

## Influence of plastic strain on deformation-induced martensitic transformations

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The effects of plastic strain on deformation-induced martensitic transformations have been investigated experimentally. Austenitic metastable stainless steel samples were heated to a temperature at which the transformation is suppressed and were plastically strained to different amounts. The resulting pre-strained material was cooled to room temperature and a tensile test was conducted during which transformation was monitored via a magnetic sensor. Results of these tests are discussed concerning the existing theories that describe the mechanically induced martensitic transformation phenomenon.

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There have been many studies regarding the physics underlying the deformation-induced martensitic phase transformations [1]. Part of these studies have been concerned with the TRIP (transformation-induced plasticity) phenomenon and part with understanding the driving mechanisms for transformation.

The TRIP effect was first proposed by Greenwood and Johnson [2] to be due to the accommodation strains necessary to compensate for the mismatch of the volumes of the parent and the product phases. Magee [3], however, showed experimentally that the Greenwood–Johnson effect fails to describe some of the characteristics of the martensitic transformation and proposed another mechanism. In his theory TRIP occurs because of the activation of preferred martensitic variants under stress. Olson and Cohen [4] related the transformation kinetics to creation of nucleation sites due to shear band intersections under plastic deformation, suggesting the so-called “strain-induced” transformation. In recent micromechanical studies the two different phenomena of TRIP and mechanically induced transformation have been combined in a single model [5,6].

Experimentally it is hard to distinguish the different aspects of transformation and observe them individu-

ally. For instance, in the context of strain-induced transformation, plastic strain is assumed to be the driving mechanism for transformation. However, in a tensile test at room temperature transformation usually starts at stress levels which are above the yield point. This makes it hard to differentiate between the effect of stress and plastic strain on the kinetics of transformation. In addition, transformation itself causes an inelastic (TRIP) strain. It is therefore not easy to quantify the plastic strain or observe the effects of it. The effect of stress state on the transformation kinetics has been investigated by the authors in an earlier study [7].

In this study the aim is to separate the plastic strain from other influences, i.e., make it an independent variable and observe changes in the kinetics of transformation with respect to the changes in its amount.

The material used in the experiments is a low carbon metastable austenitic stainless steel, 12Cr–9Ni–4Mo, with the following nominal composition: C + N < 0.05%, Cr = 12%, Ni = 9%, Mo = 4%, Cu = 2%, Ti = 0.9%, Al = 0.4%, Si < 0.5%. The steel sheet as received was fully austenitic at room temperature.

The constitutive behavior and the deformation-induced transformation characteristics of this material at different temperatures have been thoroughly studied by Post [8]. Referring to that study, it is known that the material has very slow transformation kinetics at temperatures above 120 °C.

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The test equipment used in this study is a Zwick Z020 tensile stage that is placed in a temperature controlled furnace. The sensors used are a Fiedler PS-e100-0153-af Laser extensometer, an inductive coil to measure permeability and a thermocouple that touches the specimen. The setup is schematically illustrated in Figure 1.

The width, thickness and length of the specimens are ~20, ~0.5 and ~120 mm, respectively. The initial gauge length used in the current tests is ~50 mm.

The specimens after clamping are heated in the furnace from room temperature (20 °C) to 120 °C slowly, with ~3 °C/min, and any load that occurs due to expansion is relaxed. Then at 120 °C a tensile test is carried out until specified strains are reached after which the specimens are cooled to room temperature, with ~-3 °C/min, in the furnace while continuously unloading the forces due to shrinkage. This procedure allows to plastically strain the material without having any significant martensitic transformation. At around 20% strain less than 15% of martensite is detected (Fig. 4). Finally, the tensile test is continued at room temperature.

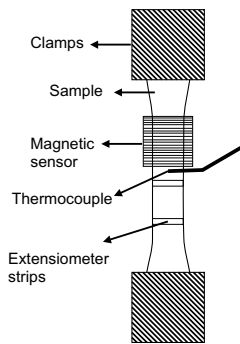
In Figures 2 and 3, the stress-strain results of each test during the pre-straining stage at 120 °C and the second stage at 20 °C are shown, respectively.

