STRAIN AGING IN AISI 304 STAINLESS STEEL

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Abstract. *The control of static and dynamic strain aging in the thermomechanical processing of steels is receiving increasing attention due to their practical consequences, which determine the formability and/or the behavior in service of this class of materials. The studies in this area aim to optimize the potential of strain aging to increase the strength and/or to minimize the effects of this process related to the decrease in ductility, which compromises the material's performance in forming operations. The amount of strain-induced martensite (α'-martensite) affects the maximum increase in the yield strength and the more α'- martensite is present, the higher values are obtained. However, the combined action of temperature increase and the strain applied during the forming operation can lead to strain aging of the martensite, which compromises the material's performance in the forming press. The aim of the present work was to evaluate the effects of temperature in the strain aging susceptibility of strain-induced martensite in AISI 304 stainless steel. Static strain aging of austenitic stainless steel AISI 304 was investigated by means of uniaxial tensile tests and the fraction of α'-martensite was determined by X-ray diffraction. According to the results, strain aging occurs in this class of material and is associated mainly with increase in yield strength. The α'-martensite content remained unaffected by the aging heat treatment and the presence of strain-induced martensite is necessary for the manifestation of strain aging phenomenon.*

Keywords: *strain aging, strain-induced martensite, austenitic stainless steel.*

1. Introduction

It is well known that one of the factors responsible for the good stretch formability of AISI 304 stainless steels is the transformation of metastable austenite to martensite during deformation (Pickering, 1976; Rintamaa and Sulonen, 1982; Llewellyn, 1997; Lewis *et al.*, 1999; Lebedev and Kosarchuk, 2000). The formation of strain-induced martensite (α'-martensite) significantly affects the mechanical behavior of austenitic stainless steels by enhancing work hardening. The extend of α'-martensite transformation depends on chemical composition of the steel, deformation temperature and the extent of plastic strain (Mészáros *et al.*, 1996; Nohara, 1997; Gonzalez *et al.*, 2003; Talonen *et al.*, 2005).

Austenitic stainless steels AISI 301 are known to exhibit dynamic strain aging and the short range ordering in a α'-martensite is the mechanism responsible for these effects (Boratto and Gonzalez, 1982). Mangonon and Thomas (1970) applied tensile deformation to AISI 304 steel samples at -196ºC and performed aging treatments at temperatures up to 500ºC. The pronounced increase in yield strength after the heat treatment, was found a function of the aging temperature and was proportional to the amount of volume fraction of martensite. The martensite formation has been attributed to a local increase in the Ms temperature caused by a depletion of chromium and carbon in the surrounding matrix due to precipitation of fine carbides.

Matlock *et al.* (2000) studied strain aging behavior of pre-deformed AISI 301, 302 and 305 stainless steels at temperatures ranging between 100ºC and 600ºC. Low temperature aging at austenitic stainless steels containing strain-induced martensite increased the yield strength and a peak aging temperature of 300ºC was observed. The strength increase occurs with no change in volume fraction of martensite. Talonen *et al.* (2004) also studied the strain aging of stainless steels containing strain-induced martensite. According to their results, strain aging occurs in austenitic stainless steel only when strain-induced α'-martensite is present in the material and the more α'-martensite is present, the higher values of upper yield strength were obtained. They showed that α'-martensite remains unaffected by the aging heat treatments and the austenite stability seems to be unaffected by the aging. According to the authors the strain aging process of these materials involves the re-distribution of nitrogen and carbon atoms in strain-induced martensite.

There is no reference in the literature about static strain aging in strain induced martensite in AISI 304 stainless steel. Talonen *et al.* (2004) have studied this phenomenon in metastable AISI 301 stainless steels, but the calculated activation energies found by the authors (around 130 kJ/mol) have shown that the process was evaluate in austenitic phase, not in strain induced martensite as they have discussed. Matlock *et al.* (2000) also studied the strain aging behavior of austenitic stainless steels containing strain induced martensite and have found activation energies around 7 – 14kJ/mol, which is certainly about the activation energy for static strain aging in martensite. So, it's interesting to evaluate this phenomenon in metastable AISI 304 stainless steel. The aim of the present work was to evaluate the effects of temperature in the strain aging susceptibility of strain-induced martensite in AISI 304 stainless steel and study the possibility of improving the mechanical strength of cold worked AISI 304 austenitic stainless steels aged at temperatures around 200ºC.

