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A Simplified Model of the Strain-Induced Phase Transformation in Austenitic Stainless Steels for Low Temperature Applications

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Abstract

Austenitic stainless steels are commonly used in low temperature applications because of their mechanical properties specially preserving the ductility. The strain-induced martensitic transformation greatly affects the plastic behavior of the metastable austenitic stainless steels. This paper provides a simple constitutive model for considering the strain-induced martensitic transformation of the metastable austenitic stainless steels at low temperature. A modified kinetics model is represented to consider the effect of TRIP in martensite evolution explicitly. In addition, a modified power law hardening for the continuously reforming material is represented to describe the great hardening effect of the phase transformation. Developing an incremental integration algorithm, the constitutive model was implemented in the Abaqus/Standard via a user-defiened material subroutine (UMAT). The results showed that the rate of martensite evolution with plastic strain in the modified model is accelerated which significantly affects the plastic behavior. In addition, the hardening behavior could be well described with the modified power law. Numerical examples show the capability of the constituative model in simulating the strain-induced transformation at low temperatures.

Nomenclature

$\boldsymbol{\sigma}$	Cauchy stress	$\mathbb{C}^e$	Linear elasticity tensor
$\boldsymbol{S}$	Deviatoric stress	K	Bulk modulus
$\bar{\sigma}$	Vin-Mises effective stress	G	Shear modulus
σ_{y0}	Initial yield stress	J_2	Second invariant of deviatoric stress
$\boldsymbol{\varepsilon}^e$	Elastic strain	ϕ	Yield function
$\boldsymbol{\varepsilon}^p$	Plastic strain	R	Hardening function
$\boldsymbol{\varepsilon}^{tr}$	Transformation strain	ξ	Martensite volume fraction
$\boldsymbol{\varepsilon}^{ir}$	Irreversible strain	ξ_L	Martensite saturation limit
$\bar{\varepsilon}^p$	Accumulative plastic strain	$\mathbb{I}_d$	deviatoric projection tensor
$\bar{\varepsilon}^p_0$	Threshold plastic strain for transformation	ε^{tr}_V	Transformation volumetric strain
$\dot{\gamma}$	Plastic multiplier	$\boldsymbol{N}$	Flow direction

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K_A, n_A	Hardening coeficients of austenite	K, n	Hardening coeficients of material
β_1, β_2	Coeficients of the Modified hardening rule	A	Phase transformation kinetics coeficient
B, B_0, B_1	TRIP effect coeficients	S_A^*	Reference deviatoric stress

1. Introduction

The austenitic stainless steels are widely used as constructional materials at cryogenic temperatures because of their high strength and excellent toughness even at temperatures down to 4.2K. These steels, however, undergo a strain-induced martensitic transformation, where the austenite phase is transformed to the thermodynamically more stable α'-martensite phase during the plastic deformation. This phenomenon is accelerated at low temperatures. The strain-induced martensitic transformation greatly enhances the work hardening of the metastable austenitic stainless steels and consequently affects their ductility. The martensitic transformation changes the initially homogeneous material into a strongly heterogeneous bi-phase one. Therefore, the plastic behavior of these stainless steels has been extensively investigated to understand how the continuously reforming bi-phase material responds to the applied loads.

Majority of the studies on the topic evaluated the two, kinetics of the phase transformation and the hardening behavior of the material during transformation. On the kinetics, the first reliable model by Olson and Cohen [1] denotes the intersection of the shear bands as the main mechanism contributing to the martensitic transformation. In this model, the kinetics of the phase transformation is dependent only on the temperature and the accumulated plastic strain. Further development to the kinetics was provided by Stringfellow et al. [2] in which the effect of stress state is included in the model. Other studies in order to consider the effects of the strain rate [3], the grain size [4] and the pre-strain [5] in the kinetics model are available. In addition, Ramirez et al. [6] by adopting the concept of reaction rate per unit austenite proposed a kinetics relation. In the model represented by Shin et al. [7] the transformation is considered to be the process of strain energy relaxation. Moreover, exploring the transformation under tension-compression as well as torsion cyclic loading conditions, Luo et al. [8] proposed a unified kinetics model for both monotonic and cyclic loading conditions.

In all cases, the transformation shows a sigmoidal curve for the martensite fraction against the strain. Typical shapes are illustrated in Figure 1 in which the slope of the sigmoidal curve increases as the temperature decreases. At significantly low temperatures (typically below 77K) the steep part of the sigmoidal curve tends to a line. Accordingly, a simplified linear evolution law for the volume fraction of martensite at low temperatures was proposed by Garion and Skoczen [9].

