ADVANCED MATERIAL AND STRUCTURAL BEHAVIOR IN INNOVATIVE FORMING PROCESSES – APPLICATION TO PROCESS-INTEGRATED RING ROLLING

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Abstract. The increasing demand for flexibility and economy in production has a significant impact on production methodologies. In the last decades, several innovative manufacturing processes were developed to meet these requirements. To carry out such a redesign in an efficient manner (which means by computational analysis), new computational models and methods are needed.

Process-integrated powder coating is a new kind of ring-rolling process. It takes advantage of the high temperatures and high forces of the ring rolling process. This is not only to increase the ring’s diameter, but also to integrate powder metallurgical multi-functional coatings within the same process. To improve the feasibility assessment of the proposed geometries and material combinations as well as to investigate important quantities such as e.g. the stress state in the rolling gap and the residual porosity of the powder metallurgically produced layer, the versatile application of the finite element method (FEM) is crucial. Therefore, a parameterized 3D finite element (FE) model is developed on the basis of a finite strain viscoplastic material formulation.

In order to increase the strength and wear properties of relevant steels, an appropriate heat treatment should be carried out. Therefore, an implicit numerical scheme is applied to investigate the thermomechanical-metallurgical response of multi-phase steel during phase transformation. The paper is concluded by a detailed description of the process simulation and a comparison of its results with experimental data.

1 INTRODUCTION

Ring rolling represents an incremental forming process which is used to manufacture precisely dimensioned seamless rings. Its first scientific developments were made in the 20th century (see [6]). Typical applications can be found in aerospace, automotive and
railroad industries [9], e.g. rings for railway wheels and tires [19]. In many applications, it is advantageous to equip the rolled ring with a wear resistant smart functional layer (see [4]). Examples are the rolls in crushing and briquetting mills used in mineral industries. There are several techniques (as e.g. thermal spraying, buildup welding, hot isostatic pressing) available to manufacture these coatings. The disadvantages of these methods are discussed in [10].

In process-integrated powder coating, the integration of the compaction process into the rolling stage is thought to break the limitations of alternative coating processes. The manufactured products can have a diameter up to 12 m and a height up to 2.8 m. Although this novel process is reasonably efficient with respect to energy, process time and costs, there exists some difficulties. The encapsulation has to maintain vacuum conditions and conventional rolling strategies are not applicable. To support the design of this new process and to predict the influence of several geometry and process parameters on the residual porosity in the layer, a parameterized FE model is developed on the basis of a finite strain viscoplastic material formulation.

After the rolling process, in order to increase the tensile strength and the wear properties of investigated steels, thermal treatment is initiated (see [7]). Since process temperatures in hot rolling are within the range of austenitizing temperatures for the investigated steels, controlled cooling can be conducted directly from process heat subsequent to the deformation process. A main factor of this procedure is cooling speed [1]. On the one hand, low-speed cooling leads to formation of a perlitic microstructure which has poorer mechanical properties than a martensitic or bainitic microstructure [14]. Furthermore, it cannot be transformed into those. On the other hand, fast-speed cooling leads to the formation of martensitic microstructure which comes along with a change in the crystal lattice causing a volume increase of the material. In this case, the subsequent residual stresses can be high enough to crack the coating. Therefore, the temperature should be controlled in such a way that the temperature range for transformation remains below the perlitic range (500-800°C), but above the martensitic range (less than 200°C) to enter the bainitic range before cooling to room temperature. Therefore, the paper deals with the numerical modeling of the heat treatment. This study concerns the investigation of transformation induced plasticity (TRIP) under various loading conditions. The applied tests enable us to modify Leblond’s transformation plasticity model [13]. Furthermore, a suitable implicit numerical scheme is implemented into a finite element code to investigate the thermo-mechanical-metallurgical response of multi-phase steel during the phase transformation also numerically.

The paper is structured as follows. In the next section the principles of the process-integrated powder coating are shown. Afterwards, the material model which describes the phase transformation will be discussed. The last section is devoted to the description of the process simulation and a comparison of its results with experimental data. The paper closes with some concluding remarks.
2 PROCESS-INTEGRATED POWDER COATING

The principle of the rolling process is sketched in Figure 1a. The mandrel pushes the ring towards the main roll which is driven by angular velocity. Friction between the ring and the main roll as well as between the ring and the mandrel lead to a rotation of the ring. By decreasing the radial rolling gap the ring grows in tangential and in axial direction. In the opposing axial rolling gap the height of the ring is controlled and reduced by the axial rolls.

![Figure 1: Process-integrated powder coating: (a) principle of ring rolling [17], (b) sectional view.](image)

The setup of the new process is depicted in Figure 1b. Here, a sheet metal is welded circumferentially around the outside of an unrolled ring blank. Powder layer material (metal matrix composite, MMC) is placed inside the resulting chamber.

