Static strain aging of stabilized ferritic stainless steels

M. Palosaari, T. Manninen, R. Toppila, T. Kauppi

Static strain aging (SSA) of stabilized ferritic stainless steels of type 1.4509 (AISI '441') and 1.4521 (AISI 444) was investigated. The test materials were prestrained to a 5% tensile elongation and subsequently aged at low temperatures ranging from 150°C to 250°C for 1800 seconds. The results show that stabilized ferritics are indeed susceptible to static strain aging. The elevated yield point returned in both grades aged above 200ºC. Furthermore, strength increments in the order of 50 MPa were achieved. This indicates that strain aging might be used as a hardening mechanism for this type of steels.

Keywords:
Ferritic stainless steel; Bake-hardening; Stabilization; Static strain aging; 1.4509; 1.4521

INTRODUCTION

The Static strain aging (SSA) is a fairly general phenomenon in metals. Static strain aging restores the elevated yield point, increases both yield and tensile strength and decreases ductility. These changes are schematically illustrated in Figure 1.
SSA occurs in steels containing interstitial elements such as carbon or nitrogen in solid solution. The interstitial elements segregate near dislocations thus inducing dislocation pinning. The strain aging phenomenon can take place in two stages. The first stage is Snoek rearrangement of interstitials and formation of solute atmosphere around dislocations. Depending on the concentration of interstitials, the first step may be followed by a formation of discrete clusters or precipitates. It is now universally accepted that the strain aging process can be explained with the Cottrell-Bilby theory [1].
Unstabilized ferritic stainless steels are known to be susceptible to SSA [2, 3]. Consequently bake-hardening is one possible hardening mechanism for this type of steels. A strength increment of 50 MPa has been reported after 30 minutes heat treatment at 180ºC for 1.4016 (AISI 430). The strength increment was attributed to migration of interstitial carbon to dislocations [2]. A considerably higher strength increment of 200 MPa has been achieved by a combination of cold work and subsequent annealing at the 475°C embrittlement temperature. This strengthening was explained by formation of Cr-rich α'' phase in the dislocations and has been industrially applied for slat-band conveyor chains made of AISI 430 type stainless steel [3, 4].
In stabilized ferritics, free interstitial elements are bound to stable nitrides/carbides by the stabilizing elements such as Nb, Zr and Ti. Therefore, the stabilized ferritics should not be susceptible to a low temperature SSA by formation of atom atmospheres around dislocations. In short, stabilized ferritics are believed to be non-strain aging materials. However, experimental results

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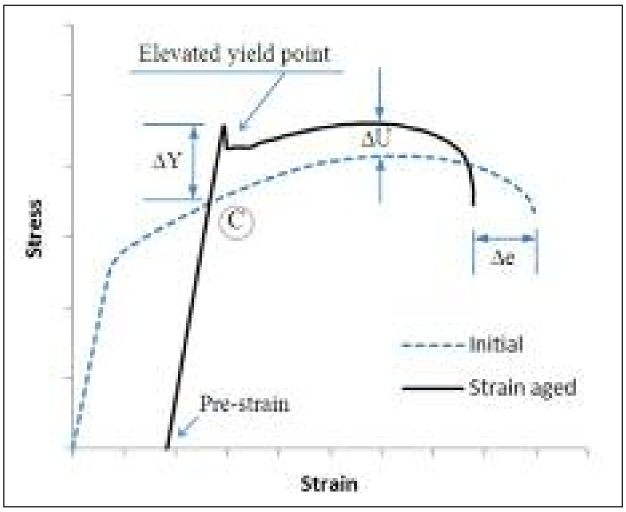

FIG. 1 ***The influence of strain aging on the stress-strain curve of skin-pass rolled steel. The elevated yield point is restored, both yield and tensile strength increase by ΔY and ΔU, respectively, and the total elongation decreases by Δe. In the absence of strain aging, the stress-strain curve of the pre-strained material would join the initial curve at the point C.***

Influenza dell'invecchiamento per deformazione sulla curva tensione-deformazione di acciaio laminato mediante processo skin-pass. L'alto limite di snervamento è ripristinato, sia il carico di snervamento che la resistenza meccanica aumentano rispettivamente di ΔY e ΔU, e l'allungamento totale diminuisce di Δe. In assenza di invecchiamento la curva carico-deformazione del materiale pre-deformato si unirebbe alla curva iniziale in corrispondenza del punto C.

of static strain aging in stabilized ferritics have not yet been reported.
The aim of the present work is to investigate strain aging of stabilized ferritic stainless steels. Commercial stainless steel sheets of 1.4509 and 1.4521–type were used as test materials and an unstabilized grade 1.4016 was used as a reference material. The kinetics of the aging were determined by tensile testing.