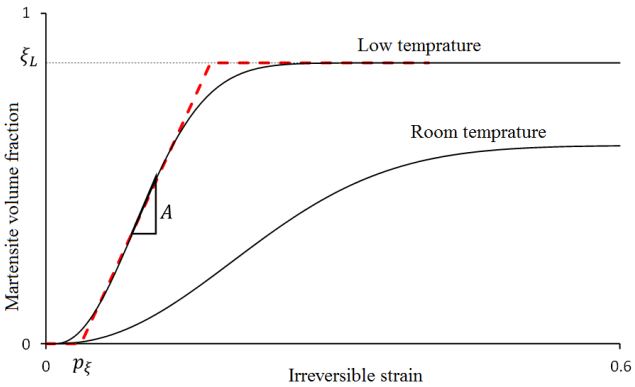


Fig. 1. Typical shape of martensite evolution curves and the parameters of the model by Garion and Skoczen [9].

Great changes in mechanical properties are the resultant of the harder martensite structure. The substituted harder martensite makes the material deforming harder. In addition, these harder inclusions constraint the deformation of the retained austenite leading to an additional hardening. Transformation-Induced Plasticity (TRIP) is another phenomenon accompanied by the transformation. TRIP (the plastic deformation induced by the phase transformation) is the main mechanism of the irreversible deformation in the stress-assisted phase transformations as this type of transformation occurs in the elastic region. However, in the case of the strain-induced transformation, the TRIP enforced by the plastic deformation makes an additional irreversible deformation (including both the volumetric and deviatoric parts). This additional deformation which is not explicitly driven by the stress is often interpreted as the dynamic softening. Despite the several micromechanical-based models, phenomenological macroscopic constitutive models have been proposed for plastic behavior under transformation. The main problems to be considered are: characterizing the overall behavior of the resultant heterogeneous composite material including the hardening of the bi-phase material and the TRIP effect. Based on experimental evidences, the effect of mechanical parameters such as strain rate, stress state, rate dependency, and temperature changes have been implemented in different cases.

Constitutive models range from simple 1D models to general implicit 3D models. In 1D models, the hardening behavior resulted from the tension test is expressed as a function of plastic material parameters and martensite volume fraction. In general models, a homogenization method is used to represent the overall behavior in terms of the constituents' properties. The main problem in the homogenization methods is the

martensite material parameters. Martensites formed at different levels of strain, could not be found and examined separately to evaluate the material properties. Using martensite structures, in some different conditions, may not be reliable. The simplest homogenization scheme, the rule of mixtures, have been used in early works by [10-12]. The rule of mixture and the modified rule of mixtures are mostly implemented in predicting the behavior of multi-phase steels [13, 14].

The first and the most significant general model for strain-induced phase transformation was represented by Stringfellow et al. [2]. In this model, the total irreversible strain is decomposed into a transformation strain (TRIP effect) and a common slipping plastic deformation. A distinct evolution rule for transformation strain has been presented. Furthermore, a consistent homogenization method based on the Eshelby's solution [15] has been used to represent the overall hardening behavior. Both the austenite and the martensite are assumed to have a rate-dependent power law viscoplastic behavior. Ramirez et al. [6] proposed a distinct model introducing the plastic interaction concept in homogenization. Additionally, a set of experiments was conducted to characterize the individual phases. Using a loading function including the third invariant of the deviatoric stress, Tomita and Iwamoto [16] proposed a model to consider the difference between the tension and compression in cyclic loadings. Some other constitutive models with minor modifications could be found in the literature [17-20]. Neglecting the homogenization, Mróz and Ziętek [21], proposed a constitutive model with the combined isotropic-kinematic hardening and cyclic stress evolution dependent on martensite volume fraction. In some models, the classical engineering hardening rules have been modified to be best fitted with the experimental results of the transformation plasticity. For example, Zeng and Yuan [22] implemented the conventional plasticity with an additional power-law hardening in terms of the martensite fraction. In the work by Ding et al. [23] the classical Ludwigson relation is modified based on the assumption that the mechanical work difference between the experimental and fitted Ludwigson curves is linearly proportional to the martensite content. Moreover, Mahnken and Schneidt [24] presented a general thermo-mechanical model for transformation-induced plasticity, within a thermodynamic framework at large strains.