3 CONSTITUTIVE MODELING

The model used to describe the compressible layer material is based on a finite strain elasto-plastic material formulation. Since the process takes place at high temperatures rate dependence is taken into account. A comprehensive description of the material model can be found in [3]. Here, we discuss the integration of heat treatment of the rolled ring into the subsequent cooling process which goes along with phase transformations.

3.1 TRANSFORMATION KINETICS

In this study, we use the modified version of the Johnson-Mehl-Avrami-Kolmogorov (JMAK) [8] equation which comprises two sequences of bainitic transformations

\[ p = \tilde{p}_1[1 - e^{-\left(\frac{t}{\tau_1}\right)^{n_1}}] + \tilde{p}_2[1 - e^{-\left(\frac{t}{\tau_2}\right)^{n_2}}] \]  

(1)

The parameters \( \tilde{p}_1 \) and \( \tilde{p}_2 \) describe the thermodynamic equilibrium fraction, which can be determined from the equilibrium phase diagram at a given temperature. The quantities \( \tau_1 \) and \( \tau_2 \) are the times needed to reach a perfect transformation, \( n_1 \) and \( n_2 \) are the Avrami
exponents. These parameters are determined by appropriate experimental investigations. The transformation rate $\dot{p}$ is given by the first derivative of Eq.1 with respect to time.

$$
\dot{p} = n_1 \frac{\bar{p}_1 - p}{\tau_1} \left[ \ln \left( \frac{\bar{p}_1}{\bar{p}_1 - p} \right) \right]^{n_1-1} + n_2 \frac{\bar{p}_2 - p}{\tau_2} \left[ \ln \left( \frac{\bar{p}_2}{\bar{p}_2 - p} \right) \right]^{n_2-1} \tag{2}
$$

The JMAK equation is proposed for an isothermal condition. However, it is not directly applicable for the nonisothermal case. Therefore, we apply the isokinetic relationships of nonisothermal systems (see [18, 16]). Accordingly, the cooling curve is divided into a number of small time steps, and the amount of transformation at each time step is calculated using the JMAK equation. Finally, the martensitic transformation is taken account by using the general form of Koistinen-Marburger [12] equation as

$$
p = \bar{p}_m \left[ 1 - e^{-\left( \frac{M_s - T}{b} \right)^n} \right] \tag{3}
$$

Herein, $\bar{p}_m$ denotes the volume fraction of the retained austenite. $M_s$ designates the temperature where martensitic transformation starts. The quantities $b$ and $n$ are material constants which should be justified by experimental results.

### 3.1.1 TRANSFORMATION PLASTICITY

The plastic behaviour of steels during the transformations can be separated into two parts. The first is classical plasticity due to plastic flow from variations of the applied stress and the temperature (see [5]). Secondly, transformation plasticity arises due to plastic flow from variations of the phase proportions (see [2]).

Following this, the total strain

$$
\varepsilon = \varepsilon_{el} + \varepsilon_{th} + \varepsilon_p \tag{4}
$$

splits into elastic, thermal, and plastic parts, respectively. Each phase has different thermal properties. In order to take this fact and the rate of volumetric change due to the phase transformation into account, the rate of the thermal strain is defined by a linear mixture rule as:

$$
\dot{\varepsilon}_{th} = \sum_{i=1}^{n_p} \left[ \dot{p}_i \alpha_i (T - T_0) + p_i \alpha_i \dot{T} \right] \mathbf{I} \tag{5}
$$

where, $p_i$ is the volume fraction of phase $i$. Additionally, $\alpha_i$ denotes the thermal expansion coefficient, $n_p$ is the total number of the involved phases, $T$ and $T_0$ designate the current and initial temperature, and $\mathbf{I}$ is the identity tensor. Furthermore, the material time derivative is shown by $(\bullet) = d\bullet/dt$, the subscripts $s$ and $h$ denote the soft and hard phase and $\Delta (\bullet)_{s \to h}$ designates the variation of $\bullet$ from softer to harder phase.

The rate of the plastic strain

$$
\dot{\varepsilon}_p = \dot{\varepsilon}_{cp} + \dot{\varepsilon}_{tp} \tag{6}
$$
is decomposed into classical and transformation plasticity. Consequently, the rate of classical microscopic plastic strain
\[
\dot{\varepsilon}_{cp} = \dot{\varepsilon}_{\sigma}^{cp} + \dot{\varepsilon}_{T}^{cp}
\] (7)
splits into two parts: the plastic strain induced from the deformation of the soft phase,
\[
\dot{\varepsilon}_{\sigma}^{cp} = \frac{3(1 - p_h) l(p_h)}{2 \sigma_y^*} \frac{\sigma_D}{E} \dot{\varepsilon}_{eq}
\] (8)
and the rate of the plastic strain induced from the variation of temperature:
\[
\dot{\varepsilon}_{T}^{cp} = \frac{3 \Delta \alpha_{s \rightarrow h}}{\sigma_y^*} p_h \ln(p(h)) \sigma_D \dot{T}
\] (9)
In order to include the low values of volume fraction, the functions \( l(p_h) \) and \( k(p_h) \) are defined by \[13\] (see Table 1).

