Short communication

Deformation induced martensitic transformation in a 201 modified austenitic stainless steel

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ABSTRACT

The production of low nickel austenitic stainless steels has increased considerably mainly due to nickel price evolution in the last years. In the present work, the susceptibility to deformation induced martensitic transformation of a 201 modified stainless steel was evaluated. The results were compared to existing results of traditional AISI 304 steel. The variation of martensite volume fraction against true strain was modeled by a sigmoidal equation and the transformation rate was also determined.

1. Introduction

Austenitic stainless steels (SS) such as AISI 301, 304 and 316 are susceptible to deformation induced martensitic transformations, where austenite transforms to martensite via displacement of atomic planes. Two distinct types of martensite can be formed through this mechanism: ε martensite, a paramagnetic phase (just as the austenite), bearing hexagonal close packed (hcp) structure, and α' martensite, ferromagnetic, body centered cubic (bcc) with the same crystallographic lattice parameters of ferrite phase.

The martensitic transformation in conventional 300 series austenitic steels has been extensively studied [1–4]. It is generally accepted that the susceptibility to martensite induced transformation in austenitic stainless steels is related to the stacking fault energy, a parameter influenced by temperature and chemical composition of austenite. Martensitic transformations $\gamma \rightarrow \varepsilon$ and $\gamma \rightarrow \alpha'$ are favored by lower stacking fault energy For instance, in order of decreasing degree of metastability, AISI steels 301, 304 and 316 present stacking fault energy values around 6.0, 18.0 and 60.0 mJ/m^2 [2,3].

Many authors [5–9] have investigated the influence of alloying elements on the stacking fault energy of austenitic steels. Nickel, manganese, molybdenum and copper are found to increase the stacking fault energy, while nitrogen decreases the stacking fault energy. Of course, the analysis of the influences of individual elements is complicated due to multiple interaction effects. For example, according to Ferreira and Müllner [6] chromium can increase or decrease the stacking fault energy depending on the nickel content in Fe–Cr–Ni alloys. Vitos et al. [7] and Dumay et al. [8] predicted the decrease of the stacking fault energy with chromium addition while the formulae proposed by Scharam and Reed [9]

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Table 1 – Chemical composition of 201Mod, AISI 304 and AISI 201 steels (wt.%).

Steel	C	Mn	Si	P	S	Cr	Ni	Cu	N
201Mod	0.06	7.07	0.45	0.03	0.01	15.00	3.99	1.57	0.05
AISI 201	0.15	5.5–7.5	1.00	0.06	0.03	16.0–18.0	3.5–5.5	–	0.25
AISI 304	0.08	2.00	1.00	0.03	0.03	18.0–20.0	8.0–10.0	–	–

estimate the increase of stacking fault energy with the increase of chromium addition:

$$SFE = -53 + 6.2(\%\,Ni) + 0.7(\%\,Cr) + 3.2(\%\,Mn) + 9.3(\%\,Mo)(\mathrm{mJ/m^2}) \quad (1)$$

In the present work, the susceptibility to martensitic transformation induced by cold rolling in a low Ni, Mn–Cu–N alloyed stainless steel, called 201 modified, was studied. This grade belongs to the 200 series austenitic stainless steels. In this group, nickel is partially replaced by other austenitizing elements such as Mn, N and Cu. For instance, it is generally accepted that 1% Ni can be replaced by approximately 2% Mn. A pronounced production increase of these steels has been observed in the last years, due to nickel price increase [10]. The 201 modified replaces the traditional AISI 304 steel in some applications. For this reason the data obtained are compared to AISI 304 previous results.

The martensite volume fraction was determined by magnetization saturation measurements. Curves of the martensite volume fraction against true strain were determined and fitted by sigmoidal equation.

2. Experimental

In this work, specimens from a thin sheet (0.430 mm) of modified 201 SS were used. The sheet's chemical composition is shown in Table 1. For comparison, nominal chemical compositions of AISI 304 and AISI 201 are also included in Table 1. The mechanical properties of the 201Mod in as received condition were: σ_y=290 MPa, σ_{UTS}=782 MPa and elongation=62.5%. Small 10×20 mm specimens were cold rolled at room temperature to different degrees of true strain, which is calculated by $\varepsilon_1 = \ln(t/t_o)$, where t_o and t are initial and final thickness respectively. Rolling passes were conducted in plain strain state, without lubrication. The specimens were rolled always in the same direction. Table 2 shows the specimens' identification, respective thickness and true strain.