Garion and Skoczen [9] developed a model specifically for extremely low temperatures where the plastic behavior is relatively independent of the stress state and strain rate. In this model, the homogenization method of Mori and Tanaka [25] was used to determine the hardening behavior and only the dilatation part of the transformation strain was considered. In applying the homogenization, the martensite content is assumed to behave elastically; an assumption which could be less realistic as the material shows a considerable strain even after the martensite saturation. However, few number of material parameters make the model more attractive. Accompanied with a continuum damage concept and discountinoues plastic flow models the model further developed [26-29]. Some studies on different problems have used this model at low temperatures [30-38].

This paper provides a simplified constitutive model for considering the strain-induced martensitic transformation of the metastable austenitic stainless steels at low temperatures (typically below 100K). Considering the difficulties of the experiments at low temperature, the main goal is simplifying the model adequately to be calibrated with few experiments i.e. uniaxial tension and XRD tests. The focus is on the interaction between the strain-induced martensitic transformation and TRIP and the consequent work-hardening behavior. Homogenization methods are ignored, because a fully elastic martensite assumption could not be adjustable, also the plastic parameters of the martensites, formed at different levels of strain, could not be separately determined. In addition, most of the homogenization methods (For example Mori-Tanaka and Eshelby's Solution) are reliable for small amounts of inclusions; an assumption completely rejected in our problem.

In this paper, a new hardening law has been proposed assuming that we are facing a continuously changing material with varying plastic parameters in terms of martensite evolution. Furthermore, the linear kinetics model of Garion and Skoczen [9] has been modified to implement the transformation strain. The constitutive model has been compared with available experiments on two grades of stainless steels 304L and 316L at temperature 77K. Finally, some numerical simulations were performed implementing the model in the user defined material subroutine (UMAT) in Abaqus/Standard.

2. Equations

In the plastic behavior of materials under transformation, the overall strain could be divided into two major parts: A recoverable elastic strain and an irreversible strain. The irreversible deformation itself is originated from two different phenomena: The well-known slipping plastic deformation and deformation due to the sudden change of crystalline structure during phase transformation. Thus, the following relation is assumed:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p + \boldsymbol{\varepsilon}^{tr} \tag{1}$$

where ε^p and ε^{tr} are the strain measures of the plastic slipping and phase transformation respectively. Considering isotropic linear elastic law, the state equation

is written as the following:

$$\boldsymbol{\sigma} = \mathbb{C}^e : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p - \boldsymbol{\varepsilon}^{tr}) \tag{2}$$

To formulate the plastic behavior, the familiar Von-Mises yield surface is assumed:

$$\phi = \sqrt{3J_2(\boldsymbol{\sigma})} - R(\bar{\varepsilon}^p, \xi) = 0 \tag{3}$$

In Eq. (3), $\bar{\varepsilon}^p$ is the accumulated plastic strain and ξ is the martensite volume fraction which is often the only internal variable responsible for the phase transformation. Additionally, $R(\bar{\varepsilon}^p, \xi)$ represents the isotropic hardening of the material. As stated, the hardening is greatly influenced by the phase transformation and martensite content.

Considering an associated normality rule, the plastic evolution follows:

$$\dot{\boldsymbol{\varepsilon}}^p = \dot{\gamma}\frac{\partial \phi}{\partial \boldsymbol{\sigma}} = \dot{\gamma}\boldsymbol{N} \tag{4}$$

where $\dot{\gamma}$ is the plastic multiplier and N is the flow direction. To complete the constitutive equations, evolution of the transformation strain, kinetics of the martensite evolution, and hardening behavior of the continuously developing bi-phase material are to be determined.

2.1. TRIP Effect

Microstructural changes during phase transformation causes an irreversible deformation called Transformation-Induced Plasticity (TRIP). Generally, these deformations include both the deviatoric and dilatation components. Deviatoric part is assumed to be co-axial with the deviatoric stress [2, 39]. The following equation has been proposed for transformation strain evolution:

$$\dot{\boldsymbol{\varepsilon}}^{tr} = \dot{\xi}(B\boldsymbol{N} + \varepsilon_V^{tr}\boldsymbol{I}) \tag{5}$$

where the parameter B is assumed to be linearly increased with stress [2]:

$$B = B_0 + B_1\frac{\bar{\sigma}}{S_A^*} \tag{6}$$

In Eq. (6), S_A^* is a reference stress of the austenite and the effective Mises stress $\bar{\sigma}$ is defined as:

$$\bar{\sigma} = \sqrt{3\boldsymbol{J}_2(\boldsymbol{\sigma})} = \sqrt{\frac{3}{2}\boldsymbol{S} : \boldsymbol{S}} \tag{7}$$

