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Effect of copper on strain-induced martensite and the parameters that simulate the stress-strain curve of an austenitic stainless steel AISI 304

L.C.M. Gilapa [a,*], C.A.S. Oliveira [b], M.R. Silva [c]
[a] Federal Institute of Santa Catarina, Pavão 1337 street, Joinville, Brazil
[b] Federal University of Santa Catarina, Bairro Trindade 88040-970 Florianópolis Santa Catarina, Brazil
[c] Federal University of Itajubá, Avenida Bps 1303, 37500-903 Minas Gerais, Brazil
* Corresponding e-mail address: leonidas@ifsc.edu.br

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ABSTRACT

Purpose: This study examined the effect of copper on the phase transformation (γ → α´)-induced by the deformation and in the variables of the equation that simulates the stress- equivalent strain curve.
Design/methodology/approach: The phase transformation (γ → α´) was studied through the magnetic properties using a vibrating sample magnetometer - VSM. The simulation of the stress-equivalent strain curve was performed using the obtained results in experimental studies, using the commercial software Maple.
Findings: It was observed that the addition of copper in the austenitic stainless steel (ASS) AISI 304 promotes increased stability of the austenite, slowing therefore, the formation of martensite induced by deformation. It was also observed that the addition of copper influences on the values of the variables of the equation that simulate the stress-equivalent strain curve.
Research limitations/implications: The stress-equivalent strain curve was simulated satisfactorily, however it was observed that the equation that simulates the curve displays values of the variables not usually found, this may be due to the approximations made in applying the rule of mixtures.
Practical implications: It was observed that with the increase of copper, the ASS tend to increase the stability of the austenitic phase, which implies a delay in hardening of the material and a probable influence on the variables of the equation that simulates the stressequivalent strain curve.
Originality/value: The influence of copper on the formation of magnetic martensite (α´) and consequent influence in obtaining the variables of the equation that generates the stress-equivalent strain curve.
Keywords: Austenitic stainless steels; Plastic deformation, TRIP effect; Simulating the stress-strain curve

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1. Introduction

Austenitic stainless steels (ASS) can be used in applications where high resistance and good formability are required, characteristics that can be obtained in metastable ASS. These can undergo transformation of the initial austenite (γ) and FCC into martensite (ε), paramagnetic HCP or into ferromagnetic martensite (α) BCC by plastic deformation at temperatures below M_d. M_d, this the maximum temperature in which occurs the formation of martensite α´ induced by plastic deformation. The phase transformation causes in the material an increase of the mechanical resistance, ductility (increased drawability) and variation in initial magnetic behaviour The increased plasticity, caused by the formation of martensite, is known as TRIP effect (Transformation Induced Plasticity) [1].

The phase transformation in Krupp et. al opinion [2], can comply with the sequence γ→ε→α´ under conditions of low levels and deformation rates or with high levels of deformation, according to the sequence γ→α´ as suggested by several authors [3-5]. The stacking-fault energy (SFE) is an important parameter that influences the formation and the amount of martensite ε e α´ specifically the intrinsic SFE [6]. It has been reported that the martensite ε can be formed when the intrinsic SFE is less than 20 MJ/m^2 . According to Krupp et. al. and Hausild et. al. [2,7] martensite α´ nucleates in materials around 20 mJ/ m^2 SFE.

The addition of copper in the ASS increases the SFE of the austenite, promoting a decrease of the parameter that assesses the stability of the asutenita's (M_{D30}) deformation, decreases the rate of hardening by deformation and reduces the formation of the martensite ε [8-10].

The increase of the yield strength and of the ASS resistance is due to the transformation of austenite (γ) into magnetic martensite (α´) and the hardening of the phases present-induced deformation of the material. This increase can be directly related to the volume fraction of each phase (γ and α´). The term law of mixtures usually refers to the expression that contains the relative contribution of the mechanical properties of each phase (γ and α´) on the mechanical properties of the mixture of constituent phases [11].

