016/j.ijpvp.2007.06.009

TORNA ALL'INDICE >