where $\boldsymbol{S}$ is the deviatoric part of the stress tensor. Larger crystalline structure of the BCC martensite phase, with respect to the initial FCC austenite, results in the dilatation part of the transformation strain field:

$$\varepsilon_V^{tr} = \frac{1}{3}\frac{\upsilon_M - \upsilon_A}{\upsilon_A} \tag{8}$$

where υ_M and υ_A represent the unstressed specific volumes occupied by the austenite and the martensite, respectively. The values of ε_V^{tr} typically range 0.03-0.05. It should be noted that the transformation plasticity itself has a softening effect, because it results an additional deformation that is not conjugated to the stress; although the overall effect of the strain-induced transformation is a great hardening.

2.2. Modified Kinetics of the Phase Transformation

In kinetics models, martensite evolution is primarily a function of the plastic deformation. The plastic deformation is evaluated by the irreversible deformation in unloading process, experimentally. However, the total irreversible deformation consists an additional transformation-induced deformation, usually not distinguished in constitutive models. In this study, the linear kinetics model by Garion and Skoczen [9] for low temperatures is modified to consider the TRIP effect. In this way, the kinetics of the strain-induced transformation is rewritten in terms of irreversible strain as the following equation:

$$d\xi = AH\big((\bar{\varepsilon}^p - \bar{\varepsilon}_0^p)(\xi_L - \xi)\big)d\varepsilon^{ir} \tag{9}$$

where A is a material parameter generally dependent on the temperature, stress state, and strain rate, and $H(\ )$ is the step function. Moreover, ε^{ir} denotes the total irreversible strain in the tensile test:

$$\dot{\boldsymbol{\varepsilon}}^{ir} = \dot{\boldsymbol{\varepsilon}}^p + \dot{\boldsymbol{\varepsilon}}^{tr} \tag{10}$$

Using Eqs. (5) and (10), the increment of the irreversible strain is as follows:

$$d\varepsilon^{ir} = d\varepsilon^p + d\xi(B + \varepsilon_V^{tr}) \tag{11}$$

Combining Eqs. (9) and (11), the rate of martensite evolution in terms of the slipping plastic strain during the phase transformation is represented by the following relation:

$$\frac{d\xi}{d\varepsilon^p} = \frac{A}{1 - BA - A\varepsilon_V^{tr}} \tag{12}$$

From Eq. (12), it could be seen that the relation is not linear nevertheless. Actually, the material parameter A is increased by a factor dependent on the loading state thorough the parameter B. Neglecting the deviatoric part of the transformation strain, as in [9], A is constant and an increase of about 8% in A is introduced during the modification.

2.3. Hardening Rule

In this study, no homogenization scheme is implemented. The hardening rule is explicitly expressed as a function of not only the slipping plastic strain $\bar{\varepsilon}^p$ but the martensite volume fraction ξ to capture the great hardening of the strain-induced phase transformation.

Material with different values of the martensite phase in different levels of deformation, actually exhibits a great different plastic behavior. Thus, it seems that during the phase transformation different materials in plasticity are incrementally developed in such a way that the primary moderately soft material transforms into a completely different hardened material in the saturated state. This continuous changing of the material could be described assuming that the plastic constants of the material are evolved with the volume fraction of the martensite. Therefore, the following modified power law of hardening is proposed:

$$\sigma_y = \sigma_{y_0} + K(\xi)\bar{\varepsilon}^{p^{n(\xi)}} \tag{13}$$

where it is assumed that the hardening parameters are linearly increased by the martensite content:

$$K(\xi) = \left(1 + \beta_1 \frac{\xi}{\xi_L}\right) K_A \tag{14}$$

$$n(\xi) = \left(1 + \beta_2 \frac{\xi}{\xi_L}\right) n_A \tag{15}$$

In Eqs. (14) and (15), K_A and n_A are hardening coefficients of the austenite phase before the transformation and the constants β_1 and β_2 are material parameters.

2.4. Parameter Identification Procedure

Experimental procedures at low temperatures are often difficult and costly, so an important notion is to reducing the required tests for identifying the parameters of the constitutive model. In the present model, a specific way for determining the parameters B_0, B_1, β_1, β_2, K_A and n_A, all coupled in the plastic behavior of the material, from the only stress-strain curve of the simple tension test is represented. Accordingly, we consider three steps in the total deformation; before, during and after the transformation, separated with the parameters $\bar{\varepsilon}_0^p$ and ξ_L (or $\bar{\varepsilon}_L^p$) (Fig. 2).