It has been experimentally shown that the resistance to traction of a two-phase steel (ferrite and martensite) σ_c increases linearly with the variation of volume fraction of phases, which is given by the law of mixtures, Equation 1 [12,13]:

$$\sigma_c = \sigma_\alpha (1 - V_m) + \sigma_m V_m \quad (1)$$

Where: σ_α is the resistance of the ferrite, σ_m is the resistance of the martensite, and (1-Vm) and V_m are the volume fractions of ferrite and martensite, respectively.

The present study aims to examine the effect of copper on the martensitic transformations and the influence of martensite and strain hardening in the simulation of curve tension - equivalent deformation for the ASS AISI 304, using for this the law of mixtures applied to low carbon dual-phase steels.

2. Materials and experimental procedure

In this study were studied two austenitic stainless steel AISI 304 whose chemical composition is shown in Table 1. The 304H steel with low copper content and the steel 304N with copper content equal to 1.56% by weight.

2.1. Nakajima test

The Nakajima test was performed according with standard ASTM E2218-02, in order to deform test specimens and obtain various paths of deformation [14]. The deformations obtained in the test specimens were converted to equivalent deformation (ε_{eq}) using the Equation 2.

$$\varepsilon_{eq} = \sqrt{\frac{2}{9}\{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\}} \quad (2)$$

2.2. Magnetic measurements

For the magnetic characterization it was used a vibrating sample magnetometer - VSM (Lake Shore mod. 7400), aiming to obtain the maximum magnetic inductor field of each sample. Samples with 8 mm diameter were subjected to a magnetic field inducing maximum (±) 14000 G with a frequency of 60 Hz at room temperature.

To determine the volume fraction of martensite - α´, $V_{\alpha'}$(%) it was used the Equation suggested by [15]:

$$V_{\alpha'}(\%) = (4.\pi.\sigma'_S).100/10^4\sigma_S \quad (3)$$

Where: σ'_S is the magnetic saturation of the tested sample in VSM and σ_S is the magnetic saturation of the sample considering the total transformation into martensite α'. σ_S was calculated using the Equation (4) obtained from the Slater-Pauling curve [15]:

$$\sigma_S \text{ (Tesla)} = \{2.2 . (1 - x - y) + 0.6x\}. 1.003 \quad (4)$$

Where: x and y are the mole fractions of Ni and Cr, respectively.

Table 1.
Chemical composition of steels 304H and 304N

Steel	C	Mn	Si	P	S	Cr	Ni	Mo	Al	Cu	Co	V	Nb	Ti
304H	0.063	1.007	0.48	0.030	0.003	18.270	8.100	0.057	0.0029	0.0950	0.048	0.046	0.011	0.0065
304N	0.038	0.884	0.46	0.033	0.003	18.020	8.060	0.072	0.0045	**1.5690**	0.115	0.047	0.015	0.0071

2.3. Simulation of stress-strain curves

To simulate the stress-strain curve obtained in the tensile test were used results of tests performed, processed in a Maple commercial software . The used results and how they were used are mentioned below for both steels:

- The stress-strain curves obtained in tensile testing [16] were converted into equivalent stress-strain curves using the Equation 2,
- There were obtained the equations of the curves approximating the points obtained from the magnetic variation of the martensite (percentage) with equivalent deformation,
- It was set up the equation that simulates the equivalent stress-strain curve, using the rule of mixtures, considering the yield strengths of austenite, magnetic and paramagnetic martensite, and the strain hardening behaviour of the material;
- In the previous section it was performed the simplification of the quoted equation, considering the results of tests performed in this work and the conditions of the tests;
- The simplified equation has three variables named A (yield stress of martensite α´), K (plastic constant of resistance) and "n" (strain hardening coefficient),
- Starting from the simplified equation and the equation that generates the curve of the evolution of magnetic martensite, there were assembled three equations in order to calculate the variables mentioned in the previous item,
- The equations were solved in the Maple commercial software and, after the processing, there were obtained the values of variables.

3. Results and discussions

The volume fraction of martensite α' for the ASS 304H and 304N, was calculated based on the results obtained in the magnetic characterization, using the Shimozono Equation (2). Fig. 1 shows the variation of volume fraction of martensite α' in function of the equivalent strain for both steels.