2. Experimental procedure

The test material used in the investigation was industrially manufactured austenitic stainless steel grade AISI 304, received in the form of 0,6mm thick sheets and annealed condition. The chemical composition of the material is shown in Tab. 1.

Table 1: chemical composition of the steel investigated (in wt. %)

C	N	Ni	Cu	Cr	Mo	Mn	Si	Co
0,027	0,0407	8,9	0,112	18,26	0,039	1,086	0,54	0,064

Phase analysis and volume fraction of α' - martensite (VFM) in the specimens was performed by using X-ray diffraction (XRD). Samples with 2,0 x 2,0mm were cut out from gauge length of the test materials and measurements were made on a Philips PW1710 diffractometer using Cu-Kα radiation. During the tests a measuring range between 40-90º and a stepsize of 0,02º was used.

For the tensile tests, strips of 25 mm in width and 180 mm long were cut from the received sheets and machined in rolling direction according to ASTM E8M-97 standards. The pre-straining, of 30% was performed in an Instron 5581 testing machine equipped with a controlled temperature chamber, at a strain rate of 2,0 x $10^{-3}s^{-1}$, at a temperature of -15º. The aging treatments were performed between 100 and 200ºC at 30 minutes. Mechanical agitation in the circulating bath, allied to a comparatively large bath volume (eight liters), rendered appropriate temperature stability, maximum variations being less than ± 1ºC. After the aging treatments the specimens were cooled in water at room temperature and stored at -10ºC to avoid natural aging. For the same reason, between pre-straining and aging, specimens were also kept at -10ºC. The specimens were tensile-tested until failure and the strain was measured with an axial extensometer. The mechanical properties of these materials were evaluated in terms of the 0,2 percent offset yield stress ($\sigma_{0,2}$), the ultimate tensile strength (UTS), the uniform elongation (e_U), and total elongation (e_T), as the average of three tensile tests, made on the same conditions. The progress of strain aging was evaluated by the change in these properties with the aging temperature.

3. Results and discussion

The mechanical properties and volume fraction of martensite (FVM) of these materials at room temperature and pre-strained are shown in Tab. 2, the changes in mechanical properties are associated with austenite strain hardening and strain-induced martensite. There is essentially no change in VFM at aging temperatures up to 200ºC.

Table 2: mechanical properties and volume fraction of martensite of not aged state of AISI 304 steel.

Material	$\sigma_{0,2}$ (MPa)	UTS (MPa)	e_u (%)	e_T(T)	FVM (%)
As-received	294	676	61,1	64,7	-
Pre-strained	930	1030	16,2	18,0	60%

In Fig. 1 the effect of aging temperature on the $\sigma_{0,2}$ is shown for samples aged for 30 minutes. The percentual increase in $\sigma_{0,2}$ at the maximum temperature was 24%, comparing with not aged state, might be attributed to pinning of dislocations caused by carbon and nitrogen atoms (Matlock et al., 2000).

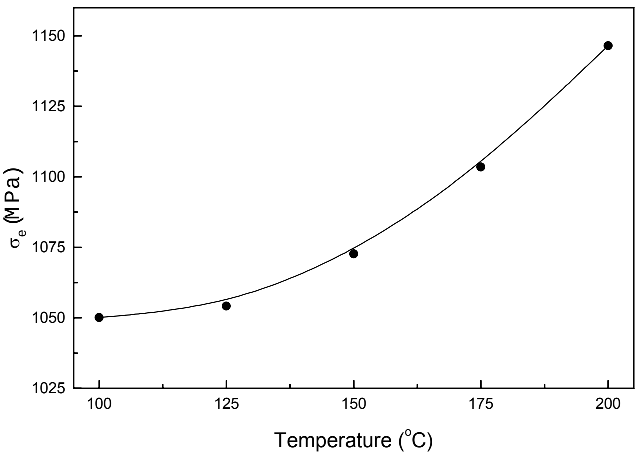

Figure 1: Effect of aging temperature on de 0,2% offset yield strength of AISI 304 steel. Samples aged 30 minutes.