The plastic parameters of the austenite phase (K_A, n_A) could be obtained normally before the transformation initiated. Additionally, (K_L, n_L) could be determined from the last step, after the transformation saturated, by fitting a curve to the experimental results after the $\bar{\varepsilon}_L^p$. Using Eqs. (14) and (15), the parameters (β_1, β_2) are calculated as follows:

$$\beta_1 = K_L/K_A - 1 \tag{16}$$

$$\beta_2 = n_L/n_A - 1 \tag{17}$$

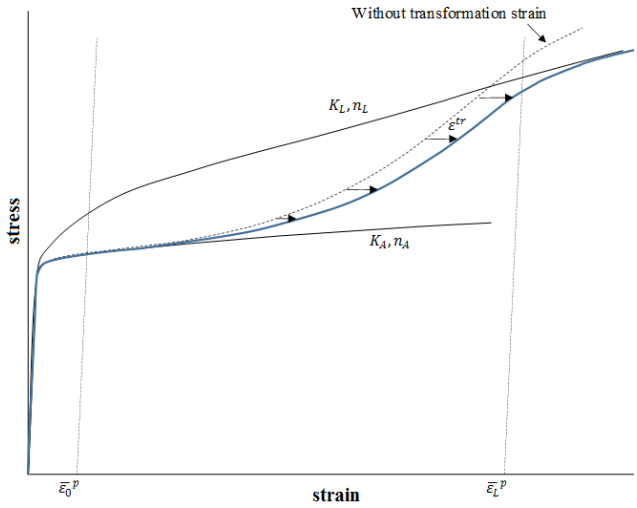


Fig. 2. Procedure of parameter identification of the model.

Using the above-mentioned parameters without considering the transformation strain results in an overestimated hardening behavior (Fig. 2). Transformation strain as an additional deformation, softens the material, so the parameters (B_0, B_1) is chosen as the best fit to the experimental curve.

3. Numerical Implementation

The constitutive model is implemented as a user defined material subroutine (UMAT) in Abaqus/Standard. The incremental return mapping scheme is used for implicit integration of the constitutive model. The algorithm could be briefly represented as follow.

3.1. The Elastic Trial Step

Given the increment of the strain,

$$\Delta\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_{n+1} - \boldsymbol{\varepsilon}_n \tag{18}$$

corresponding to a typical (pseudo-) time increment $[t_n, t_{n+1}]$, the trial elastic state is computed as:

$$\boldsymbol{\sigma}_{n+1}^{tr} = \mathbb{C}^e : \boldsymbol{\varepsilon}^{etr} = \mathbb{C}^e : (\boldsymbol{\varepsilon}_n^e + \Delta\boldsymbol{\varepsilon}) \tag{19}$$

$$\sigma_{y_{n+1}}^{tr} = \sigma_{y_n} \tag{20}$$

If the trial state lies inside the yield surface, the increment is fully elastic and the values of the internal variables $(\bar{\varepsilon}^p, \xi)$ remain fixed. Otherwise, the plastic corrector step has to be applied.

3.2. The Plastic Corrector

In the present case, the following set of nonlinear equations has to be solved for $[\sigma_{n+1}, \dot{\gamma}, \Delta\xi_{n+1}]$:

$$\boldsymbol{\sigma}_{n+1} - \mathbb{C}^e : (\boldsymbol{\varepsilon}^{etr} - (\dot{\gamma} + B_n\Delta\xi_{n+1})\boldsymbol{N} - \varepsilon_V^{tr}\Delta\xi_{n+1}\boldsymbol{I}) = 0 \tag{21}$$

$$\sqrt{3J_2(\boldsymbol{\sigma}_{n+1})} - \sigma_{y_0} - K_{\xi_n}(\bar{\varepsilon}_n^p + \dot{\gamma})^{n_{\xi_n}} = 0$$
$$\Delta\xi_{n+1} - \frac{A}{1 - B_n A - A\varepsilon_V^{tr}}\dot{\gamma} = 0$$

