Materials Science & Engineering A 631 (2015) 166–172

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Large strain cyclic behavior of metastable austenic stainless steel

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ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form
26 January 2015
Accepted 17 February 2015
Available online 25 February 2015

Keywords:
Metastable Austenite
Martensite
Mechanically induced transformation
Stress partitioning
Constitutive model

ABSTRACT

Metastable austenitic stainless steel will transform to martensite when subjected to mechanical working. In this research an austenitic stainless steel has been subjected to large amplitude strain paths containing a strain reversal. During the tests, apart from the stress and the strain also magnetic induction was measured. From the in situ magnetic induction measurements an estimate of the stress partitioning among the phases is determined.

When the strain path reversal is applied at low strains, a classical Bauschinger effect is observed. When the strain reversal is applied at higher strains, a higher flow stress is measured after the reversal compared to the flow stress before reversal. Also a stagnation of the transformation is observed, meaning that a higher strain as well as a higher stress than before the strain path change is required to restart the transformation after reversal.

The observed behavior can be explained by a model in which for the martensitic transformation a stress induced transformation model is used. The constitutive behavior of both the austenite phase and the martensite is described by a Chaboche model to account for the Bauschinger effect. Mean-field homogenization of the material behavior of the individual phases is employed to obtain a constitutive behavior of the two-phase composite. The overall applied stress, the stress in the martensite phase and the observed transformation behavior during cyclic shear are very well reproduced by the model simulations.

1. Introduction

Transformation of retained austenite under mechanical working is especially prominent in austenitic stainless steel. Under the right circumstances, the metastable austenite transforms to martensite under mechanical loading. For experimental studies see for example [1–9].

Austenitic stainless steels have a broad range of applications. In general, they have high corrosion resistance, high cryogenic toughness, high work hardening rate, high hot strength, high ductility, high hardness, an attractive appearance and low maintenance. Industrial applications of stainless steels are in chemical reactors and tubing, especially in the food industry [10], in off shore structures and in oil and gas processing installations. Other investigations concern application for H_2 storage tanks and fuel cells for automotive power generation [11] and as structural materials for nuclear fusion reactors [12]. The delayed cracking of stainless steel products is in general attributed to the presence of martensite combined with residual stress [13]. For the prediction of the martensite fraction and residual stresses it is important to have reliable models.

Olson and Cohen [14] formulated a kinetic model which explains the martensite formation from ε-phase nucleation on shear band intersections during plastic deformation [15]. This *strain induced* kinetic model for martensitic phase transformation has been combined with a mean-field homogenization model to obtain overall visco-plastic behavior from the constitutive behavior of the individual phases [16]. Also the influence of the stress state and transformation plasticity were added. Further extensions have been provided for strain rate dependence [17] and for crystal plasticity [18]. Han et al. [19] added stress dependence by evaluating the mechanical driving force on individual martensite variants. This enabled them to calculate the texture of the resulting martensite. Recently an extension with Lode angle dependence of the transformation was presented [20]. Papatriantafillou et al. [21] developed an elasto-plastic mean-field homogenization method using a strain induced transformation model. The Olson–Cohen model was successfully used in deep drawing simulations [22] and for finite element simulations of hydro-forming [23].

An alternative theory for mechanically induced martensite formation was proposed by Tamura [24]. In his model the driving force of the applied stress is considered as the reason for the transformation. When the thermodynamic driving force as defined by Patel and Cohen [25] exceeds a threshold value, the transformation will start. Several *stress induced* transformation models have been developed which are based on the thermodynamic action of the mechanical

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http://dx.doi.org/10.1016/j.msea.2015.02.047
0921-5093/

driving force [26–28]. These have been applied to micro-mechanical simulations [29–31] as well as for macro-scale simulations of austenitic steel [32,33] and of TRIP steel [34–36].

For accurate prediction of the behavior of the material during forming and its state after forming, it is important that non-proportional deformation behavior is captured correctly. Very few studies of the large amplitude cyclic and non-proportional response of metastable austenitic stainless steel are available in the literature. Van Beeck et al. [37] show results of bending-unbending experiments of austenitic stainless steel plate. During the unbending stage a pronounced non-linear effect is observed, which is not present in a non-transforming steel. An extensive experimental program, including tension-compression tests on non-transforming austenitic steel, was conducted by Spencer et al. [38]. They report a strong Bauschinger effect in the austenite stress–strain response. Results from cyclic shear tests and tensile tests followed by shear tests were presented by Gallée et al. [39]. However, they measured the martensite content only during regular tensile tests. They formulated a strain induced model [16] which was successfully applied in a deep drawing simulation [40]. Recent research [41] showed that observations during large amplitude cyclic tension-compression tests cannot be captured by the strain induced transformation model.

In the current paper we report on cyclic shear tests, which have been conducted on a low carbon 12Cr9Ni4Mo austenitic stainless steel. The austenite in this steel has previously been shown to transform to nearly 100% martensite during room temperature tensile tests [9]. During the testing the martensite transformation was monitored real-time employing a magnetic induction sensor. Maréchal et al. [42] used a similar setup to estimate the stress in the martensitic phase. A modification of their method, which becomes apparent during cyclic shear tests, will be presented.