Figure 3 can be interpreted as follows. First, as expected, the yield stress of the alloy increases with increasing amount of pre-straining. One important point to mention here is that in Ref. [8] it is reported that the yield stress of this alloy increases with decreasing tem-

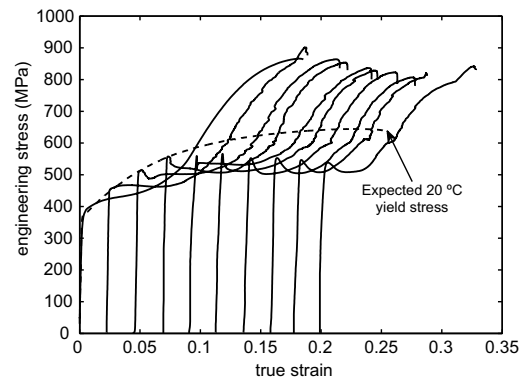
perature. Consequently, the actual yield stress at the room temperature stage is expected to be higher than the one at the 120 °C stage. This is observed up to ~7% pre-strain. However, beyond this point the material starts to yield at lower stress levels than expected, and this stress does not increase with increasing pre-strain. In the literature this behavior is reported as stress-assisted transformation, meaning that the initial inelastic deformation that occurs in the material with deformation is not caused by plastic slip but martensitic transformation instead. The very high inelastic strains accompanying the transformation correspond with experimentally observed and theoretically predicted values [3].

In Figures 4 and 5, the martensite amount is plotted vs. the tensile stress measured during the tests at 120 °C and room temperature, respectively. The small changes in the voltage that are observed during the unloading and reloading of the material are due to the magnetostriction effect, which can be briefly described as a change in the magnetic permeability of martensite under stress.

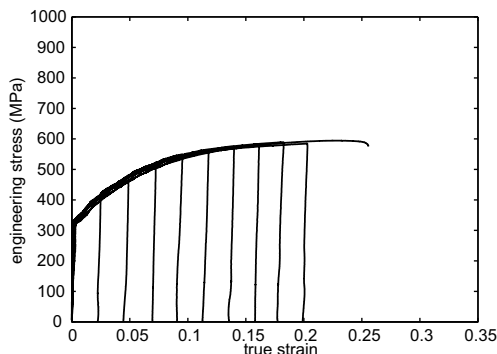
As a starting point, it is clear from Figure 5 that, within the margins of experimental error, the transformation characteristics of all samples are identical. In all the tests transformation starts distinctively at a certain stress and follows an exponential-like behavior.



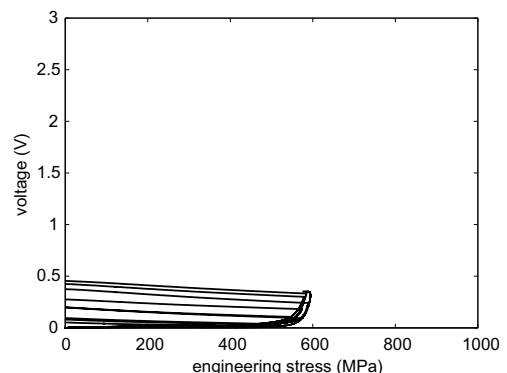
**Figure 1.** Temperature-controlled tensile test setup with laser extensometer.



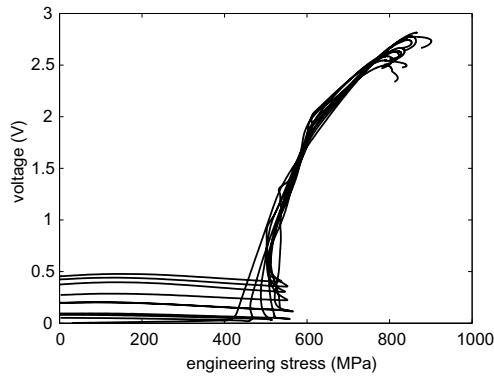
**Figure 3.** Stress–total strain curves of the pre-strained samples during the tensile test at room temperature.