TAB. 1
The chemical composition of the test materials (weight-%).
Composizione chimica del materiale di prova (peso %).

Grade	C	Si	Mn	Cr	Ni	N	Ti	Nb	Mo
1.4509	0.021	0.48	0.45	17.8	0.24	0.02	0.11	0.44	0.02
1.4016	0.048	0.28	0.51	16.2	0.26	0.03	0.00	0.00	0.03
1.4521	0.022	0.52	0.55	17.7	0.30	0.02	0.14	0.36	2.00

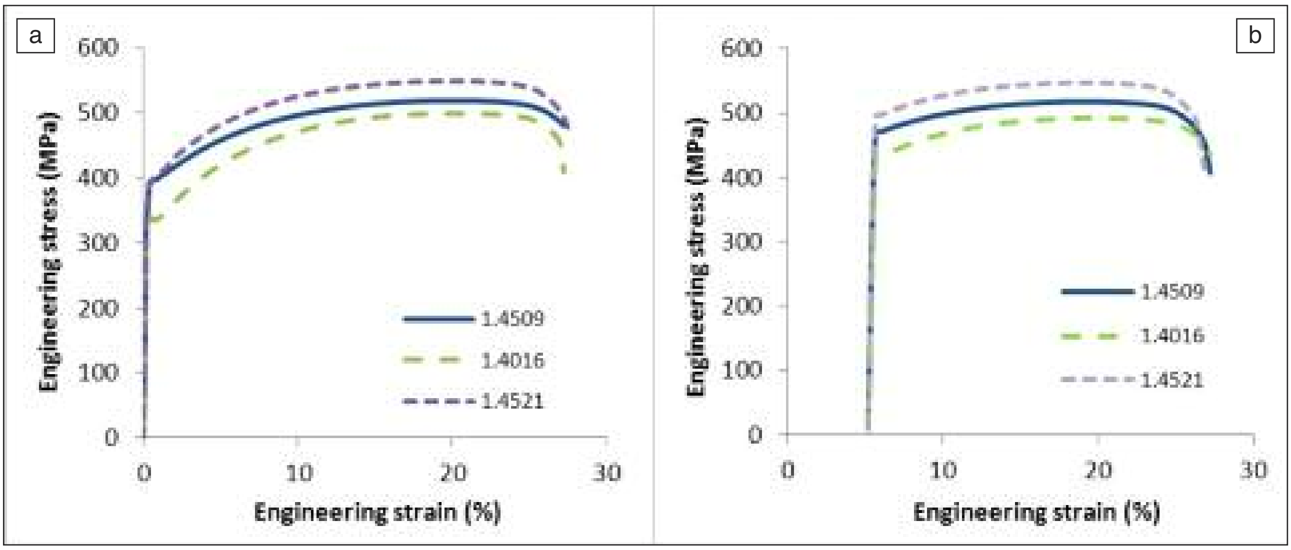

FIG. 2 ***Typical stress-strain curves in the as-received condition a) and after prestraining (b.***
Tipiche curve carico-deformazione a) nella condizione as-received e b).dopo predeformazione.

EXPERIMENTAL PROCEDURE

The test materials were commercial 1.4016, 1.4509 and 1.4521 –type cold rolled ferritic stainless steel sheets with a surface finish of 2B and thickness of 0.8 mm. The chemical composition of the materials is given in Table 1.

The test procedure employed in the present study consists of three distinct stages. In the first stage, the test materials were prestrained to a 5% tensile elongation parallel to the rolling direction. In the second stage, the prestrained materials were aged at a temperature ranging from 150°C to 250°C for 1800 seconds and subsequently quenched to water. After the heat treatment, the mechanical properties were measured by a tensile test. The prestraining and the tensile tests were carried out by means of a Zwick 250kN tensile testing machine with a maximum force of 250 kN. The prestraining and testing were performed according to the specifications of the EN10002 tensile testing standard. During the heat treatment, the annealing temperature was verified by means of three K-type thermocouples inside the oven. The stress-strain curves measured on the prestrained materials were calculated for the average original specimen cross-section and for the initial gauge length. This enables comparison of the curves with the monotonic stress-strain curves measured in the as-received condition.

RESULTS

The stress-strain curves of the test materials in the as-received condition and after the 5% tensile elongation are shown in Figure 2. From those it is clear, that the stress-strain curves measured after the prestraining coalesce with curves measured in the initial state.

The stress-strain curves for materials aged at different temperatures between 150°C and 250°C are shown in Figures 3 - 5. In order to avoid crowding of the results, the curves are displaced by 0.40% along the abscissa. The stress-strain curves show clear evidence of static strain aging. The emergence of the elevated yield point and yield point elongation is a strong indication of static strain aging.