After rolling, small 3.5 mm discs were cut by electro-erosion to magnetization tests. Magnetization curves were obtained in a Vibrating Sample Magnetometer with maximum applied field 2T. Saturation magnetization (m_s) was measured for all the specimens.

After magnetic measurements the specimens were prepared by electro-polishing for micro-hardness tests with 50 g load. Specimens of deformed AISI 304 steel were also tested in order to compare the work hardening behavior of both steels.

Some specimens were prepared by electrolytic etching with 10% oxalic acid solution (8 V, 60 s) for light optical microscopy observation. Some selected samples were also analyzed by X-

Table 2 – 201Mod specimens' identification, thickness and true strain.

Specimen	Thickness (t) (mm)	True strain (ln t/t_o)
201Mod-A	$t=t_o=0.430$	−0.0000
201Mod-B	0.400	−0.0723
201Mod-C	0.365	−0.1639
201Mod-D	0.365	−0.1639
201Mod-E	0.315	−0.3112
201Mod-F	0.315	−0.3112
201Mod-G	0.265	−0.4841
201Mod-H	0.215	−0.6931
201Mod-I	0.175	−0.8990
201Mod-J	0.175	−0.8990
201Mod-K	0.115	−1.3189
201Mod-L	0.110	−1.3633

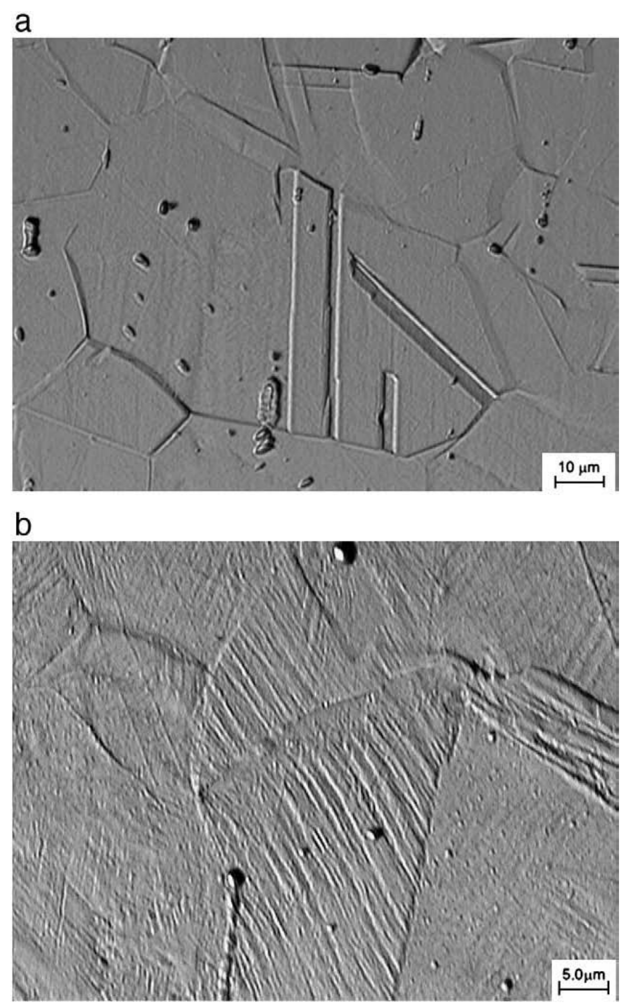

Fig. 1 – Light optical micrographs of 201 modified austenitic stainless steel specimens: (a) sample 201Mod-A (as received condition) and (b) sample 201Mod-D (deformed to ε_1=−0.1639).

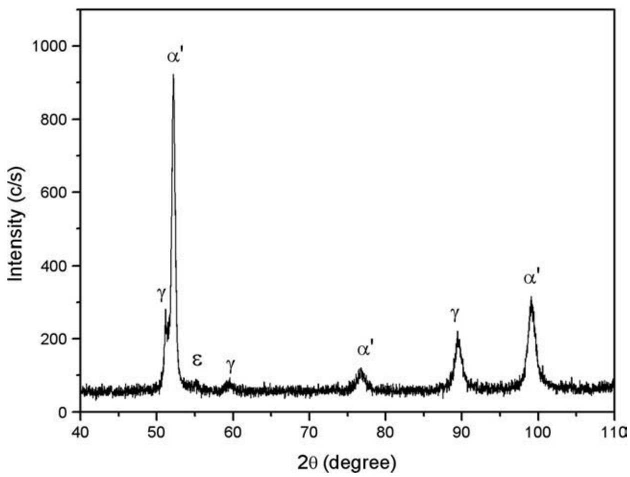

Fig. 2 – X-ray diffraction pattern collected from specimen 201Mod-B (deformed to ε_1 = −0.0723).

ray diffraction in an X'Pert PHILLIPS diffractometer using Co radiation.