These equations could be reduced to a single return mapping equation to find the $\dot{\gamma}$ following the conventional procedures of the computational plasticity (for example see [40]). It should be noted that the material coefficients $[K, n, B]$ are evaluated at the beginning of the increment. After some straight-forward calculations, the Jacobian matrix required for the numerical implementation, could be obtained as:

$$\boldsymbol{J} = \frac{\partial \boldsymbol{\sigma}_{n+1}}{\partial \boldsymbol{\varepsilon}_{n+1}} = \mathbb{C}^e - 3GC_1\left(\frac{1}{q_{n+1}^{tr}}\mathbb{I}_d + \left(\frac{\dot{\gamma}}{C_1 + \Delta\sigma_{y_{n+1}}} - \frac{1}{q_{n+1}^{tr}}\right)\boldsymbol{N}\otimes\boldsymbol{N}\right) - \sqrt{\frac{3}{2}}\frac{6GK\varepsilon_V^{tr}\Delta\xi_{n+1}}{C_1 + \Delta\sigma_{y_{n+1}}}\boldsymbol{N}\otimes\boldsymbol{I} \tag{22}$$

where

$$C_1 = 3G(\dot{\gamma} + B_n\Delta\xi_{n+1}) \tag{23}$$

$$q_{n+1}^{tr} = \sqrt{3J_2(\boldsymbol{\sigma}_{n+1}^{tr})} \tag{24}$$

In Eq. (22), $\mathbb{I}_d$ is the 4-th order deviatoric projection tensor, G and K are the elastic shear and bulk coefficients respectively and $\otimes$ denotes a dyadic product. As could be seen in Eq. (22), the Jacobian is not symmetric generally.

4. Results and Discussion

In this section, the proposed constitutive model is used to be compared with the experimental results of the austenitic stainless steels at low temperatures. Two sets of experiments at temperature 77K by Morris Jr et al. [41] and Garion et al. [42], on two grades of stainless steels 304L and 316L, commonly used in low temperature applications, are used to be verified by the model.

Using a tensile loading, the results of the model are compared to the experimental data in Fig. 3. Material parameters, identified with the procedure of section 2.4, are indicated in Table 1.

Generally, a good agreement between the results of the model and experiment could be observed in most of the plastic strain range. However, the early stage of the plastic behavior in the AISI304, before the onset of transformation, has not been predicted properly by the present model; a problem which could be found also in other significant models by Garion and Skoczen [9], Mróz and Ziętek [21], Egner and Skoczeń [27]. Actually, some of the austenitic stainless steels have a low elastic proportional limit at low tempratures, resulting a gradual deviation of the stress-strain curve from linear elastic to plastic behavior. In such materials, the onset of yielding is not clearly discernible (only the 0.2% strain criterion could be used) and until a small plastic strain the power law hardening could not meet the whole experimental curve. So, in this kind of plastic behavior the yield stress may be assumed to be around the flat portion of the curve and a usual hardening rule could be fitted to the rest of the curve albeit a loss of accuracy at low plastic strains.

The evolution parameters (β_1, β_2) of the materials have taken the values within a narrow range enabling the model to be physically adjustable. The transformation plasticity parameters (B_0, B_1, S_A^*) are determined close to the values by Stringfellow et al. [2] as well.

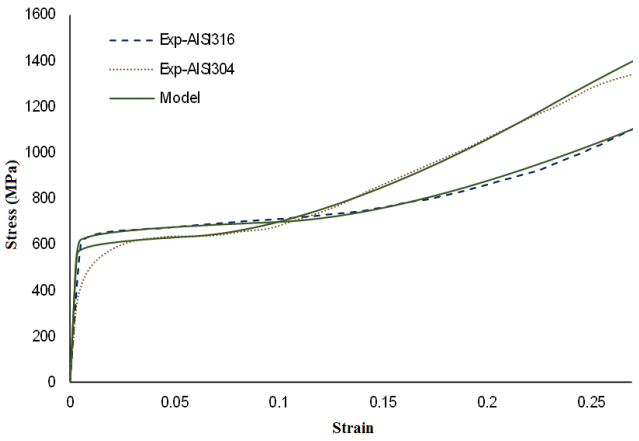


Fig. 3. Results of the model compared with the experimental data.

Table 1
Model parameters for investigated steels.

	E	ν	σ_{y_0}	$\bar{\varepsilon}_0^p$	ξ_L	A	K_A
AISI316	180GPa	0.3	580MPa	0.09	0.9	4.37	220MPa
AISI304	180GPa	0.3	550MPa	0.05	0.88	4.23	220MPa
	n_A	β_1	β_2	B_0	B_1	S_A^*	ε_V^{tr}
AISI316	0.35	19.8	0.09	0.016	0.012	697MPa	0.016
AISI304	0.37	23	0.10	0.016	0.016	697MPa	0.016

In Fig. 4 the modified kinetics model is compared with the original one proposed by Garion and Skoczen [9] for AISI316. TRIP significantly changes the rate of martensite evolution against the slipping plastic strain. The overall behavior of the modified model is not linear generally, however, the effect of the deviatoric part of the transformation strain as the nonlinear component is considerable only at high levels of stress. The saturation strain in the modified model is about 30% lower than that the original model. Moreover, the value of the martensite fraction at this point is about 30% greater. The modified model exhibits a more accelerated martensite evolution with the plastic strain i.e. the external work on the material to be flowed plastically.

