# Influence of casting defects on damage evolution and potential failures in hot rolling simulation system

U. Hanoglu, B. Šarler

In this research, a previously developed rolling simulation code, based on a novel meshless collocation method, is upgraded from a deformation theory with ideal material properties to a new mechanical model that considers predefined defects even before the rolling process occurs. Considering homogeneous casted steel free of errors to enter a rolling mill will not produce any reliable predictions of possible failures. Depending on the rolling schedule, failure might occasionally happen during rolling as well, most likely due to high strain rates, shear stress, temperature gradient, friction, etc. However, most simulations that try to foresee those possible failures by only considering the rolling process parameters are incomplete. Even at the macro level, previous defects from the casting play a crucial role in failure that might occur or come very close to during rolling. The damage variable is initially defined as the density of micro-voids in the material. Instead of fracture mechanics, continuum damage mechanics is considered here to analyse the mechanical behaviour of the rolled steel in parallel with the damage evolution. As a result, a damage tensor is calculated during the hot rolling simulation based on the current deformation state. In each deformation step, the effective stress tensor is redefined with the inclusion of the damage tensor. For simplicity, a two-dimensional slice model is considered in the simulations. These slices are aligned parallel to each other and perpendicular to the rolling direction. Since the simulations are 2D, the damage tensor has no components towards the rolling direction. The main advantage of the upgraded simulation system is to have a more realistic material model that considers the initial defects of the steel and reveals the damage effects throughout the simulation. This gives a good virtual estimation of where and when to expect failure. The user determines a critical damage state, which could also be determined based on experiments. In this work, multiple rolling schedules obtained from the industrial partner are tested considering different levels of damaged input billet to be rolled. Overall, a computer program with a user-friendly interface has been created to visualise all those essential mechanical results and the damage field based on C# and .NET framework.

**KEYWORDS:** SIMULATION; ROLLING; STEEL; SLICE MODEL; MESHLESS; RADIAL BASIS FUNCTIONS; DAMAGE

## INTRODUCTION

In this research, a rolling simulation system based on a novel meshless solution [1] is upgraded by considering a damage model. The current system can simulate the hot rolling of steel based on elastic or plastic material properties and gives out results in terms of temperature, displacement, strains and stress. The rolling mill is usually placed right after the reheating furnace, where the casted billets are heated to a certain temperature. When the billet is rolled, it is crucial to keep the amount of deformation in a certain range. In most simulations, the material is considered defect-free at the beginning, but in reality, it

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already contains defects. All those unwanted contents/ errors may be assumed as damage. In each representative volume element, the amount of damage over the volume gives us the local damage value to be used in simulations.

The first idea of including damage variables in the equations of material deformation is given by Kachanov and Rabotnov [2-3]. They introduced a scalar damage variable. Later, Lemaitre [4] and Chaboche [5-6] used laws of thermodynamics to describe damage behaviour. Lemaitre [7], Chow and Wei [8] also came up with multi-scalar models. However, a damage model with a scalar is considered in this paper.

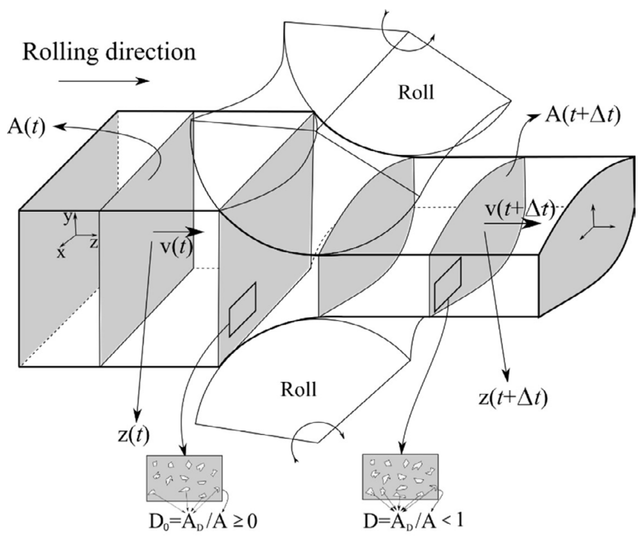


**Fig.1** - A scheme of the rolling simulation system based on the slice model.

In the simulations, a slice model assumption is used, as shown in Fig.1. This assumption lets us use 2D computational domains at each predefined position and the corresponding time. The slices are aligned towards the rolling direction. One slice at a time is subsequently simulated. Plane strain and planes remain planes assumptions are considered.