3. Results

Some compositional features of the 201 modified steel studied must be highlighted. In relation to AISI 304 steel, nickel was replaced by manganese (7.07 wt.%), nitrogen (0.05 wt.%) and copper (1.57 wt.%). The 201Mod differs from the AISI 201 as it has lower Cr and N contents and Cu addition. The stacking fault energy of the 201 modified calculated according to formulae (1) is 4.8 mJ/m^2, but it does not compute the influences of Cu and N. Using the same formulae (1) and average compositions from Table 1 the stacking fault energy of AISI 201 and AISI 304 steels are 7.6 mJ/m^2 and 19.3 mJ/m^2, respectively. According to Gonzalez et al. [11] copper and nickel additions increase the stacking fault energy of the AISI 304 steel and contribute to delay martensite transformation and control austenite's rate of work hardening. The authors have studied an AISI 304 steel modified by partial substitution of Ni by Cu (1.79%), and observed the decrease of both ε and α' martensites formation. According to Dumay et al. [8], in a Fe–Mn–C alloy the stacking fault energy increases with wt.%Cu in a rate of about 1.0 mJ/m^2/wt.%Cu. Considering these studies, it is possible to estimate a stacking fault energy of the 201 modified steel to be considerably lower than the AISI 304 steel. Considering the reported influence of Cu, the stacking fault energy of AISI 201 and 201 modified is rather similar. A lower stacking fault energy is usually related to a higher susceptibility to martensite transformation.

Fig. 1(a) and (b) shows the microstructures of specimens A and D, respectively. Specimen D was deformed to ε_1 = −0.1639 and presents many parallel and intersecting shear bands. According to Talonen and Hänninen [4], the α'-martensite nucleates at the intersections of shear bands. Fig. 2 shows the X-ray diffraction pattern for sample B, in which a small peak of ε martensite can be observed.

Fig. 3 shows the curve of magnetization saturation *versus* true strain for the 201 modified stainless steel. The $\gamma \rightarrow \alpha'$ reaches a saturation value at $m_s \approx 140.0$ Am^2/kg. This was considered to be the magnetization saturation intrinsic for the α' martensite of the 201 modified steel. Consequently, the martensite volume fraction for the various conditions can be determined by the expression:

$$C_{\alpha'} = \frac{m_s}{140.0} \tag{2}$$

where m_s is the magnetization saturation for the specimen analyzed in Am^2/kg.

Using Eq. (2) a curve of C_α *versus* true strain (ε) was constructed. The curve was modeled by a sigmoidal function of type:

$$C_{\alpha'} = C_S \cdot e^{-e(-n(\varepsilon - K))} \tag{3}$$

Where:

$C_{\alpha'}$ – Volumetric fraction of martensite α'.
C_S – Saturation value for the martensite volumetric fraction.

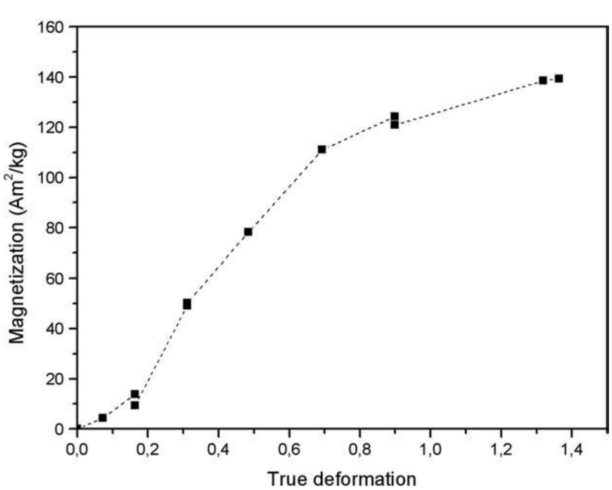

Fig. 3 – Magnetization saturation *versus* true strain curve for the 201Mod stainless steel.