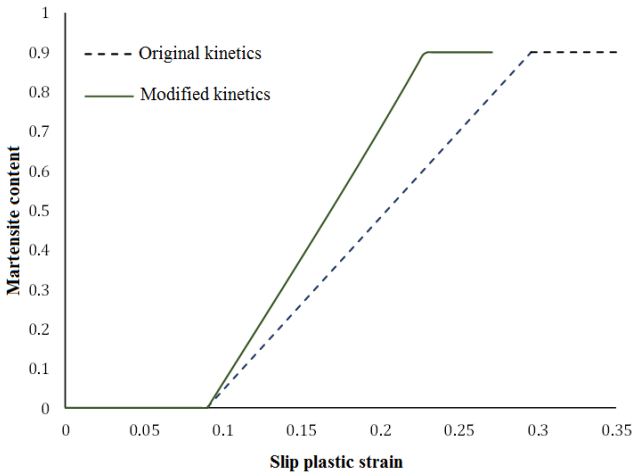


Fig. 4. Modified and the original kinetics model of strain-induced phase transformation.

Two load cases including the pure bending of a rectangular beam under an applied rotation and torsion of a cylindrical bar under an applied torque have been considered in order to investigate the capability of the model in numerical simulation of more complex problems of the transformation plasticity at low temperatures. The geometries and loadings have been shown in Fig. 5.

In the case of bending, the resulted moment against the bending rotation for both of materials is represented in Fig. 6. In addition, the distribution of martensite content is shown in Fig. 7. The results show a good agreement with previous study of [31] making the simplified model reliable. However, it should be noted that neglecting the effect of stress state in the kinetics law, leads to a symmetric distribution of martensite fraction and subsequently a pure homogeneous bending. This may be not validated specially at higher temperatures, where the growth of martensite is influenced by deformation state adequately.

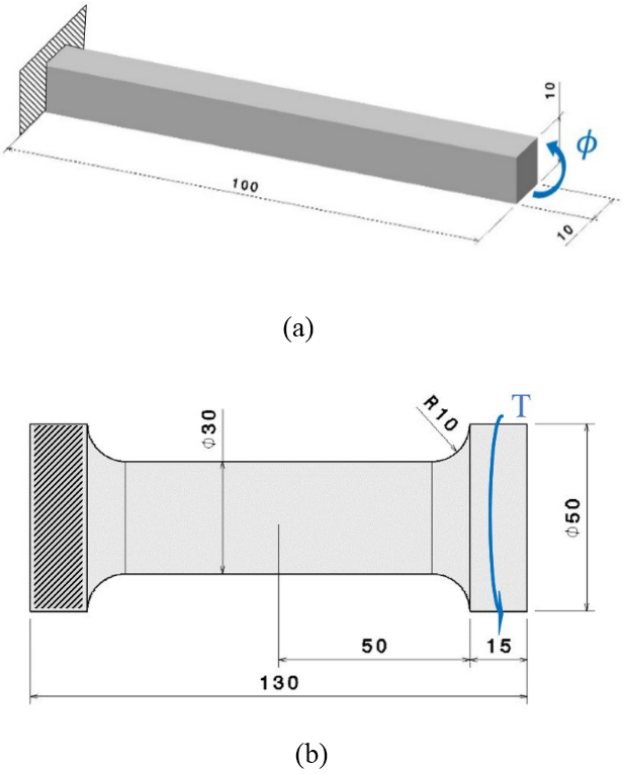


Fig. 5. Geometry and applied loads: a) The bending of a rectangular beam, b) Torsion of a cylindrical bar.