The increase in yield stress $\Delta\sigma$ due to aging is defined as a difference between yield stress of the material before and after the aging treatment. For this parameter, the stress is calculated for the current cross-section of the specimen. The change of this this parameter is shown in Figure 6.

DISCUSSION

In the present work, the static strain aging of stabilized ferritic stainless steels was studied. It is demonstrated that, in contradiction to general belief, stabilized ferritics are indeed susceptible to static strain aging. All signs of SSA, namely emergence of the elevated yield point, an increase in yield and tensile strength accompanied with a decrease in ductility were introduced during annealing of cold-worked material in relatively mild temperatures near 200°C. The strength increment of 30 – 50 MPa achieved by the heat-treatment is comparable to that of the bake-hardenable low carbon steels commonly used in the automotive industry. It follows that bake-hardening might be employed as a hardening mechanism for stabilized ferritic stainless steels in applications where strength increment can be considered as a benefit. On the other hand, the return of the elevated yield point results in propagation of Lüder's bands in subsequent forming steps. This may restrict usability of an intermediate annealing in multistep forming of stabilized ferritics.

The observed strain aging behavior is most likely caused by small amount of interstitial carbon or nitrogen retained in the matrix despite of the stabilization. During annealing the free interstitial C/N atoms diffuse to the previously introduced dislocations effectively pinning them down. In principle, the C and N concentration in solution is determined by the equilibrium partitioning between ferrite and Ti- or Nb -carbonitrides. However, the equilibrium state is only achieved in infinitely slow processes. In practice the amount of C and N in solution is determined

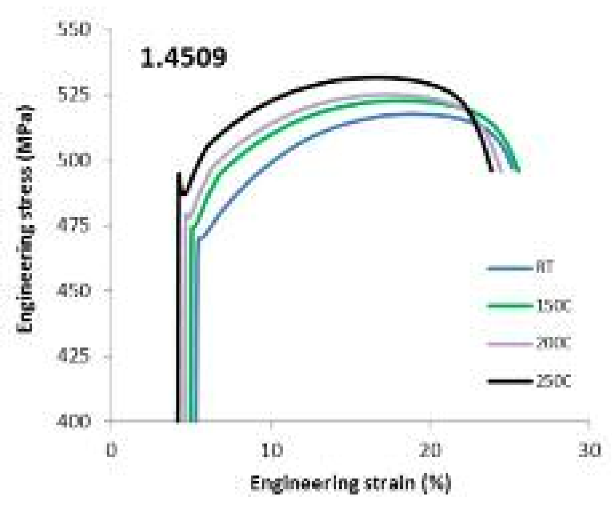

FIG. 3 ***Stress-strain curves for 1.4509 aged at different temperatures. Curves have been displaced by 0.40% along the abscissa to avoid crowding.***

Curve carico-deformazione dell'acciaio 1.4509 invecchiato a diverse temperature. Le curve sono state sfalsate dello 0,40% lungo l'ascissa per evitare la sovrapposizione.

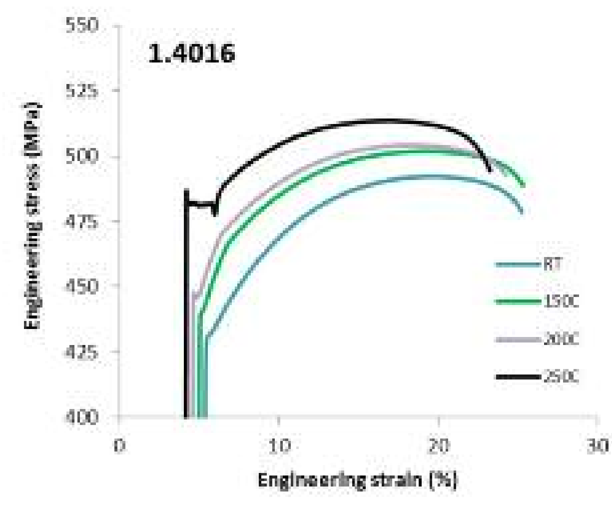

FIG. 5 ***Stress-strain curves for 1.4016 aged at different temperatures. Curves have been displaced by 0.40% along the abscissa to avoid crowding.***

Curve carico-deformazione dell'acciaio 1.4016 invecchiato a diverse temperature. Le curve sono state sfalsate dello 0,40% lungo l'ascissa per evitare la sovrapposizione.

