Communication

Effect of Strain Rate on the Martensitic Transformation During Plastic Deformation of an Austenitic Stainless Steel

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The effect of strain rate on the plastic deformation and phase transformation behavior of metastable austenitic stainless steel EN 1.4318 was studied. Strain rate jump tests were used to distinguish the direct effects of strain rate from the effects of adiabatic heating. Test results are analyzed from the viewpoint of both stress- and strain-induced martensitic transformation.

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The strain rate dependent plastic deformation behavior of metastable austenite containing stainless steels has been widely reported in the literature.[1–5] A common conclusion is that the phase transformation from austenite to α'-martensite is suppressed at high strain rates due to adiabatic heating.[1–5] The reasoning leading to this conclusion is straightforward: continued plastic deformation is needed for the transformation, and during high rate loading there is insufficient time for heat transfer. Thus the heat of deformation work and the latent heat of the martensitic transformation cause an elevation in material temperature that suppresses further phase transformation. This reasoning is valid from the view point of both strain- and stress-induced phase transformations, *i.e.*, whether one considers strain-induced creation of α'-nucleation sites or the increase of flow stress due to strain hardening as the rate controlling mechanism of the transformation. It should be noted, however, that the above-mentioned experimental evidence is mostly based on the comparison of constant strain rate tests, *i.e.*, tests carried out at different strain rates but keeping the strain rate constant during an individual experiment. Thus a question remains what happens if the strain rate is suddenly changed during plastic deformation, since temperature remains essentially constant during such a change.

The above-mentioned question is addressed in this study. Tensile specimens with 2 mm thickness, 4 mm gauge width, and 8 mm gauge length with 2 mm roundings (total length thus 12 mm) were prepared from a heat of EN 1.4318-2B stainless steel produced by Outokumpu Stainless (composition according to the manufacturer: Cr = 17.4 pct, Ni = 6.5 pct, Mn = 1.19 pct, Si = 0.48 pct, Cu = 0.22 pct, N = 0.138 pct, Mo = 0.1 pct, C = 0.023 pct, Fe = bal., grain size 14 μm in terms of mean intercept length). The specimens were tested in uniaxial tension using a servohydraulic materials testing machine for the strain rate region 2×10^{-4} … 1 s^{-1} and a Tensile Split Hopkinson Bar apparatus for strain rates near 1000 s^{-1}. Rapid upward strain rate changes were created by suddenly increasing the displacement rate of the tensile testing machine. Downward strain rate changes were carried out by using a recovery technique in conjunction with the TSHB apparatus (details presented in[6]). This allowed the specimen to be deformed at a high rate to a prescribed strain, after which the specimen was recovered and subsequently (time delay a few days) reloaded with the tensile testing machine at a low rate. The evolution of the α'-martensite content was measured with the magnetic balance method described by Livitsanos and Thomson.[7] In this technique, the force needed to detach a small permanent magnet (cylindrical magnet with 1.5 mm diameter) from the surface of the specimen is measured. Based on calibration measurements, the measured force is a linear function of the α'-volume fraction up to 50 pct martensite.

Two main conclusions can be made from the strain rate change tests. Firstly, positive instantaneous strain rate sensitivity of flow stress was observed even when the comparison between constant strain rate tests indicated a negative apparent strain rate sensitivity. Secondly, the strain hardening rate (measured as the slope of the stress–strain curve) showed a strong connection to the current value of strain rate rather than to the strain rate history. This is illustrated in Figure 1(a), which shows that a rapid increase in the strain rate from 2×10^{-4} to 1 s^{-1} at $\varepsilon_{pl} = 0.1$ leads to an immediate decrease in the strain hardening rate (at $\varepsilon_{pl} = 0.09$ the strain hardening rate is 1800 MPa at 2×10^{-4} s^{-1} and 1500 MPa at 1 s^{-1} while at $\varepsilon_{pl} = 0.11$ the strain hardening rates are in the constant strain rate tests 2700 MPa at 2×10^{-4} s^{-1} and 1600 MPa at 1 s^{-1} and in the strain rate jump test 1800 MPa). Similar behavior was observed also at higher plastic strains. It should be noted that based on in situ temperature measurements as well as on previous literature,[2–5] the low strain rate experiments can be considered isothermal while the higher strain rate experiments are at least macroscopically adiabatic.