It can be observed in Fig. 1, a parabolic growth tendency of the steel 304H. In the case of the steel 304N it presents a initially horizontal linear tendency until an equivalent deformation equal to 0.25. From that point, there is a logarithmic growth of martensite α 'with increasing equivalent deformation. This behaviour was also observed by other authors [3,8,17].

Comparing the volumetric fraction of the steel 304N and 304H, it can observed that the second quoted material formed more martensite than the first. The results show that the steel's 304N austenite is more stable. This increased stability is associated with the difference in chemical composition between the two steels, which promotes significant change in temperature of the M_{d30} parameter (parameter that evaluates the stability of austenite). It should be also noted that the steel 304N has a copper content of 1.56%. According to the equation proposed by Talonen et. al. [3], in these two ASS, the term that most contributes to the stability of the austenite is related to the copper content. The value of M_{d30} calculated [16] using the Equation proposed by Talonen et. al. [3], was 18°C and -7.6°C for steels 304H and 304N, respectively.

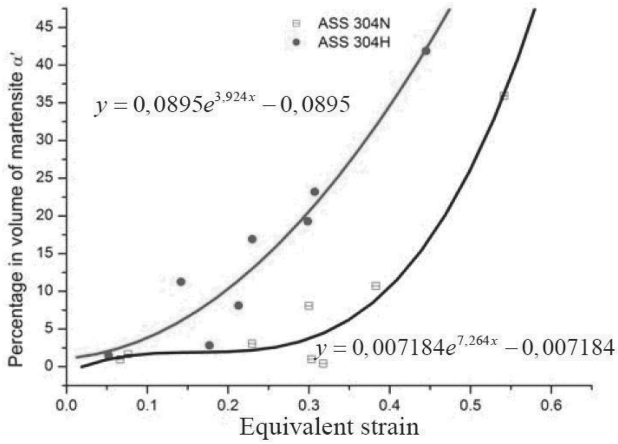

Fig. 1. Variation of the martensite's α´percentage in function of the equivalent deformation for the steels 304H and 304N

The transformation of austenite into ferromagnetic martensite or paramagnetic was characterized by X-ray diffraction by Gilapa [14]. The results showed a partial transformation of the austenite into ferromagnetic (α') and paramagnetic (ε) martensite. So the percentage of martensite α' can be considered equivalent to that observed in the magnetic analysis (Fig. 1) for both steels. Regarding paramagnetic martensite (ε) it remains constant during the deformation process and is approximately equal to 5% for both studied steels [14].

In order to assess the individual effect of martensitic transformation (ε and α´) and the strain hardening in the hardening of these steels it was developed the Equation 5 using the concepts of the rule of mixtures. This rule allows to analyse the individual effect of these parameters, and was used in order to simulate the behaviour of the curve tension - equivalent deformation, now considering the evolution of the martensitic transformation in function of equivalent strain, shown in Fig. 1.

The yield stress for the ASS 304H and 304N can be described according to the rule of mixtures, Equation 2. This Equation allows to make an individual assessment of each term and can evaluate the effect of the chemical composition of the material on the mechanical properties.

$$\sigma_{esc} = (\%M\alpha')*(\sigma_{0\alpha} + K_\alpha \varepsilon_\alpha^{n_\alpha}) + C\times(\sigma_{0HCP} M\varepsilon_{HCP} + K_{HCP}\varepsilon_{HCP}^{n_{HCP}}) + D(\sigma + K\varepsilon^n) \quad (5)$$

where:

- (%M α´) = Variation of martensite (α´) with equivalent deformation,
- ($K_\alpha \varepsilon_\alpha^{n\alpha}$) = Variation in yield strength with strain hardening of martensite (α´),
- C = % of martensite ε_{HCP} in each state of equivalent deformation,
- $\sigma_{0\,HCP}$ = Effect of martensite ε_{HCP} on yield strength,
- ($K_{HCP}\varepsilon_{HCP}^{nHCP}$) = Variation in yield strength with strain hardening of martensite ε_{HCP};
- D = Variation of austenite with deformation;
- $K\varepsilon^n$ = Variation in yield strength with strain hardening of martensite (α´).

