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Strain-Induced Martensite Transformation Simulations during Cold Rolling of AISI 301 Austenitic Stainless Steel

M. Imaninezhad [1*], T. Yan [2], A. Najafizadeh [3]

[1] Department of Biomedical Engineering, Saint Louis University, Saint Louis, 63103, MO, USA
[2] Department of Mechanical Engineering, Southern Illinois University Edwardsville, Edwardsville, 62026, IL USA
[3] Department of Materials Engineering, Fould Institue of Technology, Fould Shahar, Iran

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Abstract

Austenite is a semi-stable phase in most stainless steels that deforms to martensite under Md_{30} and forms martensite type ά and ε due to the deformation in the steels. Since the distribution of strain induced martensite plays an important role in achieving desired properties, the main objective of the present work is to model martensite distribution of ά during cold rolling using finite element method and Olsen-Cohen model. In this study, the strain induced martensite transformation of 301 stainless steel during cold rolling has been simulated by ANSYS software. First, the mesh sensitivity analysis was performed and mesh optimization was set to stimulate the strain induced martensite transformation of 301 stainless steel during cold rolling. Martensite fractions in cold-rolling was simulated and compared with experimental data. Finite element analysis was performed to obtain strain and stress during cold rolling. The amount and distribution of martensite during cold rolling has been modeled. The highest stress level was observed and applied on a friction plate which was in contact with rollers and, as a result, was under the most friction; thus, the stress reduced away from the surface toward the center of the sheet. Moreover, a similar phenomenon was observed for changes in the strain. These results were also compared with experimental data that had been obtained with X-ray diffraction, with the use of a Ferritoscope, X-ray diffraction and experimental results.

Keyword: Cold rolling; Austenitic stainless steel; Martensite transformation; Finite element; Stress-strain.

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1. Introduction

Austenitic stainless steel is widely used in industry due to its high resistance to corrosion and flexibility. The manufacturing process often involves rolling and deep drawing of the austenitic steel, where large plastic strain is present. Transformation of austenite to martensite (ά) can occur during the cold forming process and depends on several factors, such as chemical composition, strain, strain rate, temperature, and state of stress 1). The effect of these factors on the occurrence of strain-induced martensite transformation has been the aim of many studies 2-7). In the transformation process, the volume fraction of martensite increases with increasing deformation and finally, at strain saturation, reaches a maximum value. The formation of martensite increases strain hardening 8) and causes a delay in the necking stage of the material 9) .Furthermore, high internal stresses that are caused by martensitic transformation, and along with residual stresses, can cause a delayed cracking phenomenon 10, 11). In order to achieve desired mechanical properties for the alloys, it is important to understand the relationship between shape parameters and distribution of strain-induced martensite.

There are various models dealing with the formation of martensite due to transformation in austenitic stainless steel 12, 13). The Olsen-Cohen model, of the analytical models, has been quoted the most often among researchers and is widely used in many studies because of its simplicity and high compatibility with respect to empirical data 14). The Olsen-Cohen model is based on the martensite nucleation ά phase in sections of shear bands as well as finite element method (FEM), which can be successfully used for analysis of cold-rolled austenitic stainless steels. However, there is still a lack of information on the distribution of mar-

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** Coressponding author*
Tell:+1 314 977 8292
Email: mimaninezhad@gmail.com
Address: Department of Biomedical Engineering, Saint Louis University, Saint Louis, 63103, MO, USA
1. Ph.D. Candidate
2. Professor
3. Professor

tensite ά in different range of deformation during cold rolling process.

It has been known that the austenitic stainless steels may form martensite while cooling below M_s temperature. Eichelman and Hall [9] presented the following equation to determine the formation of starting temperature of martensite (M_s) in austenitic stainless steels:

$$M_s\,(°F) = 75\,(14.6 - Cr) + 110\,(8.9 - Ni) + 60\,(1.33 - Mn) + 50\,(0.47 - Si) + 3000\,[0.068 - (C+N)] \qquad \text{(Eq. 1)}$$

This equation shows that in contrast to the strong effects of interstitial elements like carbon and nitrogen, the effects of substitutional elements of Cr and Ni are moderate on M_s temperature. When the nitrogen content is mixed with carbon, it may have very powerful effects to stabilize the austenite phase. Under such circumstances, martensite may form in the surrounding grain boundary areas. In fact, this phenomenon is used as a method of precipitation hardening of austenitic stainless steels by formation of martensite in it.

