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In situ characterization of backstress effects on the austenite-to-bainite phase transformation

M.J. Holzweissig,[a,*] D. Canadinc[b] and H.J. Maier[a]

[a] University of Paderborn, Lehrstuhl für Werkstoffkunde (Materials Science), 33095 Paderborn, Germany
[b] Koc University, Advanced Materials Group, Department of Mechanical Engineering, 34450 Istanbul, Turkey

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An in situ examination of the backstress and postforming effects was carried out in a low-alloy tool steel undergoing an isothermal austenite-to-bainite phase transformation. The findings shed light on the combined role of superimposed stresses and load reduction on the nucleation, selection and growth of bainitic variants throughout the phase transformation.

Keywords: Austenitization; Transformation plasticity; Backstress; Bainite; Phase transformation

The interrelationship between superimposed stresses, load reduction, variant selection, and "backstress" and "postforming" effects was investigated in a low-alloy tool steel undergoing an isothermal austenite-to-bainite phase transformation. The thorough set of experimental results involving in situ monitoring of the evolution of strain fields demonstrated that residual stresses remaining in the microstructure upon the removal of the initially superimposed constant stress lead to the so-called "postforming effect" by further promoting the growth of the initially preferred bainitic variants. On the other hand, an opposite phenomenon, the "backstress effect", is observed when bainitic variants growing perpendicular to the initially selected ones dominate upon load reduction. The current findings constitute a step forward towards better understanding and controlling the microstructure evolution during manufacturing processes that involve phase transformations and variable stress states.

Anisotropic volume change brought about by processing-induced phase transformation constitutes a major concern surrounding various manufacturing techniques that are utilized to produce functionally graded steel work pieces, such as forging [1–3]. In particular, transformation plasticity (TP) strains, i.e. strains evolving when stresses are superimposed during austenite-to-martensite or austenite-to-bainite phase transformations, promote anisotropic volume changes [4–8].

Load reduction during solid-to-solid phase transformations has been reported to yield a backstress effect, i.e. a reconstitution of TP strains, yet the microstructural reasons have remained ambiguous to date [9,10]. In one of the most detailed analyses treating this backstress effect [10], the macroscopically observed strains in phase transformations are considered to have elastic, plastic and thermo-metallurgical components. The elastic strain results from the superimposed stresses, the plastic strain component can evolve (anisotropically) due to the Magee or Greenwood–Johnson mechanisms, and the thermo-metallurgical strain constitutes the isotropic volume change induced by the phase transformation and can be observed in the absence of superimposed stresses. Hence, the backstress effect can be associated with the thermo-metallurgical strain, causing an isotropic volume change and thereby reducing TP strains upon load reduction [10].

The TP strains are attributed to two mechanisms: the Magee model [5] associates the evolution of TP strains with an alignment of martensitic or bainitic variants by the additional energy due to residual or external stress fields. This energy favors the growth of single variants preferably oriented along the loading direction at the expense of others, which need higher energy levels to grow. The Greenwood–Johnson model [6], on the other hand, traces the evolution of TP strains back to microdeformations of the weaker phase due to a

* Corresponding author. Tel.: +49 5251 60 5235; fax: +49 5251 60 3854; e-mail: martin.joachim.holzweissig@uni-paderborn.de

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volumetric difference between the parent and the product phases. Specifically, stresses superimposed during the phase transformations favor the growth of the product phase with respect to the loading direction, yielding TP strains. Both mechanisms can be simultaneously active during phase transformation, where usually one of them dominates [7,8,11]. Recent work has also demonstrated that individual bainitic variants can be associated with local axial, diametral and TP strains utilizing digital image correlation (DIC) in combination with electron backscattered diffraction (EBSD) [12].

The current work was undertaken with the motivation of adopting this new in situ characterization technique to load reduction experiments. Specifically, the current study aims at establishing the microstructural reasons underlying the frequently observed load reduction induced backstress effects on the isothermal austenite-to-bainite phase transformation. It should be noted that the unloading experiments were considered in the current work in order to examine the role of superimposed stress levels from two perspectives: (i) by monitoring the evolution of bainite upon unloading to establish the role of the initial variant selection process and the interaction of these variants with new ones that form upon unloading; and (ii) by examining the effect of residual stresses dictated by the initially superimposed stresses upon unloading, in order to further look into the stress–variant growth relationship.

