Constitutive behaviour of the metastable stainless steel: Sandvik Nanoflex™

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Abstract. This article presents a model to describe the constitutive behaviour of corrosion-resistant Sandvik steel Nanoflex™ [1] during metal forming and hardening. This material is characterised by different phenomena. The material is metastable, which causes strain-induced transformation to take place during metal forming. Depending on the annealing conditions, the material also transforms isothermally [2, 3] (as opposed to a-thermal martensite). This transformation can also take place immediately after forming, as a result of the residual stresses present in the material. The martensite phase of this material can be aged [4].

Results of the various measurements on Sandvik Nanoflex™ are shown. The measurements mainly involved tensile tests and upsetting tests, during which both isothermal transformation and strain-induced transformation were measured by inductive sensors[5] and they were afterwards examined. The hardening of the material and the increase in hardness during ageing was also examined.

Finally, a constitutive model based on literature and the measurement are presented. This model describes the isothermal, stress-assisted transformation, strain-induced transformation, work hardening and ageing. The model has been set up in such a way that it can be simply implemented in a FEM code.

INTRODUCTION

Sandvik Nanoflex™ belongs to the category of metastable austenitic stainless steels. The martensite phase of this steel can be aged [1, 4]. The chemical composition is given in table(1). Below the $M_s$ temperature, which for Sandvik Nanoflex™ is about 83 K, a-thermal martensite forms. This martensite formation is outside the scope of this study, because of the low $M_s$ temperature.

Depending on the stability of the steel, isothermal transformation (as opposed to a-thermal martensite) occurs. The influence of temperature and stress state on the transformation is shown in figure (1) [3, 6]. Transformation occurs below the flow stress of the composite and during plastic deformation. The transformation rate depends on the composition of the material, the austenitising conditions, the temperature and the stress to which the material is subjected.

This transformation, i.e. the transformation below the flow stress of the austenite will be referred to as stress-assisted transformation. Above the flow stress of the austenite, strain-induced transformation will occur. This transformation is accompanied by plastic deformation.

If the austenite is deformed, the flow stress of the austenite rises because of work hardening. Depending on the residual stress level, the strain-induced transformation may turn into stress-assisted transformation after plastic deformation.

As martensite has a higher flow stress than austenite ($Re_\gamma = \pm 200N/mm^2$ and $Re_\alpha = \pm 700N/mm^2$), transfor-
formation will cause extra hardening during plastic deformation. This is referred to as transformation hardening, as opposed to normal work hardening. There are three phenomena taking place during plastic deformation:

- an extra transformation hardening, caused by the transformation, which leads to a greater attainable plastic strain,
- an extra plastic strain component arises as a result of the stress field that accompanies transformation. This strain component is called: transformation plasticity,
- a strain component also develops as a result of the volume change induced by transformation: dilatation strain[7, 8].

These three effects taken together are referred to as TRIP effect.

During forming of Sandvik Nanoflex™, both - stress assisted and strain induced- transformations occur simultaneously. Mass production frequently uses multi-stage forming processes. Between two forming stages, there is a waiting time that may lead to stress-assisted transformation, depending on the residual stress distribution. This leads to deformation of the product. Moreover, stress-assisted transformation may also occur after forming. Finally, the product can be re-austenitised, after which stress-assisted transformation may occur, depending on the austenitimising conditions.

Finally a simple empirical model of ageing was implemented, to predict the hardness after aging.

For creating the model, the following issues are considered:

- a rate formulation to implement the path dependency of the transformation and work hardening,
- the inheritance of the dislocation structure or work hardening from austenite to martensite. Therefore the dislocation structure is implemented as an internal state variable for both phases,
- The strain induced and stress assisted transformation are included. They can be active simultaneously,
- dilatation strain and transformation plasticity have to be implemented to describe the dimensional changes during the transformation,
- The heat generation during plastic deformation influences the transformation behaviour. Therefore the model must be fully thermo-mechanically coupled.

**THE MACROSCOPIC MODEL**

The transformations depend on temperature and hydrostatic stress. We can split the transformation into two parts:

- one beyond the elastic zone, this means that the transformation is strain induced, because it is accompanied by plastic deformation, see figure 2 and 3. In both figures, the left-most lines correspond to a temperature of 223 K whereas the right-most lines correspond to 423 K, increment 20 K.