**Figure 2.** Stress–strain curves of the samples during the pre-straining tensile stage at 120 °C.



**Figure 4.** Magnetic voltage vs. stress curves of the samples during the pre-straining tensile stage at 120 °C.



**Figure 5.** Magnetic voltage vs. stress curves of the pre-strained samples during the tensile stage at room temperature.

It is important to note that each sample has a different amount of accumulated plastic strain, which leads to different numbers of nucleation sites, that should have caused a significant difference in the transformation characteristics. Consequently, for this alloy, no evidence relating to creation of nucleation sites by plastic deformation is observed, as suggested by Olson and Cohen [4]. The effect of plastic strain then can be reduced to simply hardening the material. Since the flow stress of the alloy is increased, it is possible to resolve more stress in the material, which in turn makes it possible to observe in Figure 3 the stress at which transformation starts. In other words, the driving force necessary for slip becomes higher than that necessary to initiate martensitic transformation.

Although the results suggest that there is no effect of plastic strain on the transformation, in Ref. [9] differences are found in the surface relief between stress-assisted and strain-induced martensite. However, one might argue that the enhanced surface relief and the angle difference are caused by plastic deformation rather than by a change in transformation mechanism.

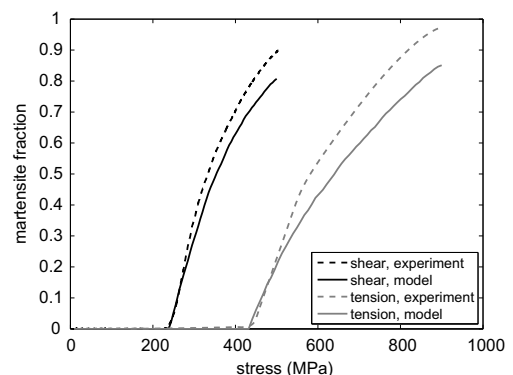
Our results fit perfectly to the transformation model described by Magee [3]. Although in that study only the effects of preferred variant selection on TRIP are investigated, it is perfectly applicable as a transformation model. This type of approach is also found in the recent work of Kundu and Bhadeshia [10]. There, as a function of the resolved driving force in a polycrystalline material, random or textured, the grains are allowed to transform and the resultant transformation texture is calculated. Tamura [11] also suggested that the effect of stress is dominant on deformation-induced martensitic transformations compared with that of plastic strain, and he proposed a stress-driven transformation model.

Following the approach of Patel and Cohen [12], the driving force for transformation resolved on a martensitic variant with certain orientation with respect to the applied stress can be calculated. It is known from the work of Wechsler et al. [13] that in a face-centered cubic to body-centered cubic (or body-centered tetragonal) transformation, there are 24 crystallographic possibilities of transformation (martensitic variants) that will satisfy the invariant plane strain condition. These can be calculated provided the lattice parameters of the

parent and the product phases are known. Using X-ray diffraction analysis, the lattice parameters of this alloy for austenite and martensite phases are determined to be 2.87351 Å and 3.59690 Å, respectively. Following the procedures presented in Ref. [13], the habit planes and the corresponding shear directions are found to be  $\mathbf{n} = \{0.178 \ 0.608 \ 0.774\}$  and  $\mathbf{s} = \langle -0.046 \ -0.156 \ 0.159 \rangle$ , respectively, and the individual transformation deformation gradients associated with each martensitic variant can be calculated as  $\mathbf{F}^{\text{tr}} = \mathbf{I} + \mathbf{s} \otimes \mathbf{n}$ . With this information, it is possible to calculate the driving force on each variant once the orientations of the grains are known. For simplicity, it is assumed that the material has no texture. Therefore, a randomly oriented set of grains is generated by rotating the calculated base variants a number of times.

Following a large deformation theory, the driving forces on each variant in the system are calculated as  $U = \boldsymbol{\sigma} \cdot \mathbf{n} \cdot \mathbf{s}$ . This approach implies a serious assumption of a homogeneous stress distribution in the material. Furthermore, a constant transformation energy barrier is assumed that includes the resistance of the material to transformation, such as the elastic energy required to deform the surrounding matrix and the surface energy required to create an interface. Increasing the magnitude of the stress while keeping its direction constant, it is possible to calculate which grains have enough driving force to transform. To perform the check, if a grain will transform, only the variant with the highest resolved driving force is taken into account. The results of this simulation are plotted in Figure 6 for two different stress states, shear and tensile. In the figure, the number density of grains that have the potential to transform are plotted against the magnitude of the stresses.