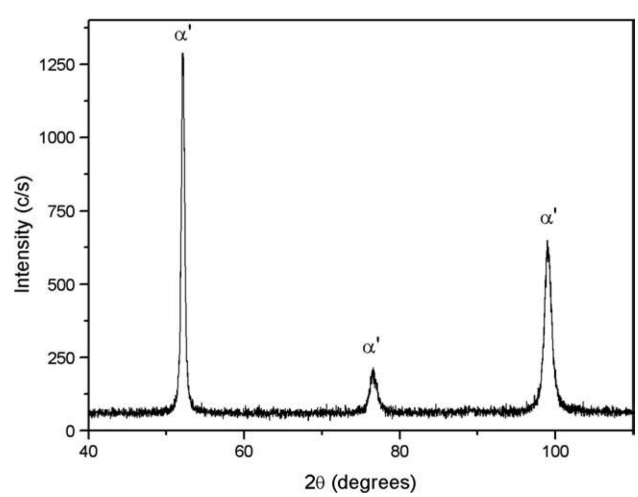

Fig. 4 – X-ray diffraction pattern from a highly deformed specimen of 201Mod stainless steel specimen (201Mo-K), showing the complete transformation from austenite to martensite.

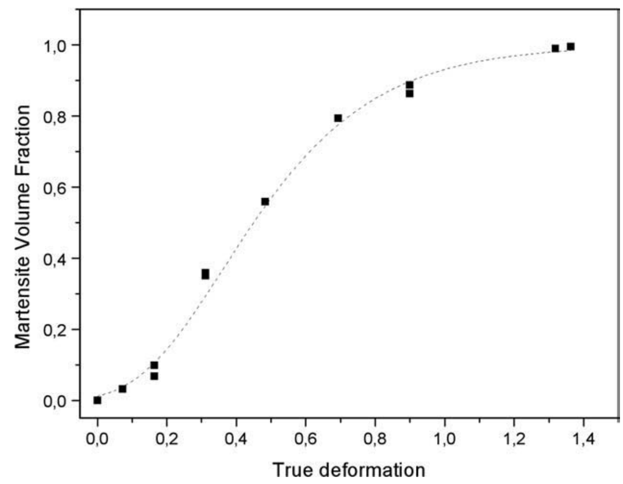

Fig. 5 – Fitting of the martensite volume fraction (C_α) *versus* true deformation (ε) curve and the experimental data. The solid squares represent the collected experimental data and the dotted line represents the fitting curve.

n – Constant related to the velocity of precipitation.
ε – True strain.
K – Time constant, related to the initial stage of transformation.

The linearization of Eq. (3)) allows the obtaining of constants n and K, as shown in Eq. (4).

$$ln\left[-ln\left(\frac{C_{\alpha'}}{C_S}\right)\right] = -n\cdot\varepsilon + n\cdot K \quad (4)$$

Constants n and K were determined by plotting $\ln(-\ln(C_{\alpha'}/C_S))$ *versus* ε. The C_S value was assumed to be 1, i.e., the saturation value corresponds to 100% of martensite. This is corroborated by X-ray diffraction measurements, as shown in Fig. 4.

Fig. 5 shows the fitting of C_α *versus* true strain (ε) curve and the experimental data. K and n values were 0.361 and 4.120, respectively. The correlation as coefficient was $R^2=0.993$.

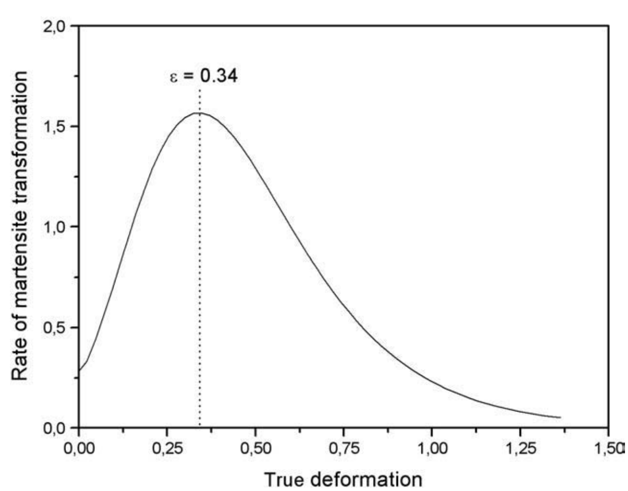

Fig. 6 – Rate of martensite transformation ($dC_{\alpha'}/d\varepsilon$) *versus* true strain (ε) curve for a 201Mod stainless steel.