To study the kinetics of strain-induced martensite nucleation mechanisms used to deal with shear bands, the increasing amount of shear bands in the martensite, which has not changed as a function of plastic strain in austenite, is investigated. If it is assumed that the plastic deformation at low strains, resulting in "significant fraction" of shear bands, so very little of it, as "free volume in shear bands" is used. This is a simple model for the formation of shear bands (with consideration of the use of free volume in shear bands) at a fixed rate relative to the plastic strain introduced. Eq. (2) is obtained for the volume fraction of martensite as a function of plastic strain:

$$f^{\acute{\alpha}} = 1 - exp\{-\beta[1 - \exp(-\alpha\epsilon)]^n\} \qquad \text{(Eq. 2)}$$

Strain-induced martensite transformation curve is characterized by two temperature- dependent physical parameters α and β and the constant n. Parameter α, which tracks formation of shear strain, is due to the energy dependence of the defect removal; therefore, it would be temperature-sensitive. The parameter β is characterized by the possibility that shear bands in place to create a nuclei and the possibility is associated with the chemical driving force which is temperature-dependent [14].

Using a simple and less expensive method to determine the amount of austenite and martensite in the microstructure, one can provide important information in the studies of transformation of semi-stabilized austenitic stainless steels. It is especially important when it is applied to applications that determine the maximum temperature and its dependence on the length of the system is under stress as well as rate of deformation, or other process variables. There are several methods, such as X-ray diffraction analysis, magnetic induction, existed for measuring the amount of martensite ά due to strain rate in semi-stabilized austenitic stainless steels.

The objective of this study is to use finite element method to simulate and evaluate the stress and strain of a cold-rolled 301 austenitic stainless steel sheet sample. The strain will correlate to the transformation to martensite in terms of volume fraction as a function of strain at a fixed temperature.

2. Materials and Methods

2. 1. Alloys

In this study, an austenitic stainless steel (AISI 301) was used as the sample characterized by its meta stable state that shows significant martensitic transformation, even at room temperature. The chemical composition of this steel is given in Table 1.

Table 1. Chemical composition of AISI 301 stainless steel (wt. %).

C	Mn	Si	Cr	Ni	Fe
0.12	1.9	0.9	17.6	7.2	balanced

2. 2. Simulation method

The ANSYS finite element simulation software was used for the modeling. Due to the geometry of the sheet and roller, the problem assumed a two dimensional strain (surface). The symmetry of the model was assumed relative to the center line of the sheet. The plate dimensions of 0.3 (length) × 0.1 (thick) m^2 and roller radius of 0.12 m were considered. Regarding the properties of the sheet material, the combination of viscoplastic model of Perzyna [15] and nonlinear isotropic hardening model (NLISO) [16] was found suitable for describing the behavior of the sheet. Coefficient of friction between the plate and the roller was considered as 0.5 based on Perzyna model. The Perzyna model has proven that gives an ideal response during loading. Rollers and bars located in the center have elastic properties of a material with a high modulus (E= 400 GPa) and was considered to be rigid. Linear properties of the alloy sheet and its nonlinear constants of Perzyna model used in this study are presented in Table 2.

Table 2. Perzyna model alloy properties and constant.

Linear properties	E=200 GPa ν=0.3
Nonlinear properties (NLISO constant)	C1= 300 MPa C2= 1 GPa C3= 52 MPa C4= 172 MPa
Perzyna model constant	m=0.5 γ=1

Three elements mesh generator, Quad 4 node 182 Solid, 2D elastic 3 Beam and pt-to-surf 48 Contact were used (Fig. 1-a). To determine the strain-induced martensite fraction, model output for each node in the empirical equation shown in Fig. 1-b and changes in strain martensite fraction was determined.