This figure can be used to deduct some basic characteristics of the model. First, no transformation is observed until the resolved driving force on the most favorable variant reaches the critical energy barrier. When that point is reached, an increase in the stress magnitude is needed to further provoke transformation. As the stress is increased, more grains overcome the energy barrier, until finally all the grains transform into martensite. It is important to note that in this model there is only one parameter that is not known: the critical energy barrier. This barrier can be determined from the experiments as the transformation only starts when



**Figure 6.** Comparison of the Magee theory results with experimental results for the shear [7] and tension tests.

the most favorable variant has overcome that barrier. Based on this theory, it is determined to be approximately 54 MPa (6.8 J/g) and this value is used in the model to reproduce both experiments.

An excellent agreement between the predicted onset of transformation and the experiments is found. Furthermore, the shapes of the transformation curves are seen to be similar. It must be noted that the tensile stresses measured in the experiments are engineering stresses. Since the martensitic transformation is accompanied by a volumetric expansion, it is not possible to calculate the area reduction due to plastic strain. Additionally, since it is difficult to find an exact correlation of the voltage to martensite content, a linear relation is assumed, and this is scaled by the amount determined on the micrograph taken after the test.

For this material, it is suspected that  $\varepsilon$ -martensite forms at lower temperatures ( $<-50$  °C) [8,14]. It is not possible to detect  $\varepsilon$ -martensite with a magnetic sensor as it is paramagnetic; only  $\alpha'$ -martensite can be measured. Since the sensor readings are fully synchronous with the observed mechanical phenomena, there is no need to invoke transformation to  $\varepsilon$ -martensite to explain the observed behavior.

It should also be noted that the stress that is measured with the experimental setup is the overall stress of the material, whereas the driving force for transformation is dependent only on the stress that is concentrated in the austenite grains. Since austenite is a soft phase with a yield stress of around 250 Mpa, compared with that of martensite, which is around 800 Mpa [8], it is obvious that during the evolution of deformation the stress of the composite will start to differ from that of austenite. On the other hand, the initiation of transformation will always be from a virgin 100% austenite material and to certain extent the stress in austenite will equal that of the composite.

Considering the factors described above, it can be deduced that the model starts to underestimate the transformation after a certain amount of martensite has transformed. This discrepancy can be credited to the existence of an autocatalytic effect, which is known to exist for other types of martensitic transformation, such as isothermal or athermal transformations. Additionally, the assumption that the material has no texture can lead to deviations of the results from the experiments.

In summary, the effect of plastic strain on mechanically induced martensitic transformation was studied to quantify how the nucleation behavior affects the kinetics of transformation. Austenitic samples were plastically deformed at 120 °C, at which temperature the transformation was suppressed. Following this pre-straining, a second tensile stage was utilized at room temperature. During both stages the transformation was monitored with the help of a magnetic sensor measuring the permeability of the sample.

No evidence of an influence of the amount of plastic pre-straining on the kinetics of transformation was observed. All samples followed the same transformation behavior regardless of the different plastic strain histories. An initial resistance to transformation is observed in samples with high plastic pre-straining, in terms of an increase in the stress level that is required to initiate transformation. However, this increase is always followed by a relaxation. This resistance might be explained by considering the local stress fields created due to the increasing density of dislocations; however, this theory requires more experimental proof.

A strong effect of plastic deformation is found to be the strain hardening of the material. This allows higher magnitudes of stress to be applied to the material and this, in turn, results in a higher resolved driving force.

The transformation is simulated using the Magee theory. For the calculations, the Patel–Cohen theory is combined with results of the Wechsler–Lieberman–Read theory. A good agreement is found between the model predictions and the experiments in terms of the stress magnitude that initiates the transformation. It is also observed that, in a qualitative sense, the shape of the modeled transformation curves are similar to those experimentally attained.

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