The hot rolling simulation system used here was previously developed in [9], and uses a novel Local Radial Basis Function Collocation Method (LRBFCM) for the numerical solution. This method was first used to solve heat transfer problems [10] and afterwards applied to fluid flow [11] and solid mechanics [12].

## SOLUTION PROCEDURE

From the deformation theory, the equilibrium equation has the following form

$$\nabla \cdot \mathbf{T} + \mathbf{b} = \mathbf{0} \qquad [1]$$

where $\mathbf{T}$ is the stress tensor, $\mathbf{b}$ is the body force vector. Stress tensor components $T_{ij}$ may be related to the strain tensor components $\varepsilon_{kl}$ with a 4th order stiffness tensor $C_{ijkl}$,

$$T_{ij} = C_{ijkl}\varepsilon_{kl} \qquad [2]$$

The Eq. 1 may be written in a vector form for over a 2D Cartesian coordinate system

$$\underbrace{\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{bmatrix}}_{\boldsymbol{\sigma}} = \underbrace{\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{bmatrix}}_{\boldsymbol{\varepsilon}} \qquad [3]$$

If a scalar damage parameter $D$ is introduced, the stress-strain relation becomes

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{xy}\end{bmatrix}=\underbrace{\begin{bmatrix}1-D & 0 & 0\\ 0 & 1-D & 0\\ 0 & 0 & 1-D\end{bmatrix}}_{\mathbf{D}}\begin{bmatrix}C_{11} & C_{12} & C_{13}\\ C_{21} & C_{22} & C_{23}\\ C_{31} & C_{32} & C_{33}\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{xy}\end{bmatrix} \quad [4]$$

The change of damage is related to

$$\dot{D}=\frac{\partial\psi}{\partial Y},\ Y=-\rho\frac{\partial\psi}{\partial D} \quad [5]$$

where $Y$ is the dissipation power and $\psi(\boldsymbol{\varepsilon},D)$ is the free energy per unit volume, separated into elastic and plastic parts

$$\psi=\psi_e+\psi_p \quad [6]$$

For an undamaged state the free energy from the elastic part is calculated as $\psi_e=\frac{1}{2\rho}\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{C}\boldsymbol{\varepsilon}$ . Based on the damage theory, the following relations may be obtained

$$\psi_e=\frac{1}{2\rho}\boldsymbol{\varepsilon}^{\mathrm{T}}\tilde{\mathbf{C}}\boldsymbol{\varepsilon}=\frac{1}{2\rho}\boldsymbol{\sigma}^{\mathrm{T}}\tilde{\mathbf{C}}^{-1}\boldsymbol{\sigma}=\frac{1}{2\rho}\boldsymbol{\sigma}^{\mathrm{T}}\mathbf{M}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{M}\boldsymbol{\sigma} \quad [7]$$

$$Y=-\rho\frac{\partial\psi}{\partial D}=-\frac{1}{2}\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{C}\boldsymbol{\varepsilon},\ \tilde{Y}=-\frac{1}{2}\boldsymbol{\varepsilon}^{\mathrm{T}}\tilde{\mathbf{C}}\boldsymbol{\varepsilon}| \quad [8]$$

For the simulation of rolling, one of the following damage-included models may now be replaced with the non-damage model given in Eq. 3,

$$\boldsymbol{\sigma}=\mathbf{DC}\boldsymbol{\varepsilon}=\tilde{\mathbf{C}}\boldsymbol{\varepsilon},\quad \mathbf{D}^{-1}\boldsymbol{\sigma}=\mathbf{M}\boldsymbol{\sigma}=\mathbf{C}\boldsymbol{\varepsilon} \quad [9]$$

The relation for the damage evolution model is defined in [13] as

$$1-D=\frac{Y_0(1-A)}{\tilde{Y}}+A\exp\left[-B\left(\tilde{Y}-Y_0\right)\right] \quad [10]$$

$A,B$ are material constants, $Y_0$ is the threshold for damage to start, and $\tilde{Y}$ is the damaged value of $Y$ .

## NUMERICAL IMPLEMENTATION

The solution is obtained through local interpolation of the unknown displacement field. In the governing equation, the strain vector components may be written in terms of displacement vector components in 2D, as shown below:

$$\varepsilon_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \quad [11]$$

Instead of meshing, many collocation nodes are allocated over a computational domain which is a slice at a position under the roll. For each collocation node, displacement vector components and their derivatives are interpolated locally by considering only a certain number of nearest neighbouring nodes ( $N=7$ ). $\varphi(\mathbf{p})$ is the multi-quadrics radial basis function at the position $\mathbf{p}=p_x\mathbf{i}_x+p_y\mathbf{i}_y$ .