A series of interrupted tests was carried out to measure the evolution of the α'-martensite content. The plastic strain of 0.1 was selected as the point of strain rate increase in the jump tests, since around this strain the strain hardening rates observed at different strain rates start to diverge notably from each other (being the higher the lower the strain rate). As seen in

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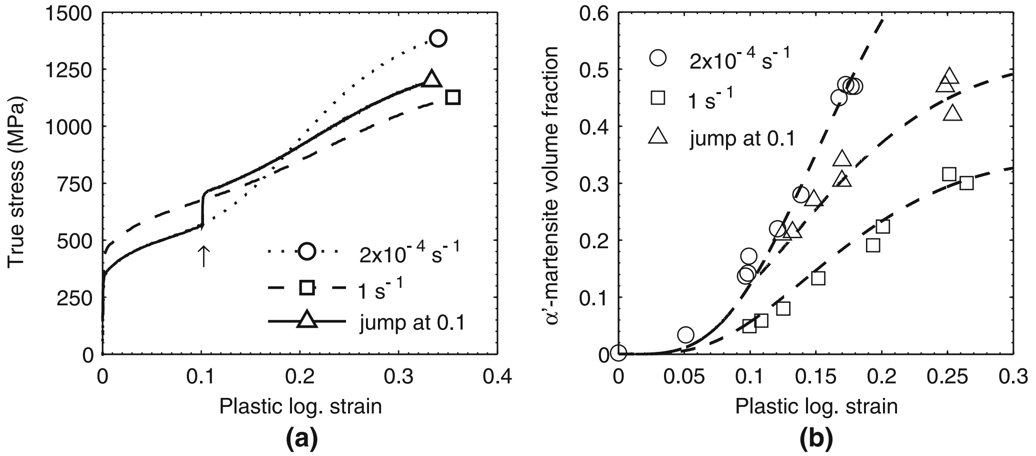

Fig. 1—(*a*) Stress–strain curves obtained in tensile tests at strain rates 2×10^{-4} s^{-1} and 1 s^{-1} as well as in an upward strain rate jump from the lower to the higher strain rate at 0.1 plastic strain (*b*) corresponding evolution of the α'-volume fraction. The dashed lines in (b) represent the modified Olson–Cohen model fitted to the data.

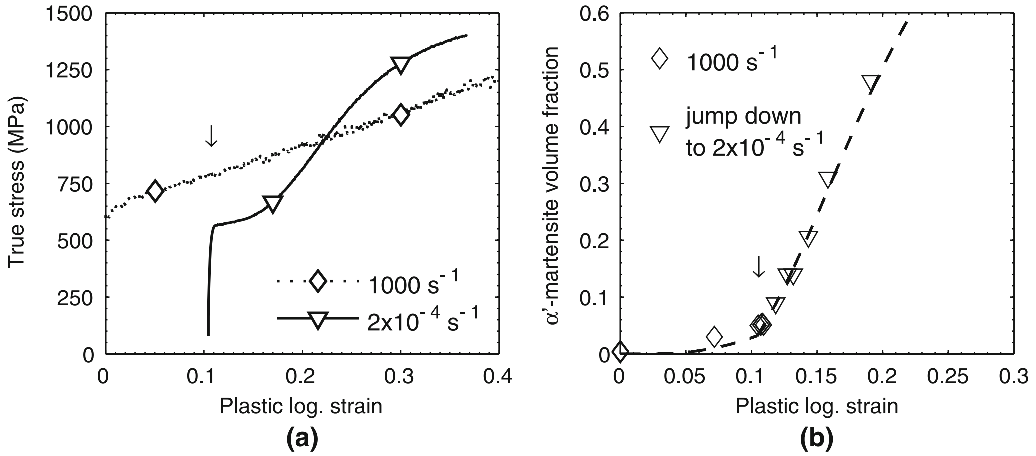

Fig. 2—(*a*) Stress–strain curves obtained in tensile tests at strain rate 1000 s^{-1} and during reloading at 2×10^{-4} s^{-1} after deformation to 0.1 plastic strain at 1000 s^{-1} (*b*) corresponding evolution of the α'-volume fraction. The dashed line in (b) represents the modified Olson–Cohen model fitted to the data.

Figure 1(b), the α'-transformation rate appears to decrease immediately after the strain rate increase. This behavior, which is similar to that of the strain hardening rate, implies that in addition to adiabatic heating there is a direct negative (reducing) effect of strain rate on the α'-transformation.