For this purpose, a completely transforming low-alloy 40CrMnMoS8-6 tool steel was studied. Specimens machined via electrodischarge machining featured a flat 1 mm thick and 10 mm wide gage section to ensure homogeneous temperature distribution during heating via a direct current. A custom-built test rig utilizing a servohydraulic test frame was employed for loading the samples, where a chamber placed around the specimen equipped with nozzles provided a nitrogen excess pressure [12]. Additionally, the test rig was equipped with a two-color pyrometer, to control the temperature–time paths; extensometers, to measure the axial and diametral strains simultaneously; and a camera, to take images of the gage section while the bainite evolved. Prior to the experiments, the gage sections of the samples were polished for the sake of reliable computation of strain fields via DIC.

The specimens were heated to an austenitization temperature of 1200 °C within 15 s, and held there for 10 s. In order to obtain bainite, quenching down to the isothermal phase transformation temperature of 340 °C was carried out at a nominal rate of 70 °C s^{-1} by reduction of the direct electric current, such that any unintended phase transformation could be avoided. Since backstress effects on the evolution of TP strains are assumed to prevail when the superimposed stresses during phase transformations are reduced before the phase transformation is completed [9], two different magnitudes of superimposed stresses were applied (50 and 100 MPa), which were reduced to 0 MPa once 50% of the maximum TP strain observed in the corresponding constant stress experiment was reached. The stresses were lower than the yield strength of the supercooled austenite at 340 °C of the current steel and were applied once the isothermal phase transformation temperature was attained, but before the onset of the phase transformation. The TP strains were determined based on the time-dependent volume change, and the axial and diametral strains [12]. In order to trace the backstress effect back to the local evolution of the bainite, an EBSD measurement was carried out with a scanning electron microscope operating at a nominal voltage of 20 kV. For EBSD, the specimens were electropolished with a 5% perchloric acid solution.

The phase transformation experiments revealed that the axial strain increases much more rapidly than the magnitude of the diametral component for both stress levels prior to load reduction (Fig. 1a), which is even more pronounced in the case of a 100 MPa superimposed stress level. Following the load reduction to 0 MPa, which was imposed once the TP strain reached 50% of the value attained upon complete phase transformation under the corresponding constant stress level, the rate of the increase in the axial strain component was reduced for both stress levels, even though the increase was still larger in the case of the 100 MPa experiment.

Further analysis of the experimental results revealed that the TP strains increased concomitant with the superimposed stress level (Fig. 1b). Specifically, the growth of fewer variants is favored as the stress increases, and the anisotropic shape change [4,5,7,8,11,12] brought about by the austenite-to-bainite phase transformation promotes axial strain components that are larger than the diametral strains (Fig. 1a). However, a different trend is observed following the load

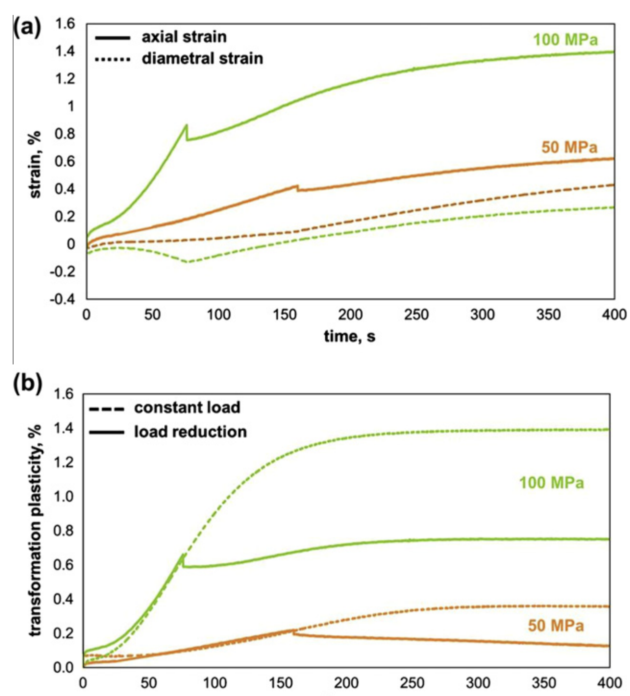

Figure 1. Evolution of (a) axial and diametral, and (b) TP strains during isothermal bainitic transformation at 340 °C under superimposed stresses of 50 and 100 MPa. The load was reduced to 0 MPa once 50% of the TP strains exhibited in the constant stress experiments were attained.