![FIGURE 2](image1.png)

**FIGURE 2.** The fitted model and the measured data for the flow stress.

![FIGURE 3](image2.png)

**FIGURE 3.** The fitted model and the measuring data for the strain-induced martensite.

- one below the flowstress, this means that the transformation occurs without plastic deformation, but is strongly dependent on the applied stress, see figure 6, 7 and 8.

Based on the information of the model of strain-induced martensite after Olson et. al.[2] and Estrin[9], a general differential equation is chosen. This model is fitted to the
measured data. Because the work hardening of the material is complex and path-dependent in relation to martensite content and plastic strain, it was decided to use a modified Estrin [10] model with two internal state variables to describe the dislocation densities. A rate formulation is chosen to incorporate the path dependence.

**Strain-induced transformation.**

The following equation is used to describe the strain-induced transformation:

\[
\phi_{\text{strain}} = C_{\text{strain}}(T, \sigma^H, Z)[(D_1 + \varphi)^{n_1}(f_{\text{strain}} - \varphi)^{n_2}]e^p
\]

Where \( \varphi \) is the martensite content and \( C_{\text{strain}} \) is a function that describes the temperature, hydrostatic stress and material structure dependency of the transformation. \( Z \) is a parameter that depends on the annealing conditions before metal forming, the chemical composition and on the crystal orientation. Figs (4) and (5) show the temperature dependency of the transformation. \( C_{\text{strain}} \) is related to the thermodynamics of the transformation, \( T \) is the temperature in Kelvin and \( \sigma^H \) is the hydrostatic stress. The parameter \( f_{\text{strain}} = 0.95 \) is the saturation value of the transformation and \( n_1 \) and \( n_2 \) are fit constants. The following function is assumed, based on curve fitting:

\[
C_{\text{strain}} = Q_1 \big(1 + Q_2 \tanh(Q_3 \sigma^H)\big) \left( e^{\left(\frac{T - 232}{40}\right)} - Q_5 \right) \quad (2)
\]

**FIGURE 4.** The temperature dependency of the strain-induced transformation \( n_1 \).

Here \( Q_1 \) is a constant describing the mean transformation rate, \( Q_2, Q_3 \) describe the influence of the stress state and \( Q_4, Q_5 \) describe the influence of the temperature on the transformation. The influence of the chemical composition and the crystal orientation are neglected, so \( Z \) is treated as a constant.

**Stress-assisted transformation**

The description of the stress-assisted transformation is based on Raghavan[11], but expressed in a more general form:

\[
\phi_{\text{stress}} = C_{\text{stress}}(T, \sigma^H, \varepsilon_p, Z)[(D_2 + \varphi)^{n_3}(f_{\text{stress}} - \varphi)^{n_4}]e^p
\]

Where \( C_{\text{stress}} \) is a function that describes the dependence of transformation on stress, temperature and material structure, \( T \) is the temperature, \( \sigma^H \) is the hydrostatic stress, \( f_{\text{stress}} \) is the saturation value for the transformation, depending on \( T, \sigma^H \) and \( Z \), and \( n_3 \) and \( n_4 \) are fit constants.

**FIGURE 5.** The temperature dependency of the strain-induced transformation \( C_{\text{strain}} \).

For both annealing conditions, figs 6 and 7, the following model is used to describe the transformation. The interaction between the state variables influencing the transformation has not been investigated. Therefore, the dependency of \( C_{\text{stress}} \) and \( f_{\text{stress}} \) can be split into a temperature dependency, a hydrostatic stress dependency and an plastic strain dependency. \( D \) is a constant.

\[
C_{\text{stress}}(T, \sigma_h, \varepsilon_p) = C^1_{\text{stress}}(T) \ C^2_{\text{stress}}(\sigma^H) \ C^3_{\text{stress}}(\varepsilon_p) \quad (4)
\]

\[
f_{\text{stress}}(T, \sigma^H, \varepsilon_p) = f^1_{\text{stress}}(T) \ f^2_{\text{stress}}(\sigma^H) \ f^3_{\text{stress}}(\varepsilon_p) \quad (5)
\]

The following relationship between \( C_{\text{stress}} \), \( D \) and \( f_{\text{stress}} \) have been proposed, where \( R_1 \ldots R_{17} \) are constants.
Total martensite content.