The increase in UTS as a function of temperature is shown in Fig. 2. It can be seen that UTS also increases with the increase of aging temperature by 12% comparing with not aged state and it seems to tend to saturation level above 200ºC. The less intense variation in UTS with aging temperature, compared with $\sigma_{0,2}$, and tending to saturation level in lower temperature is typical of strain aging phenomenon in low carbon steels (Matlock et al., 2000; Leslie, 1982), that is another evidence that the effects observed in the Fig. 1 and 2 are associated to carbon and nitrogen interaction with dislocations in strain aging of martensite.

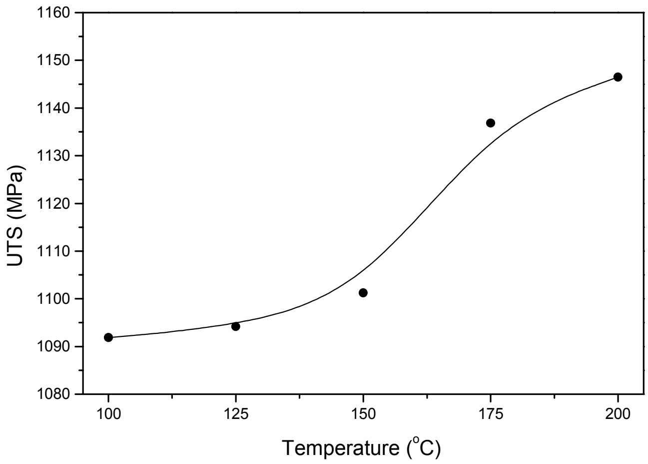

Figure 2: Effect of aging temperature on de ultimate tensile strength of AISI 304 steel. Samples aged 30 minutes.

Figure 3 shows the variation in uniform elongation and total elongation as a function of aging temperature for the pre-strained steel. Another characteristic aspect about strain aging in low carbon steel is observed in this figure: the minimum value in uniform elongation and total elongation with aging temperature although in the strain aging of martensite in an AISI 304 this effect is sharper, compared with low carbon steels in which the minimum elongation in the most severe conditions is about 10% (Leslie, 1982; Dieter, 1986).

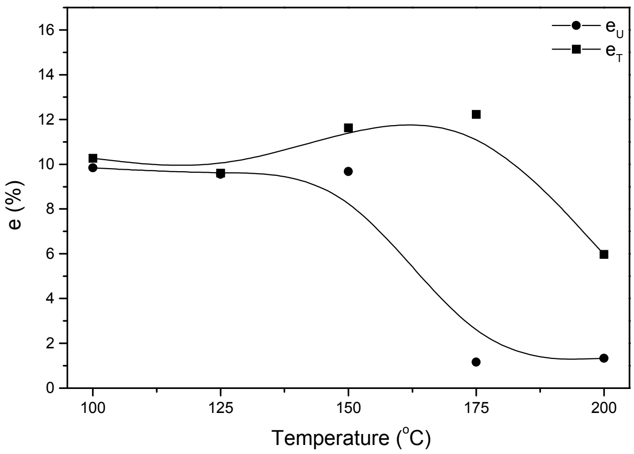

Figure 3: Effect of aging temperature on the uniform and total elongation of AISI 304 steel. Samples aged 30 minutes.

In the present work, the minimum value in the uniform elongation was more pronounced, which in the deep drawing operations involving stretch decreases the drawability of steel.

4. Conclusions

The aging of stainless steel containing strain-induced martensite shows significantly increase in mechanical properties compatible with the strain aging characteristics observed in low carbon steels. The maximum increasing in ultimate tensile strength and the maximum decreasing in ductility properties associated with martensite strain aging in AISI 304 steel occur at 200ºC in a treatment time of 30 minutes. The strain aging of martensite in this class of materials affects significantly the uniform elongation which compromises the material's performance in forming operations suggests the importance of the control of strain aging during drawing. There is essentially no change in VFM at aging temperatures up to 200ºC.

5. Acknowledgements

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