Interpolation of a displacement vector component and its derivative is shown below:

$$u_i(\mathbf{p}) = \sum_{n=1}^{N} \varphi_n(\mathbf{p})\gamma_n\,, \quad \frac{\partial u_i(\mathbf{p})}{\partial x_j} = \sum_{n=1}^{N} \frac{\partial \varphi_n(\mathbf{p})}{\partial x_j}\gamma_n \qquad [12]$$

$\gamma_i$ are the collocation coefficients to be determined as a part of the solution procedure.

## RESULTS

After the continuous casting of steel, the billet first goes into reversing rolling mill. Fig. 2-left below shows a part of the billet's initial cross-section before rolling. In the pre-process of simulation, porosity over the slice is notated with a simple image processing algorithm Fig.2-right. This data is transferred into colloca-tion nodes over the computational domain for the first slice before deformation takes place.

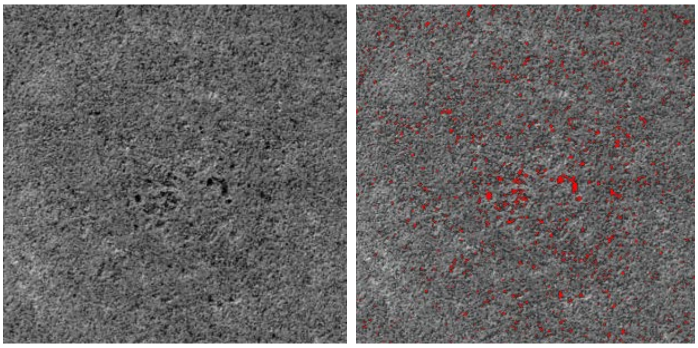

**Fig.2** - A 60x60 mm section of the initial slice with damage on the left and damaged areas are marked with red for simulation on the right with an overall 2.21 % of porosity considered as damage.

A numerical simulation is carried out with the initial damage data over a 180x180 mm slice with quarter symmetry considering only elastic deformation in 26 deformation steps with 900 uniformly distributed collocation nodes. The damage evolution results are shown in Fig.3 be-low, where the initial damage effect is still visible, and the highest damage is observed very locally at the corners. The parameters used in the damage evolution model, which should be experimentally defined, are $A = 0.001$ , $B = 0.9$ and $Y_0 = 100\ \mathrm{MJ/m^3}$.

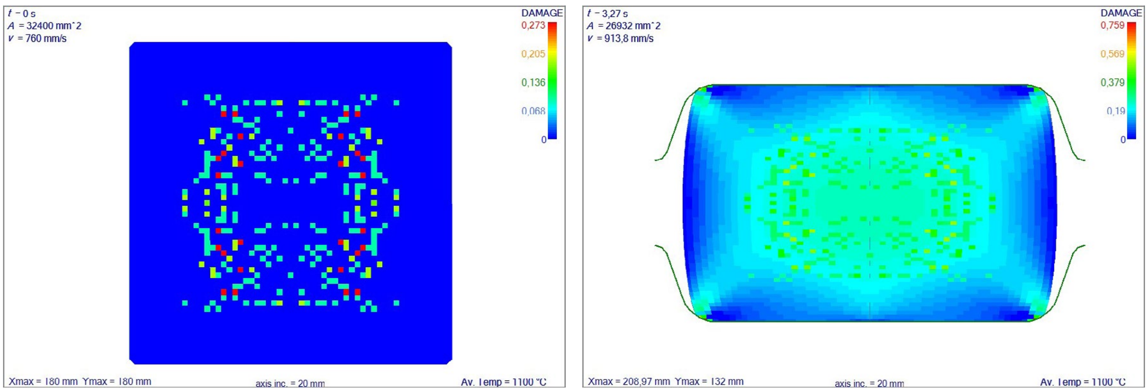


**Fig.3** - Initial damage state is shown on the left, and the damage state after the first roll pass is shown on the right.

## CONCLUSION

This work describes a rolling simulation system considering a damage model. In the simulations, a billet with porosity is considered, and initial values of the damage field are transferred into the simulation. After the first pass, damage results are shown. The inclusion of a damage model in a rolling simulation system has two major outcomes. First, damage sets limits to material deformation based on the accumulated deformation history, which is much lower than the ideal material without damage. Second, the initial damage values are read and included in the damage evolution model to observe a more realistic damage evolution.

The damage value in damage evolution models tends to increase with deformation. However, in rolling, compressive stresses are dominant. Based on observations, most porosities might be eliminated with proper rolling schedules. In the future, we need to experimentally investigate damage evolution in compression and develop a more appropriate damage model for rolling simulations.

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