To simplify the Equation (5) there were made the following considerations:

- In the elastic limit, D=1 and $\sigma = \sigma_{esc}$;
- (%M α´), Equation that describes the increase of martensite (α´) with the equivalent deformation (Fig. 1) for both ASS 304H and 304N;
- The term: $C \times (M\varepsilon_{HCP} + K_{HCP}\varepsilon_{HCP}{}^{n_{HCP}})$ it was not considered in the final equation because:
- Note that the martensite ε_{HCP} may have been formed during cooling or during the manufacturing process, remaining constant during the deformation process [14];
- The percentage of paramagnetic martensite exists in the material (5%), it should not have significant influence on the mechanical properties [18].
- ($K_{\alpha}\varepsilon_{\alpha}{}^{n\ \alpha}$), considered as constant and equal to "A";

There were also carried out the following additional considerations:

- There was obtained the curve tension - deformation of the tensile test as an equivalent curve tension - equivalent deformation;
- The strain hardening of the austenite is given by the equation of Hollomon.

The final Equation turns into the Equation (6):

$$\sigma_{esc} = A(\%M\alpha') + (1 - \%M\alpha')(\sigma + K\varepsilon^{n}) \qquad (6)$$

Through the simplified Equation (6) were obtained the variables A, K and n, using the Maple software. For this purpose, were used the Equations of the variation's curves in the percentage of magnetic martensite with the equivalent deformation (Fig. 1). The results shown in Fig. 2 represent the surfaces generated by the equations, and the result is the intersection of these surfaces.

It can still be observed in Fig. 2 that for low values of equivalent deformation and subsequent percentage of magnetic martensite, the Equation becomes quite unstable, while for high values of equivalent deformation (above 0.30) the Equation becomes more stable.

Substituting the incognitos values of Table 2 in the Equation 6, there can be obtained the curves shown in Fig. 3a for the steel 304N and 3b for the stainless steel 304H. It can be observed for both steels, that the curve tension - equivalent deformation obtained by tensile test (solid line) is adequately simulated by the curve (dashed line) obtained by the suggested equation. It may also be noted that the curves in the figure reflect the sum of the strain hardening and phase shift of the material, shown in Equation 6.

Analysing the Equation 6 and the obtained curves in Fig. 3, it can be said that the formed magnetic martensite causes an increase in values of maximum voltage and at the same time a shift to the right of maximum tension. These results confirm the characteristic of steels with phase change that causes an increase in mechanical strength and ductility by plastic deformation.

The A, K and n values are presented in Table 2:

Table 2.
A, K and n values for the ASS 304H and 304N

Variable / ASS	A (MPa)	K (MPa)	n
304H	600	850	0.58
304N	150	800	0.6

a) b)