A second set of experiments was carried out by first deforming specimens to 0.1 plastic strain at the strain rate of 1000 s^{-1} and subsequently reloading them at the strain rate of 2×10^{-4} s^{-1}. Some of the specimens were reloaded incrementally at the low rate with intermittent α'-content measurements, while some of the specimens were reloaded directly to the final plastic strain. This was not found to affect the measured α'-evolution behavior. Figure 2(a) presents an example of the downward strain rate change tests. A remarkable feature is the region of low strain hardening rate in the beginning of the low rate reloading. Figure 2(b) shows that this is connected to a rapid α'-transformation that begins without any apparent "incubation strain". This region of low strain hardening rate is in agreement with previous reports,[3,8] according to which the α'-transformation can actually promote plastic deformation. This leads to low strain hardening rate before the hardening contribution of the α'-particles begins to dominate. A note should be made here: unlike the upward strain rate jumps, the downward jumps are not isothermal, but the heat generated during the high rate loading is transferred to the surroundings before the low rate loading commences. The maximum change in temperature can be estimated by assuming that the work done by plastic deformation is fully converted to heat during the high rate loading. Integration of the flow curve results in a dissipated work of 70 MJ/m^3 at $\varepsilon_{\mathrm{pl}} = 0.1$. According to the calculations made by Talonen,[3] the latent heat release of the transformation

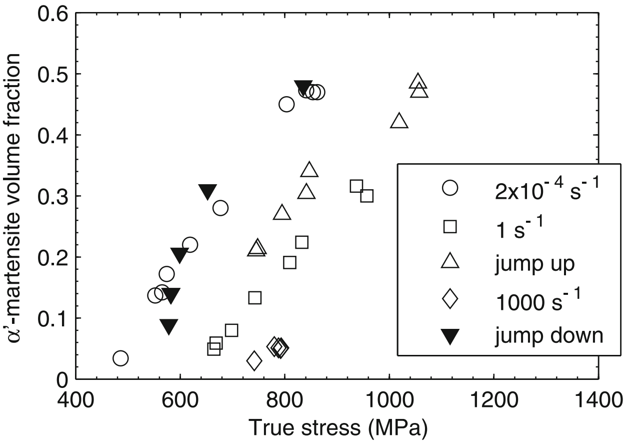

Fig. 3—Data presented in Figs. 1(b) and 2(b) plotted in terms of α'-volume fraction as a function of the stress acting on the material prior to unloading.

is around 220 MJ/m^3 for complete transformation, and thus 11 MJ/m^3 (~5 pct) for the high rate loading discussed here. Based on these values, the temperature increase is estimated to be 21 K, when material density is taken as 7900 kg/m^3 and specific heat as 500 J/(kgK).

Previously it has been suggested[9,10] that the kinetics of the α'-transformation taking place during plastic deformation can be described by the thermodynamic effect of applied stress, *i.e.*, the increasing stress due to strain hardening adds to the chemical driving force and thus causes continued transformation. From this it can be predicted that a rapid increase in the flow stress due to the strain rate increase should cause a rapid increase in the α'-content. Figure 3 plots the α'-content data presented in Figures 1(b) and 2(b) with respect to flow stress. For this graph, the flow stress was calculated by dividing the measured force with the cross-sectional area of the specimen measured manually after each reloading (*i.e.*, before measurement of the α'-content). This method allows determining the true flow stress despite the volume change due to the α'-transformation. The difference between this method and the calculations based on the assumption of volume constancy were, however, found to be small and mostly within the experimental uncertainty. As can be seen in Figure 3, the test data for different strain rates are separated into distinct curves, the flow stress required for a certain α'-content being the higher the higher the strain rate.

Comparison of the constant strain rate tests is complicated by the fact that the data presented in Figure 3 are not isothermal in the case of high rate tests. However, the analysis can be continued by noting that the martensitic transformation is irreversible at the studied conditions. Thus, during the course of deformation the extent of α'-transformation should depend only on the maximum attained value of stress *vs* material temperature at that time, if stress-induced nucleation is the rate controlling mechanism. The results of the strain rate change tests appear to be in contradiction with this assumption. In the upward strain rate jump from 2×10^{-4} to 1 s^{-1}, the flow stress increases immediately from 560 to 710 MPa (estimated based on the stress–strain curve) at room temperature which, according to the low rate data, should lead to an increase in the α'-volume fraction from ~0.15 to ~0.32. Instead, only 0.21 α'-volume fraction is detected after the jump test is interrupted at 750 MPa. Similarly, at the strain rate of 1000 s^{-1} the material yields at room temperature at a stress exceeding 600 MPa, which should lead to an α'-volume fraction of ~0.2. However, only 0.05 volume fraction is detected after the high rate loading is interrupted at 0.1 plastic strain. Interestingly, during the subsequent low rate loading the α'-content—flow stress data seem to align with the data obtained from the constant low rate tests. It is yet unclear, if this relates to the transformation kinetics. The relatively small strain rate sensitivity of the strain hardening rate at plastic strains below 0.1 tends, after a strain rate decrease, to lead to a flow stress level similar to the constant low rate test.