From (3) and (1) follows the total martensite content:

\[ \psi = \psi_{\text{strain}} + \psi_{\text{stress}} \]  

(13)

The kinetics of the strain-induced martensite transformation depends on the amount of plastic energy generated during deformation. Therefore, the saturation value is constant and has a high level (95-100 %). The kinetics of the stress-assisted transformation is based on the chemical composition and austenitising conditions of the material. There is no plastic energy. Therefore the saturation value \( f_{\text{stress}} \) is not a constant.

Path-dependent dislocation based on work hardening

For this study it is assumed that the work hardening depends on plastic strain, martensite content, temperature, and the influence of strain rate. The model used is based on the physical-based models of Y. Estrin [10], describing dislocation densities as internal state variables. The work hardening mechanism is not only based on change in dislocation density but also on other structural defects like subgrains, grain size etc. Therefore, parameter Y is not the dislocation density alone but the resistance of dislocation movement caused by structural defects in relation to plastic deformation. In this study, only one dislocation density is used for every phase. The original model is modified to make it as simple as possible to reduce the number of unknowns. For the flow stress of austenite, it is assumed:

\[ \sigma_{\alpha}^Y = \sigma_{0\alpha}^Y \sqrt{\psi_{\alpha}} (1 + \frac{\dot{\varepsilon}^p}{\psi_{\alpha}}) \frac{1}{\psi_{\alpha}} \]  

(14)

And for the flow stress of martensite:

\[ \sigma_{\gamma}^Y = \sigma_{0\gamma}^Y \sqrt{\psi_{\gamma}} (1 + \frac{\dot{\varepsilon}^p}{\psi_{\gamma}}) \frac{1}{\psi_{\gamma}} \]  

(15)

FIGURE 7. The influence of the hydrostatic stress on the stress-assisted transformation, after deforming the specimen until the strain induced martensite reaches 0.5, at plastic strain about 0.15. Annealing conditions: 60 s. at 1323K.

FIGURE 8. Temperature dependency of the stress assisted transformation. Annealing conditions: 1800 s. at 1323K.

See for the temperature dependency of the stress assisted transformation figure 8.
To describe the recovery effect the following is proposed:

\[ \sigma^Y = \sigma_0^Y + \frac{1 + \tanh(\frac{\phi - \phi_0}{q})}{2}(\sigma^Y - \sigma_0^Y) \]  
(16)

In these equations \( \sigma_0 \) is the basic stress that depends on strain rate and temperature, \( \phi \) represents the martensite content, \( Y \) the general dislocation density for one phase, \( \dot{\varepsilon}_p \) is the equivalent plastic strain rate, \( \psi_\alpha \) and \( \psi_\gamma \) are the reference strain rates for both the phases and \( m_\alpha \) and \( m_\gamma \) fit constants depending on temperature. The values \( \phi_0 \) and \( q \) are introduced to describe the non-linear relationship between the flow stresses as a mixture rule. At low martensite contents the influence of martensite content will be lower than at high levels of martensite content. The evolution of the dislocation density in the austenite is described as follows:

\[ \dot{Y}_\gamma = [C_1(C_2 - Y_\gamma)C_3 + C_4(\dot{\varepsilon}^p, T)]\dot{\varepsilon}^p \]  
\[ \text{if } Y_\gamma < C_2 \]
\[ \dot{Y}_\gamma = [C_4(\dot{\varepsilon}^p, T)]\dot{\varepsilon}^p \]  
\[ \text{if } Y_\gamma > C_2 \]

(17)

Where \( C_1, C_2, C_3 \) are material constants and \( C_4 \) depends on temperature and strain rate. The constants are not directly related to physical phenomena but are chosen to fit the model. In a similar way the following applies to the dislocation density in the martensite phase:

\[ \dot{Y}_\alpha = [C_5(C_6 - Y_\alpha)C_7 + C_8(\dot{\varepsilon}^p, T)]\dot{\varepsilon}^p \]  
\[ \text{if } Y_\alpha < C_7 \]
\[ \dot{Y}_\alpha = [C_8(\dot{\varepsilon}^p, T)]\dot{\varepsilon}^p \]  
\[ \text{if } Y_\alpha > C_7 \]