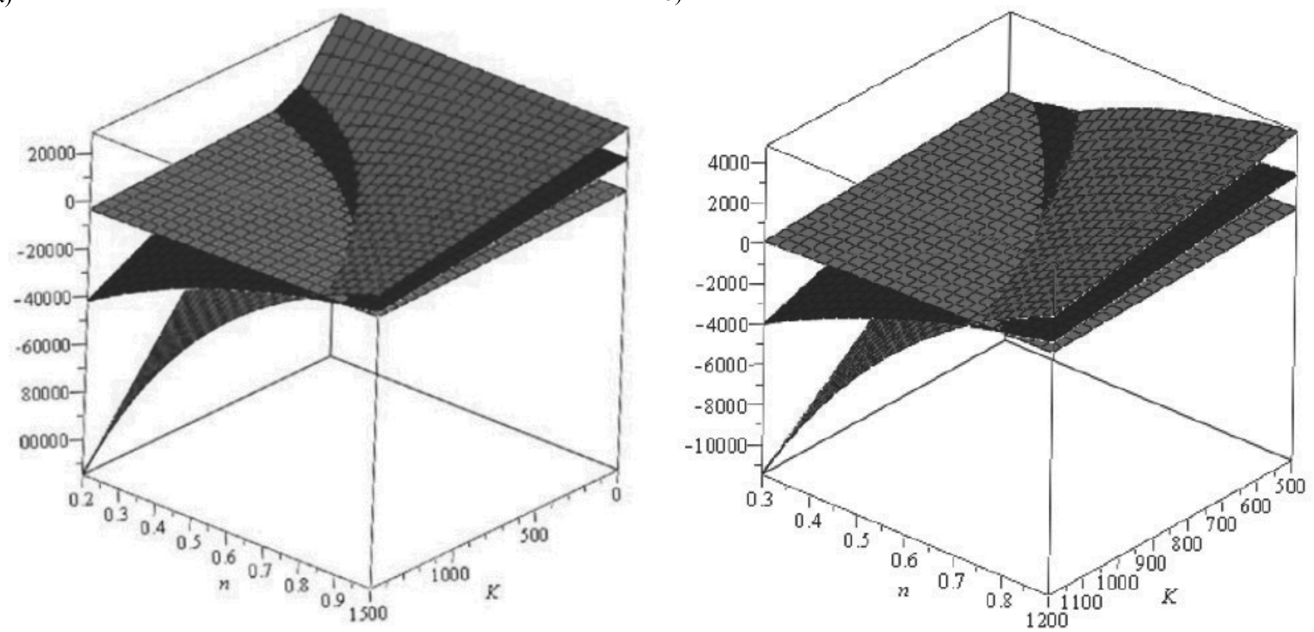

Fig. 2. Surfaces generated by the equations in the commercial software Maple a) steel 304N and b) steel 304H

a) b)

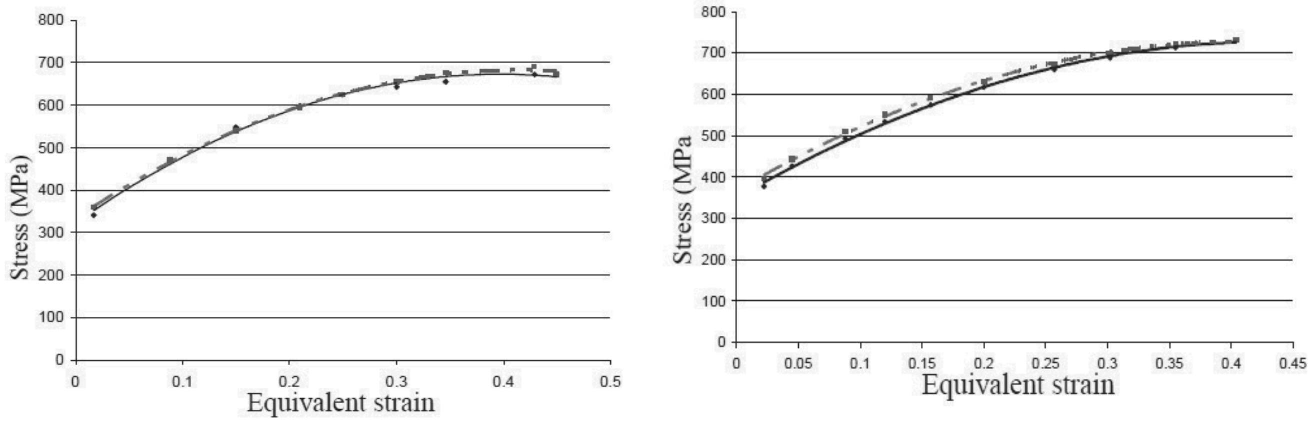

Fig. 3. Stress-strain curve equivalent obtained by traction assay (solid line) and simulated by the Equation 6 (dashed line), (a) for the ASS 304 N and (b) ASS 304H

4. Conclusions

In this study the effect of copper on the martensitic transformations and their influence on the values of variables that simulate the curve tension - equivalent deformation were studied. Based on the results the following conclusions can be observed:

- For the same equivalent strain values, it is obtained a greater percentage of martensite α in steel 304H than in the steel 304N. This fact is attributed to the difference in copper content between the two steels, which changes the temperature M_d.
- The approximation of curve tension - deformation for both steels, using the rule of mixtures, had satisfactory approximation. However, the values of the variables "A" (yield strength of martensite α´) and "n" (coefficient of strain hardening of austenite) in Maple software presented unexpected values, which may be due to approximations made in the Equation.
- The portion corresponding to the magnetic martensite in the Equation in 6 causes an increase and shift to the right of the maximum voltage of the equivalent stress-strain curve.

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