Table 1: Correction factors to take account of more phases in the case of local yielding [13].

<table>
<thead>
<tr>
<th>p</th>
<th>0.00</th>
<th>0.125</th>
<th>0.250</th>
<th>0.500</th>
<th>0.750</th>
<th>1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>k(p)</td>
<td>0.00</td>
<td>0.440</td>
<td>0.124</td>
<td>0.391</td>
<td>0.668</td>
<td>1.00</td>
</tr>
<tr>
<td>l(p)</td>
<td>0.00</td>
<td>2.53</td>
<td>4.00</td>
<td>2.76</td>
<td>1.33</td>
<td>1.00</td>
</tr>
</tbody>
</table>

The accumulated plastic strain during the bainitic transformation in the austenitic phase is given by \[15\]
\[
\dot{\varepsilon}_{eff} = \frac{-2 \Delta \varepsilon_{s \rightarrow h}}{1 - p_h} h(\frac{\sigma_{eq}}{\sigma_y^*}) l(p_h) \dot{p}_h + \frac{l(p_h)}{E} \dot{\varepsilon}_{eq} - \frac{2 \Delta \alpha_{s \rightarrow h}}{1 - p_h} p_h \ln(p(h)) \dot{T}
\] (10)
where \( \Delta \alpha_{s \rightarrow h} \) is the difference of the thermal expansion coefficients in the soft and the hard phase and \( E \) is Young’s modulus. The bainitic phase inherits the strain hardening of austenite which is defined by
\[
\dot{\varepsilon}_{eff}^h = -\frac{\dot{p}_h}{p_h} \dot{\varepsilon}_{eff}^s + \theta \frac{\dot{p}_h}{p_h} \dot{\varepsilon}_{eff}^s
\] (11)
Herein, \( \theta \) is a parameter depending on the transformation, it is changed between 0 (without transformation) and 1 (perfect transformation). Additionally, we assume that during diffusional transformation, no strain hardening is included and \( \theta = 0 \). Finally, the stress tensor is obtained by
\[
\sigma = C(\varepsilon - \varepsilon_{th} - \varepsilon_p)
\] (12)
Under the global yielding, there is no difference between classical plasticity and transformation plasticity. In this case, all involved phases are influenced by plastic deformation [11]. Therefore, conventional elastoplasticity can be applied.
An implicit numerical solution algorithm to calculate the plastic deformation of each phase is implemented into ABAQUS via an user material subroutine UMAT.
4 RESULTS

4.1 DENSIFICATION OF THE LAYER

To guarantee the functionality of the coating it is important to reach a high state of compaction inside the layer. Therefore, parameter studies are carried out. The powder material which is applied in the layer is a hot work tool steel 56NiCrMoV7 (see Table 2). Additionally, for the substrate (encapsulation) a cold work tool steel X220CrVMo13-4 is used.

Table 2: Chemical combination of the applied materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Cr</td>
</tr>
<tr>
<td>56NiCrMoV7</td>
<td>0.55</td>
<td>1.10</td>
</tr>
<tr>
<td>X220CrVMo13-4</td>
<td>2.30</td>
<td>12.50</td>
</tr>
</tbody>
</table>

Consequently, different radii for the main roll and the mandrel are chosen (see Table 3). The ratio of the main roll radius (RMR) with respect to the mandrel radius (RMA) is defined as $k$.

Figure 2: Relative density of compacted layer (hot work steel) after 15 seconds rolling: (a) $k = 1$, (b) $k = 2.7$, (c) $k = 3.5$, (d) $k = 7$.

Figure 2 (a)-(d) demonstrate the influence of $k$ on the relative density. It can be seen that the increase of $k$ leads to a small decrease of the relative density. This result can
Table 3: Variation of geometric parameters.

<table>
<thead>
<tr>
<th>k</th>
<th>Main roll</th>
<th>Mandrel</th>
<th>Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>130</td>
<td>218.5</td>
</tr>
<tr>
<td>2.7</td>
<td>175</td>
<td>65</td>
<td>141</td>
</tr>
<tr>
<td>3.5</td>
<td>350</td>
<td>100</td>
<td>218</td>
</tr>
<tr>
<td>7</td>
<td>455</td>
<td>65</td>
<td>141</td>
</tr>
</tbody>
</table>

Figure 3: Influence of geometrical parameters on relative density: (a) relative density with respect to the time, (b) relative density with respect to k.

be observed in Figure 3 (a). Figure 3 (b) shows the predicted influence of $k$ on the relative density at the end of the rolling process. These results emphasize that with $k = 1$ the highest values for the relative density can be obtained. Working with $k = 1$ might not be realistic for a practical application. But it confirms the strategy to improve the compaction behavior by increasing the pass reduction at the main roll.