2. 3. Mesh sensitivity analysis

The numbers of meshes were varied to perform a sensitivity study of the mesh in order to further determination of the optimal mesh for the simulation study. A representative point of 0.03 m (1/10th) length) from the edge of the plate is selected to be used to monitor the mesh effect on the strain. Five meshes were constructed in the size of 10 × 5, 20 × 5, 30 × 5, 50 × 10 and 70 × 15.

Fig. 1 shows the variation of calculated strain as a function of mesh size. It is observed that mesh-dependent results were achieved for mesh of 30 × 5 and finer. The simulations were thus performed using 30 × 5 mesh.

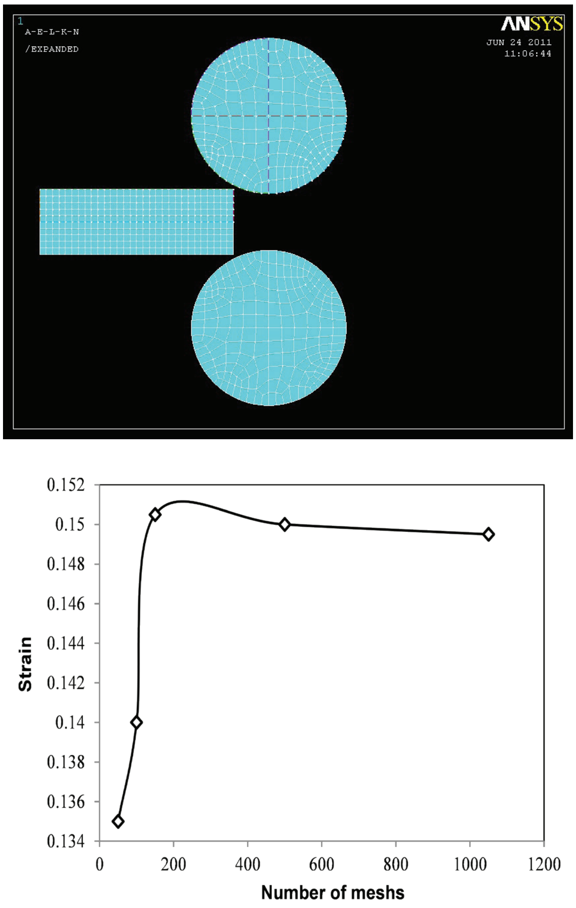

Fig. 1. a) Meshing of sheet and rollers, b) Sensitivity analysis of meshing.

3. Results and Discussions

The relationship between the fraction of martensite and the applied strain has been obtained by using experimental data from Eskandari et al. [17, 18]. The Olsen-Cohen model was used to rely the best equation can be derived based on the results and by considering f as ά martensite volume fraction and the strain ε, Eq. (2) is proposed. In this equation, α and β parameters are temperature-dependent and can be considered constant, n is generally equal to 2.

Fig. 2 shows the Olson-Cohen correlation for the amount of ά martensite as a function of deformation for the cold rolled samples. In this figure, curve fitting function plotted with a regression goodness value of R^2 =0.9974.

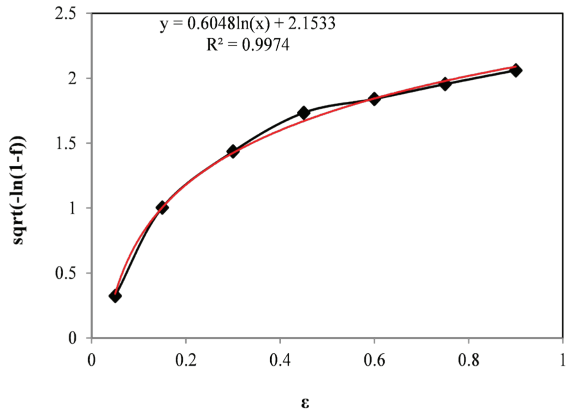

Fig. 2. Martensite fraction change as a function of strain in cold rolled austenitic stainless steel 301.