Returning back to the evolution of the α'-content with respect to plastic strain, an attempt to fit the phenomenological kinetics model originally proposed by Olson and Cohen[11] is made. In order to take into account the changes in the deformation history (temperature and strain rate), the model is stated in a differential form and integrated over the deformation path.[4] For strain rates 1 and 1000 s^{-1} adiabatic conditions are assumed and temperature is estimated by integrating over the measured flow stress and α'-transformation curves using the same material parameters as above. Starting from the low strain rate data previously published for this material,[3] it turns out that the data presented in Figure 1(b) can be well fitted, when one assumes a linear temperature (T) dependence of the parameters α_{OC} and β_{OC} as well as a logarithmic strain rate ($\mathrm{d}\varepsilon_{\mathrm{p}}/\mathrm{d}t$) sensitivity of the parameter β_{OC}. The appropriate equations including the fitting parameters are presented in Eqs. [1] to [4]. Following the original model, value of 4.5 was used for the constant n_{OC}. Results of the fitting are superimposed in Figures 1(b) and 2(b). As can be seen, this rather crude phenomenological modification of the α'-nucleation probability in the model appears to fit the experimental results surprisingly well. The model, however, underestimates the α'-transformation at the strain rate of 1000 s^{-1} revealing the limitations of the simple logarithmic strain rate sensitivity used here.

$$\frac{\mathrm{d}f^{\mathrm{sb}}}{\mathrm{d}\varepsilon_{\mathrm{p}}} = \alpha_{\mathrm{OC}}\left(1 - f^{\mathrm{sb}}\right) \qquad [1]$$

$$\frac{\mathrm{d}f^{\alpha}}{\mathrm{d}\varepsilon_{p}} = \beta_{\mathrm{OC}} n_{\mathrm{OC}} (1 - f^{\alpha})\left(f^{\mathrm{sb}}\right)^{n_{\mathrm{OC}}-1} \frac{\mathrm{d}f^{\mathrm{sb}}}{\mathrm{d}\varepsilon_{\mathrm{p}}} \qquad [2]$$

$$\alpha_{\mathrm{OC}} = -0.072\ \mathrm{K}^{-1}(T - 297.15\ \mathrm{K}) + 6.4 \qquad [3]$$

$$\beta_{\mathrm{OC}} = \left(-0.015\ \mathrm{K}^{-1}(T - 297.15\ \mathrm{K}) + 3.8\right) \times \left(1 - 0.1 \times \log_{10} \frac{\mathrm{d}\varepsilon_{\mathrm{p}}/\mathrm{d}t}{2 \times 10^{-4}\mathrm{s}^{-1}}\right) \qquad [4]$$

The findings of this study are in contrast to the previous studies[3,12,13] which have indicated a small positive effect of strain rate on the phase transformation. These previous studies were carried out on relatively stable alloys and the positive strain rate effect was related to the enhanced generation of nucleation points (shear bands) at higher strain rates,[3,12,13] *i.e.*, the parameter α_{OC} would increase with increasing strain rate. It appears that in the current alloy, in which both shear band formation and α'-transformation take readily place near room temperature, the above-mentioned effect is small at the studied deformation conditions. A natural test of this theory would be to carry out the measurements presented here at a higher deformation temperature, at which both the stacking fault energy and stability of the austenite phase are higher.

As a conclusion, in this paper the plastic deformation and phase transformation behavior of metastable austenitic stainless steel EN 1.4318 were studied by means of strain rate jumps during uniaxial tension. The results reveal a direct negative effect of strain rate on the α'-martensite phase transformation that cannot be explained by macroscopic adiabatic heating. However, it appears that the observed effect can be phenomenologically accounted for by assuming negative strain rate sensitivity of the nucleation probability in the Olson–Cohen model. Further work is, however, needed to elucidate the physics of the underlying phenomena.

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