(18)

Where \( C_5, C_6, C_7 \) are material constants and \( C_8 \) depends on temperature and strain rate. During transformation three different phenomena occur:

- recovery takes place due to generation of virgin martensite,
- the dislocation density, in the austenite will not annihilate during the transformation but is partly transferred to the martensite. This second effect depends on the temperature. In the work of Holmquist et al. [1] it is seen from a TTT diagram, that the transformation rate is the highest at a temperature of 223 K. At this temperature, constant \( C_9 \) will reach its maximum.
- During the transformation new dislocations are formed on the transformation boundary.

To describe the recovery effect the following is proposed:

\[ \dot{Y}_\alpha = -\frac{\phi}{\phi_\alpha}Y_\alpha \]  
(19)

For the dislocation transfer during transformation the following equation is introduced:

\[ \dot{Y}_{\alpha 3} = \frac{\phi_{\alpha \text{strain}}}{\phi_{\alpha \text{strain}}} \left( C_9(T)Y_\gamma + C_{10} \right) \]  
(20)

Where \( C_9 \) is a constant that depends on temperature, see fig 10.

**FIGURE 10.** The dislocation inheritance parameter \( C_9 \)

The values of \( C_9 \) and \( C_{10} \) were calculated by curve fitting. From (18),(19) and (20) the following equation is defined for the dislocation density in the martensite:

\[ \dot{Y}_\alpha = \dot{Y}_{\alpha 1} + \dot{Y}_{\alpha 2} + \dot{Y}_{\alpha 3} \]  
(21)

The recovery effect is related to the total martensite content, the inheritance is only related to the strain induced transformation because it creates a lath martensite while stress assisted martensite is a plate martensite.

**Relation between Hardness and flow stress**

As only the martensite phase can be aged, there must be a very strong relationship between the martensite content and the change in hardness caused by the aging process. From literature it is well known that there should be a more or less linear relationship between the hardness and flow stress, as seen in figs (11) and fig(12).

**FIGURE 11.** The relationship between change in hardness and martensite content.
Dilatation strain

The change in density during the transformation is given by:

\[ \dot{\rho} = (\rho_{\alpha} - \rho_{\gamma})\phi \quad (22) \]

Where \( \rho_{\alpha} \) is the density of martensite, \( \rho_{\gamma} \) is the density of austenite and \( \phi \) is the martensite content. This change in density causes an extra strain in the material:

\[ \dot{\varepsilon}_{dil} = \frac{-\dot{\rho}}{3\rho} I \quad (23) \]

Where \( \dot{\varepsilon}_{dil} \) represents the dilatation strain rate tensor and \( I \) is a unity tensor.

Transformation plasticity

The following equation is proposed for the transformation plasticity based on [12]. The transformation plasticity as cited in [12] is only valid for strain induced martensite. In order to extend this model to strain induced and stress assisted martensite formation, the stress direction tensor \( \mathbf{n} \) is replaced by \( \frac{s}{\sigma_{eq}} \):

\[ \dot{\varepsilon}_{trip} = \phi A(\phi) \mathbf{n} = \phi (A(\phi)^* \sigma_{eq}) \frac{3}{2} \frac{s}{\sigma_{eq}} = \frac{3}{2} \phi A(\phi)^* s, \]

Here \( A(\phi) \) is:

\[ A = \frac{0.05 ((3 + \tanh(10(0.5 - \phi))))}{\sigma^Y} \quad (25) \]

CONCLUSIONS

- Sandvik Nanoflex\textsuperscript{TM} is a stainless steel belonging to the category of metastable austenites.
- It is possible to influence the stability of the stress assisted transformation by the austenitising conditions, so that the material becomes stable or spontaneous stress-assisted transformation can takes place.
- The macroscopic model provided meets the required accuracy, including both transformation, dilatation strain, transformation plasticity, and a dislocation based work hardening model.

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REFERENCES