The simulation results were also compared with the experimental data of Karimi et al. [19], which was carried out by XRD and Ferritoscope techniques. Martensite transformation and distribution was observed in this model and was confirmed by X-ray diffraction and Ferritoscope (refer to Fig. 6).

This FEM model can be used to increase the strain hardening, delaying in the onset of necking, increase of forming load, decrease corrosion resistance and delayed cracking phenomenon. Therefore, it is important to determine the evolution of amount/distribution of stress-induced martensite during forming process.

3. 1. Stress and strain distribution

Stress and strain changes during cold-rolled austenitic stainless steel AISI 301 were investigated with finite element analyses (ANSYS software). Fig.3a shows the stress distribution during the cold rolling at a fixed position. The highest stress levels are found around the contact of the rollers and plate where the sample sheet is subjected to a maximum deformation in the cross direction. The stress level decreased gradually from the contact to the center of the sample. Fig. 3b shows the stress distribution after the sample is rolled.

There are extensive studies regarding cold rolling of austenitic stainless steel. However, there is a lack of knowledge about the distribution of ά martensite. This FEM evaluated the stress distribution depending on the austenite and martensite changes in volume fraction developed during strain induced phase transformation. In addition, despite extensive studies on cold drawing of austenitic stainless steels, there is still a lack of knowledge.

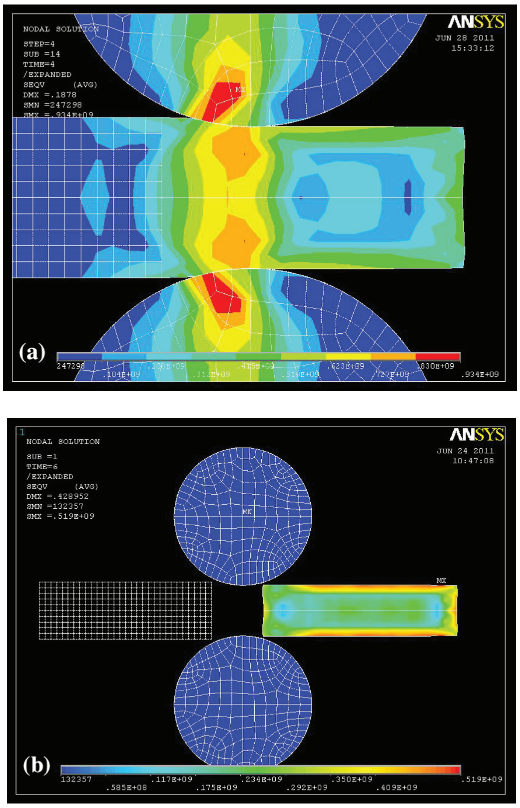

Fig. 3. Stress distribution of a) sample passing through the rollers, b) passed through the rollers.

Fig. 4 show the elastic and plastic strains in the rolled sample. It is observed that the strain changes are the same as stress.

In Fig. 5, the strain distribution in the sample passed through the rollers and the rolling have shown, schematically.

3. 2. Strain-induced martensites

The volume fraction of strain induced martensite in the sample of Austenitic stainless steel under as a function of sheet thickness reduction is shown in Fig. 6. The martensite volume fraction is calculated by the Olsen-Cohen model (Eq. 2) with the simulated strain distribution.

Dependence of strain induced martensite versus strain measured by i) X-ray diffraction, ii) Ferritoscope, and iii) simulation is shown in Fig. 6. This figure showed a very good approximation of the experimental data is consistent with the simulation results.