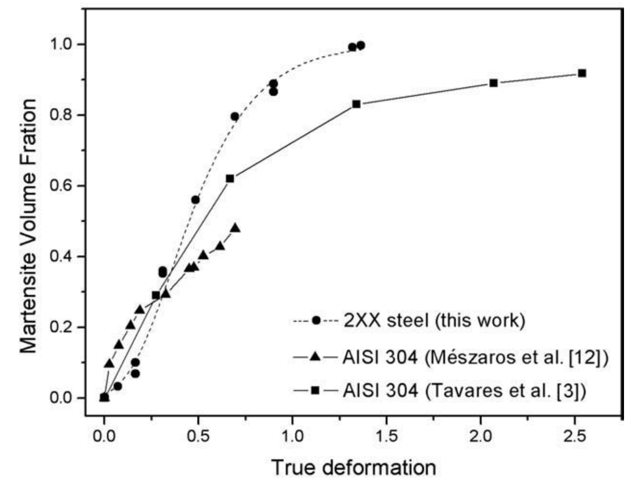

Fig. 7 – Martensite volume fraction *versus* true strain (ε) curves comparing the behavior of martensite formation of the austenitic 201Mod stainless steel and two previous works on AISI 304 steels [3,12].

Deriving Eq. (4) relative to strain, an expression for the transformation rate ($dC_{\alpha'}/d\varepsilon$) can be obtained, as follows:

$$\frac{dC_{\alpha'}}{d\varepsilon} = \left(n\cdot e^{(-n(\varepsilon-K))}\right)\cdot\left(C_S\cdot e^{-e^{(-n(\varepsilon-K))}}\right) \quad (5)$$

A plotting showing $dC_{\alpha'}/d\varepsilon$ *versus* true strain is shown in Fig. 6. The maximum rate of transformation is obtained at the inflection point of the sigmoidal curve, which corresponds to $\varepsilon=0.34$.

Fig. 7 shows the comparison amongst 201Mod steel and previous results on AISI 304 steels [3,12]. The initial rate of transformation is higher in AISI 304 steels, but becomes lower with the progress of deformation. This is a consequence of the lower stacking fault energy seen on the 201Mod steel, as compared to AISI 304. Another difference between the two steel grades is the work hardening behavior, as can be

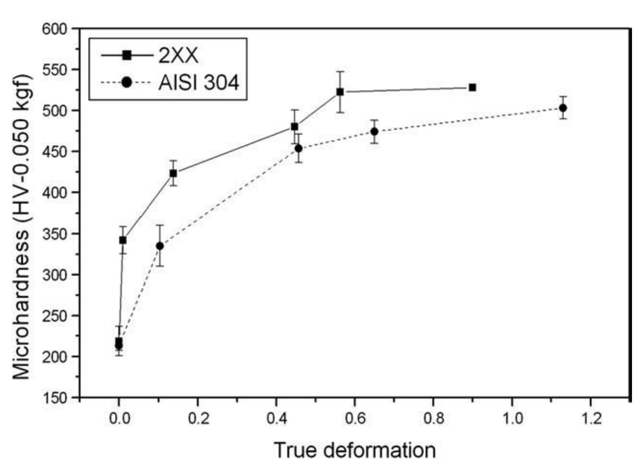

Fig. 8 – Microhardness *versus* true deformation curves for AISI 304 and 201Mod steels.

observed in the microhardness *versus* true strain curve shown in Fig. 8. The 201Mod work hardens more than the AISI 304 steel, due to manganese addition and also to its higher susceptibility to martensitic transformation.

4. Conclusions

The investigation of martensitic induced transformation in a 201 modified stainless steel with composition Fe–15%Cr–7.07% Mn, 1.6% Cu allows the following conclusions to be made:

- The 201Mod steel forms ε martensite in the initial stage of cold deformation. A great amount of α' martensite is formed with the increase of deformation.
- The magnetization saturation of martensite of the 201 modified steel investigated was found to be 140 Am^2/kg. Martensite volume fractions can be determined by magnetization saturation (m_s) measurements using the expression $MVF = m_s/140$.
- The variation of the martensite volume fraction with the amount of true strain was modeled by a sigmoidal curve. The constants of the fitted equation were determined and a good correlation coefficient ($R^2 = 0.993$) was found. The rate of martensitic transformation was obtained by derivation. The maximum rate of transformation was achieved at a true strain of 0.34.
- The comparison among the results of 201 modified steel with previous results on AISI 304 suggests that the initial rate of transformation is higher in AISI 304 steels, but becomes lower with the progress of deformation, which is probably a consequence of the lower stacking fault energy of the 201 modified steel.
- The 201 modified steel work hardens more than the AISI 304, due to the manganese addition and also to its higher susceptibility to martensite formation.

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