A constitutive model of austenitic steel which undergoes a mechanically induced transformation will be presented, where the martensitic transformation is modeled as a stress-driven process [24]. This transformation model is then incorporated into a mean-field formulation for description of the constitutive behavior of the two-phase composite.

2. Experiments

The material used in the tests is 12Cr9Ni4Mo austenitic stainless steel. Its nominal composition is given in Table 1. Specimens were cut from 0.5 mm thick sheet for deformation in shear [43], which was applied at a deformation rate of approximately 0.001 s^{-1}. The strain was measured real-time on the material surface using a camera and dot-tracking software. Dots were applied to the specimen surface before the test and the corresponding positions were recorded with a frequency of approximately 10 s^{-1}. The data was averaged and post-processed to find the 2-dimensional deformation tensor **F** in the material. The shear strain γ_{xy} is calculated as

$$\gamma_{xy} = F_{xy}F_{xx} + F_{yy}F_{yx}. \quad (1)$$

In cyclic tests a cumulative shear strain is obtained by mirroring the stress–strain curve about the zero-crossing of the unloading leg after strain reversal. The resolutions of the strain and stress measurements are approximately 0.05% and 2 MPa, respectively.

During the cyclic shear tests a tiny horse shoe shaped iron core coil was placed against the specimen and its induction was measured to monitor the course of the martensitic transformation. The induction of the coil is influenced by the magnetic permeability of the sample material. The magnetic permeability of the ferromagnetic martensite is two orders higher than that of the paramagnetic austenite. An AC voltage of 3 V at frequency 18 kHz is applied. Post et al. [9] give a description of the measurement electronics and give calibration data for a similar sensor when applied in a tensile setup. For this paper, however, the raw sensor readings will be of more interest than the actual martensite volume fractions.

The magnetic permeability also depends on the applied stress. This has been shown for tensile stresses [9,42,44] and in cyclic tensile-compression tests [45], but it is also apparent when a shear stress is applied. Moreover, the effect of the shear stress on permeability is symmetric with respect to zero stress. This has been verified by the authors by subjecting a ferritic steel sample to cyclic shear while monitoring the induction. This offers the possibility to determine the overall stress and strain at which, during the strain reversal, a zero shear stress in the martensite is reached. In this way the partitioning of the stress between both phases can be estimated.

Note that this measurement is only possible in a shear test as the effect of shear stress is symmetric with respect to positive and negative values of the shear stress. No such symmetry needs to exist with respect to tensile and compressive stresses.

Table 1
Chemical composition of the 12Cr9Ni4Mo steel used in the experiments in wt%.

C+N	Cr	Ni	Mo	Cu	Ti	Al	Si
< 0.05	12.0	9.1	4.0	2.0	0.9	0.4	< 0.5

3. Results

The measured shear stress vs. shear strain data are shown in Fig. 1 and the absolute values of the stresses and cumulative strains are plotted in Fig. 2. It is clearly seen that after strain reversal re-yielding starts at a distinctly lower stress than was attained before strain reversal. Compare for example the stress–strain behavior in the forward deformation with that after strain reversal at 4% strain (R04). In forward deformation yielding starts at a shear stress of 190 MPa, whereas after strain reversal re-yielding starts at a stress of less than 100 MPa. This indicates that the material behavior of the austenite has a strong Bauschinger effect, which agrees with the findings in literature [38]. The tests with considerable transformation before strain reversal show that soon after re-yielding a stress level is reached, which exceeds the stress level before reversal.

In Fig. 3 the magnetic induction is plotted as a function of total accumulated strain. After strain reversal considerably more strain needs to be applied for the transformation to restart. A similar stagnation of martensite transformation after strain reversal was also found in the literature [41]. In test R04 no martensite was formed before strain reversal. Yet, more plastic strain is needed to obtain a similar amount of martensite as in a monotonic test (M).

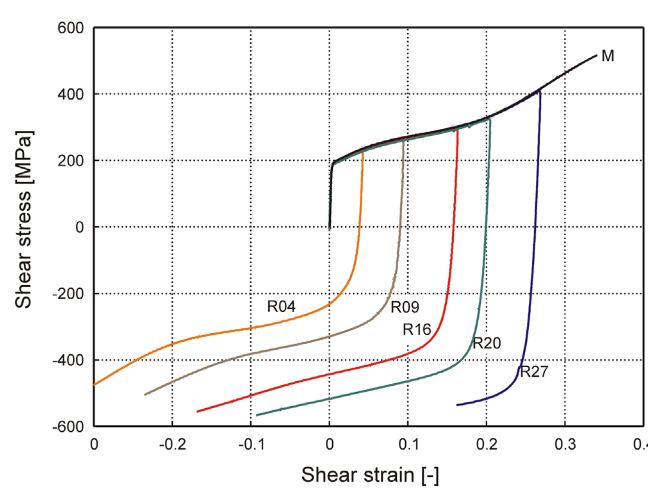

Fig. 1. Shear stress versus shear strain during cyclic shear tests.