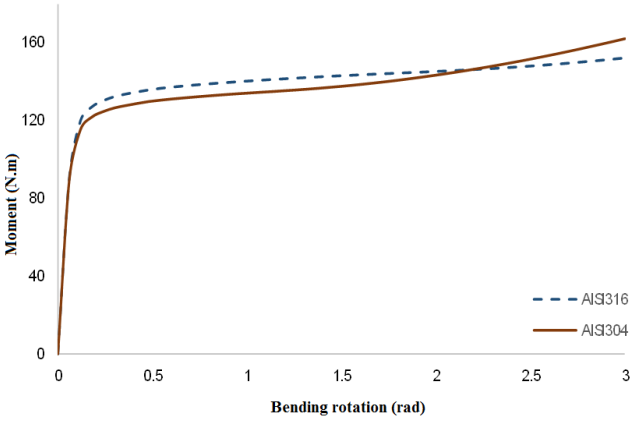


Fig. 6. Resulted moment versus the bending rotation of the beam.

Fig. 7. Distribution of martensite fraction ξ for the beam under bending with material AISI316.

In the torsion problem, the resulted twisting angle in terms of the applied torque has been shown in Fig. 8. A same behavior could be found in bending and torsion. The distribution of the martensite content value in cross-section of the specimen is depicted in Fig. 9. Numerical results reflect the trends of the experiments by Ortwein et al. [33]. In addition, the martensite content directly reflects the differences between the transformation kinetics of the two materials. Phase transformation of grade 316, initiates earlier but at a lower rate than grade 304.

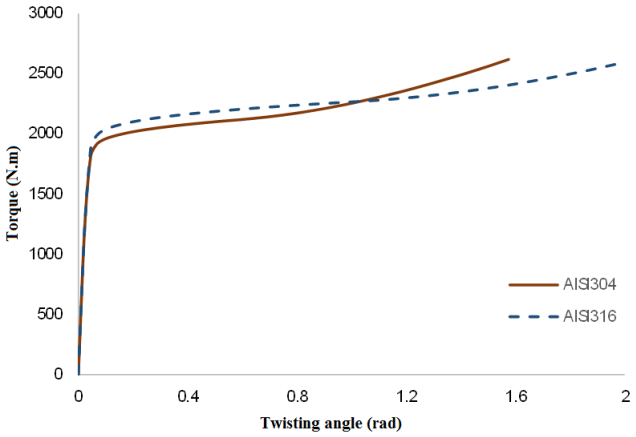
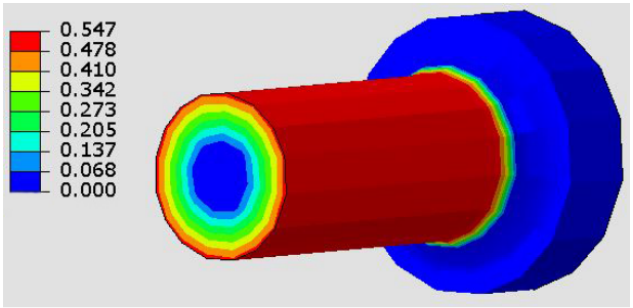
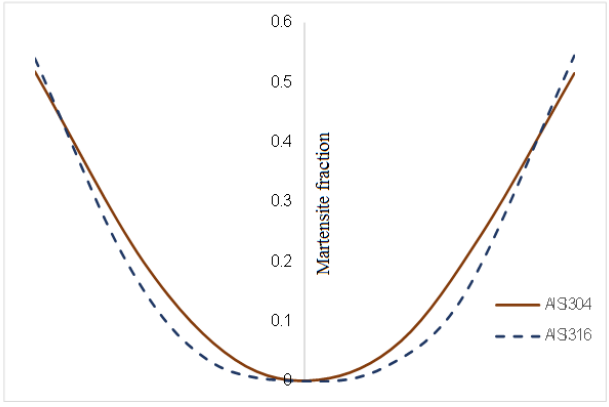


Fig. 8. Torque versus the twisting angle of the cylindrical bar.



(a)



(b)

Fig. 9. Distribution of the ε in cross section of the cylindrical bar under torsion with material AISI316.

5. Conclusions

In this study, a simplified constitutive model for plastic behavior of austenitic steels at low tempratures was proposed. In this model, the effect of transformation strain was considered. Furthermore, a modified power law hardening and a modified kineteics model of phase transformation were proposed. Developing the incremental updating procedure, the constitutive model was implemented in the Abaqus/Standard via a user defiened material subroutine (UMAT).

The results showed that the proposed modified kinetics model accelerates the transformation against the slipping plastic strain and significantly affects the plastic behavior. In addition, the modified power law hardening for the continuously changing dual phase material well describes the great hardening effect of the transformation. Numerical examples represented the capability of the constitutive model and the incremental form in well predicting the plasticity problems under the steep strain-induced phase transformation as in the case of austenitic stainless steels at low tempratures.

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