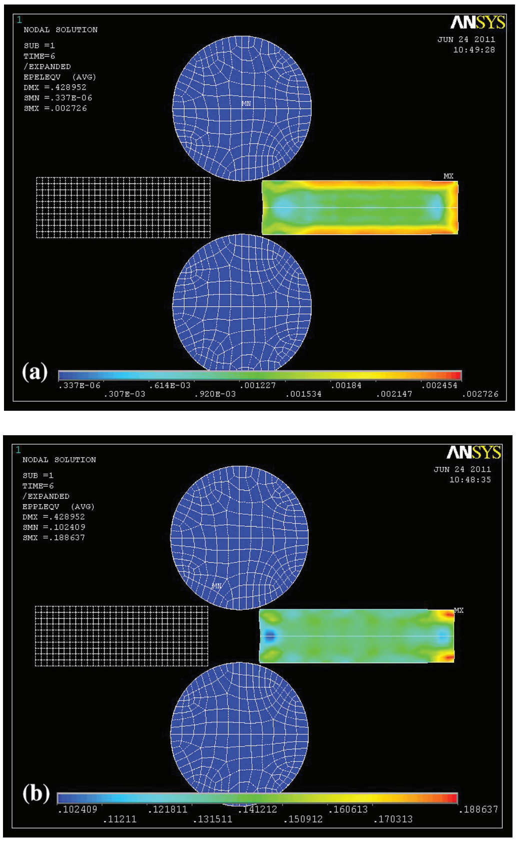

Fig. 4. Strain distribution (a) elastic and (b) plastic.

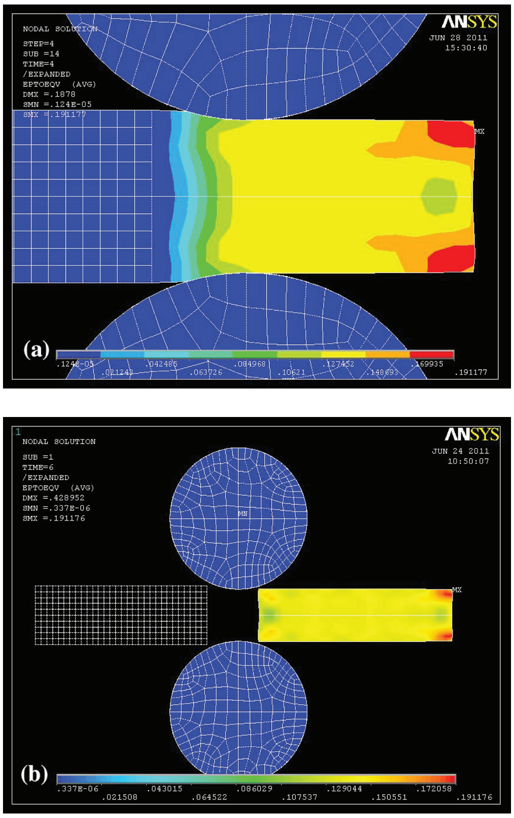

Fig. 5. Strain distribution of (a) sample passing through the rollers, and (b) passed through the rollers (To and bottom corners in the front edge area show maximum strains).

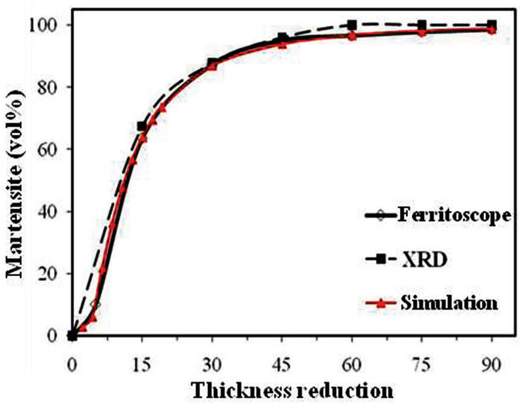

Fig. 6. Dependence of strain induced martensite versus strain measured by i) X-ray diffraction, ii) Ferritoscope, and iii) simulation.

4. CONCLUSION

In this study, the strain-induced martensitic transformation during cold rolling was stimulated for austenitic stainless steel 301. Ansys finite element simulation was used to model the process. The surface strain was analyzed due to the geometry of sheets and rollers. Also, according to the center line of symmetry of the sheet, the process was modeled using symmetry. Martensite transformation and distribution was observed in this model and its value changes with suitable adaptation model. The highest stress level was observed and applied on friction plate which was under the most friction caused by rollers and the stress reduced away from the surface toward the center of the sheet. Moreover, similar phenomenon was observed with changes in strain. The simulation results were confirmed by X-ray diffraction and Ferritoscope.

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