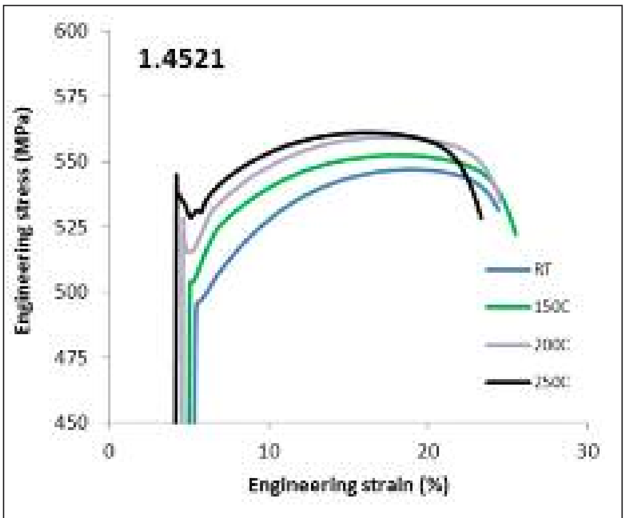

FIG. 4 ***Stress-strain curves for 1.4521 aged at different temperatures. Curves have been displaced by 0.40% along the abscissa to avoid crowding.***

Curve carico-deformazione dell'acciaio 1.4521 invecchiato a diverse temperature. Le curve sono state sfalsate dello 0,40% lungo l'ascissa per evitare la sovrapposizione.

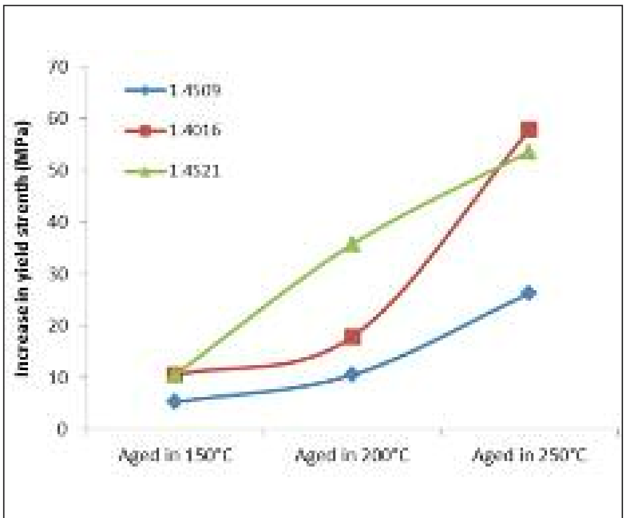

FIG. 6 ***Increase in yield strength due to aging treatment.***

Aumento del carico di snervamento dovuto al trattemento di invecchiamento.

by the kinetics of carbonitride precipitation during the various, rather rapid, heat treatment cycles in stainless steel production. Similar situation holds for ultra-low carbon IF-steels. And as shown by De et al. [5] and Startling et al. [6], ultra-low carbon IF-steels can also be strengthened by bake hardening treatments.
It seems unlikely that the observed aging phenomena would be caused by the formation of Cr-rich α'' –phase in the dislocations, since the α''-precipitation is expected at temperatures above 350°C [7, 8]. Furthermore, the aging time needed for significant age-hardening via carbonitride precipitation is typically in the order of several hours [9].

The results reported herein suggest several topics for future work, including a detailed investigation on the kinetics and on the activation energy of the aging process. Furthermore, direct or indirect measurement of solute concentrations at different stages of the bake-hardening process could also give important information concerning the atomic mechanisms of aging.

CONCLUSIONS

Static strain aging of stabilized ferritic stainless steels of type 1.4509 and 1.4521 was investigated. The results show that that stabilized ferritics are susceptible to SSA. It follows that strain-aging might be used as a hardening mechanism for this type of steels.

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Abstract

Invecchiamento da deformazione statica di acciai inossidabili ferritici stabilizzati

Parole chiave: acciaio inossidabile, invecchiamento da deformazione statica

Nel presente lavoro è stata studiato l’invecchiamento da deformazione statica (SSA) degli acciai inossidabili ferritici stabilizzati del tipo 1,4509 (AISI 441) e 1,4521 (AISI 444). I materiali di prova sono stati predeformati mediante un allungamento a trazione pari al 5% e successivamente sottoposti a invecchiamento a basse temperature comprese tra 150 °C e 250 °C per 1800 secondi. I risultati mostrano che gli acciai ferritici stabilizzati sono effettivamente suscettibili all'invecchiamento per deformazione statica. Per entrambe le composizioni il limite di snervamento è tornato elevato per invecchiamento sopra i 200 º C. Inoltre sono stati ottenuti aumenti della resistenza meccanica dell'ordine di 50 MPa. Questo indica che l'invecchiamento per deformazione potrebbe essere utilizzato come meccanismo di indurimento per questi tipi di acciai.