4.2 HEAT TREATMENT

For the material model validation several tests are done. In the first step, in order to get rid of the influence of any temperature gradient, isothermal annealing is done. Therefore, the steel is heated up to above the upper critical temperature (1050 °C) and this temperature is maintained for 10 minutes.

Then the temperature is cooled down below the lower critical temperature. Finally, it is cooled to the room temperature. As an example, the results related to the uniaxial tension tests are demonstrated (see Figure 4(a)-(b)). At the lower temperature we obtain a small deviation between experimental and modeling results for both materials. This difference becomes even smaller at higher temperatures. Additionally, we notice a decrease of the yield stress from lower to higher temperature. The main goal is to reach a bainitic microstructure formation. Therefore, the bainitic transformation is investigated. Figure 5(a)-(b) presents the percentage of austenite transformed to bainite. It can be seen that for the hot work steel at the temperature of 275 °C about 96% of austenite is transformed.
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Figure 4: Temperature dependency of stress-strain curves: (a) hot work steel, (b) cold work steel.

Figure 5: Volume fraction of bainite: (a) hot work steel, (b) cold work steel.

to bainite which is quite close to a perfect transformation. However, the cold work steel shows a weaker transformation behavior. This is due to the fact that the recovery and the recrystallization of the grains reduce the dislocation density, which has a direct effect on the transformation. Consequently, we see a longer transformation time and weaker transformation behavior.

To see the influence of TRIP, the variation of the length of the specimen which is submitted to several compressive loads is investigated under isothermal conditions at the temperature of 375 °C (see Figure 6(a)).

By increasing the load we see an extra deformation. This extra deformation is due neither to elasticity nor to viscous effects. This is another plastic effect, which is referred to as TRIP. Finally, the validated material model is applied to estimate the bainitic volume fraction in the rolled ring.

The experimental conditions are high pressure water from the inner side and heat preservation from the other side of the ring as depicted in Figure 6(b). These conditions are also considered in the simulation. In comparison with the outer side, the inner side of
the ring has a lower temperature (see Figure 7(a)). This is due to the direct contact of the inner surface with high pressure water. Furthermore, the heat preservation from the outer side which assures the required transformation, maintains the higher temperature from the outer surface of the ring. The experimental investigations confirm that the required transformation time for the hot and cold work steel are about 5000 and 72000 seconds, respectively. Furthermore, the cooling rate is chosen as -0.2 K/s for the hot work steel and -0.3 K/s for the cold one. In order to have a better insight, we first study a solid ring. Figure 7(a)-(b) illustrates the corresponding temperature fields and bainitic volume fractions. It can be seen that the transformation is nearly perfect (see Figure 7(b)). In other words, the remaining volume fraction of martensite is about 5 per cent. This is due to a very fast cooling of the inner surface with high pressure water at the beginning of the cooling process. Finally the composite ring which consists of hot work steel (substrate) and cold work steel (layer) is investigated. The distribution of temperature over the ring is demonstrated in Figure 8(a). Again, the inner surface of the ring has a lower temperature.
and the outer surface has a higher temperature. However, since both materials have different thermo-mechanical material parameters, the distribution of the temperature is different than in the solid ring. Figure 8(b) demonstrates the volume fraction of bainite. A perfect bainitic transformation is observed in the substrate and the sheet metal. In contrast to the martensitic transformations, there is not a significant change in the volume of the substrate. This avoids the creation of cracks in the coating which is proved by experimental results. Moreover, the quantitative prediction of the crack in the coating can be carried out by appropriate damage modeling which is our future task.

5 CONCLUSIONS

In this paper a parameterized FE ring rolling model was presented that is applicable to the simulation of process-integrated powder coating by radial axial rolling of rings. Furthermore, we developed a material model which is originally introduced by [13]. Additionally, the modified version of the JMAK equation is used to describe the bainitic transformation. Moreover, mathematical modeling of transformation plasticity [14] in steels which is coupled with strain hardening phenomena is modified.

As a result, a coupled thermomechanical-metallurgical numerical model is developed which enabled us to see the response of generalized multi-phase steel during phase trans-
formations from austenite to bainite and martensite. An implicit numerical scheme is applied to investigate the thermomechanical response of multi phase steel during the phase transformation. Furthermore, the applied model is able to predict transformation-induced plasticity (TRIP) under various loading conditions in the different cases of transformations. The material model is validated by several tests and the results are compared with experimental data. Consequently, the validated material model is used to simulate the transformation in composite ring.

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