Available online at www.sciencedirect.com

SciVerse ScienceDirect

www.elsevier.com/locate/matchar

In-situ characterization of transformation plasticity during an isothermal austenite-to-bainite phase transformation

M.J. Holzweissig[a, 1], D. Canadinc[b, 2], 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

ARTICLE DATA

Article history:
Received 7 November 2011
Received in revised form
9 January 2012
Accepted 10 January 2012

Keywords:
Austenitization
Transformation plasticity
Bainite
Phase transformation
Digital image correlation

ABSTRACT

This paper elucidates the stress-induced variant selection process during the isothermal austenite-to-bainite phase transformation in a tool steel. Specifically, a thorough set of experiments combining electron backscatter diffraction and in-situ digital image correlation (DIC) was carried out to establish the role of superimposed stress level on the evolution of transformation plasticity (TP) strains. The important finding is that TP increases concomitant with the superimposed stress level, and strain localization accompanies phase transformation at all stress levels considered. Furthermore, TP strain distribution within the whole material becomes more homogeneous with increasing stress, such that fewer bainitic variants are selected to grow under higher stresses, yielding a more homogeneous strain distribution. In particular, the bainitic variants oriented along [101] and [201] directions are favored to grow parallel to the loading axis and are associated with large TP strains. Overall, this very first in-situ DIC investigation of the austenite-to-bainite phase transformation in steels evidences the clear relationship between the superimposed stress level, variant selection, and evolution of TP strains.

1. Introduction

Despite the continuing efforts to utilize alternative materials, steel remains the material of choice when it comes to structural and powertrain components as it offers a wide range of mechanical properties. Furthermore, mechanical properties of steel can already be tailored at the stage of processing by varying the temperature–time–deformation path [1]. In particular, local phase transformation behavior can be influenced by inducing temperature gradients within the structure, leading to changes in the microstructure of a previously isotropic material [1,2]. This increased degree of anisotropy can be controlled and utilized to adjust the properties of the work piece to the demand, provided that a good understanding of the solid-to-solid phase transformation during processing is present, which constitutes the major motivation of the current work.

For certain production processes, such as forging, temperature and stress gradients are inevitable, and hence, an anisotropic microstructure accompanied by undesired shape changes is usually present in the final work piece [3,4]. These products typically need post-processing by milling or turning, generating additional production costs to correct the phase transformation-induced distortion. However, the temperature gradients present can be turned into an advantage as they allow for the production of functionally-graded work pieces by adjusting the process parameters [1]. Specifically, the production of functionally-graded work pieces in

* *Corresponding author*. Tel.: +49 5251 60 3856; fax: +49 5251 60 3854.
E-mail addresses: martinh@mail.upb.de (M.J. Holzweissig), dcanadinc@ku.edu.tr (D. Canadinc), hmaier@mail.upb.de (H.J. Maier).
1 Tel.: +49 5251 60 5235; fax: +49 5251 60 3854.
2 Tel.: +90 212 338 1891; fax: +90 212 338 1548.

1044-5803/$ – see front matter
doi:10.1016/j.matchar.2012.01.007

combination with a near-net-shape is an advanced technology within forging, since no additional heat treatments and subsequent machining are required.

One example for manufacturing of functionally-graded near-net-shape products by forging is gears which are supposed to be hard at the surface and tenacious in the inner parts. However, in order to optimize this process and the resulting microstructure in the presence of anisotropic volume changes leading to distortion, a solid knowledge of the factors influencing the phase transformation is mandatory. In particular, transformation plasticity (TP) strains, i.e. non-isotropic strains evolving when stresses are superimposed during the phase transformation, induce anisotropic volume changes. Hence, the modeling of TP strains gains importance in order to predict and minimize the anisotropic volume changes brought about by phase transformations in steels.

The occurrence of TP strains can be explained by two widely employed models: due to Magee [5] and Greenwood–Johnson [6]. The Magee approach, originally proposed for martensitic transformations and later adopted for bainitic transformations, associates the occurrence of TP strains with the alignment of variants by residual or external stress fields [5,7,8]. The directed additional energy by the stress fields favors the growth of preferably oriented variants at the expense of those that require higher energy levels to form and grow. The Greenwood–Johnson approach, on the other hand, associates TP strains with micro-deformations of the weaker phase due to a volume difference between the parent and the product phase [6,9]. In particular, stresses superimposed during the phase transformation favor the growth of the product phase with respect to the loading direction and at the expense of the parent phase, leading to TP strains.

During the evolution of TP strains both mechanisms can be simultaneously active, where the contribution of each mechanism is dictated by the transformation parameters [9–12]. Recent studies demonstrated that pre-deformations applied to the microstructure before the phase transformation initiates induce an alignment of the evolving bainite or martensite variants according to Magee [8,13,14]. However, when stresses below the yield strength of the supercooled austenite are superimposed during the phase transformation, both mechanisms can prevail, where an alignment of the variants according to Magee can be observed [5–8,11,15]. On the other hand, TP strains resulting from an alignment of variants would vanish during reaustenitization. In fact, repeated austenitization and bainitic phase transformation induced an accumulation of TP strains in the case of a 16MND5 steel illustrating the Greenwood–Johnson effect [9,10,16].

So far, the investigations on the relative roles of the Magee and Greenwood–Johnson mechanisms have been limited to the interpretation of the final microstructure following the phase transformation, and only investigations of the global strains and their evolution during phase transformations have been undertaken to clarify the TP strains due to each mechanism [9,10,13–15], but an in-situ investigation of the local strains and their evolution during phase transformations has not been reported yet.

The current work was undertaken with the motivation of addressing this issue, which indeed provides important information about the evolution of TP strains induced by processing parameters and the corresponding distortions within the final product. Specifically, a custom setup was designed to allow for investigating the local strain evolution at the surface of specimens by digital image correlation (DIC) during the isothermal austenite-to-bainite phase transformation under zero and various superimposed external stresses. Electron backscattered diffraction (EBSD) was carried out in order to associate single bainite variants with local axial, diametral and TP strains.

One key finding is that the bainite variants oriented along [101] and [201] directions grew preferentially parallel to the loading axis with minimum interaction with other variants, and thus, large TP strains were present upon isothermal austenite-to-bainite phase transformation under superimposed stresses. The [111]- and [001]-oriented bainite variants, on the other hand, promote smaller TP strains as their growth is hindered by one another, neutralizing the evolution of TP strains.

Overall, the current study constitutes the very first in-situ DIC investigation of the austenite-to-bainite phase transformation in steels, where combined DIC and EBSD procedures have been successfully utilized to associate single bainitic variants with strain components within the bulk material, providing detailed information about the evolution of TP strains during phase transformation.

2. Experimental Details

In order to characterize the evolution of the TP strains during an austenite-to-bainite phase transformation, a completely transforming 40CrMnMoS 8-6 tool steel [17,18] was studied, which exhibited only minor sample-to-sample variations in the chemical composition (Table 1). Specimens had a flat gage section with a width of 10 mm and a thickness of 1 mm, and were precisely machined via electro-discharge machining in order to ensure a homogeneous temperature distribution while heating the specimens via 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 (Fig. 1). The nozzles were uniformly distributed around the specimen for avoiding temperature gradients due to nitrogen supply. Additionally, the test rig was equipped with a two-color pyrometer controlling the temperature–time paths, extensometers measuring the axial and diametral strains, and a camera taking images of the gage section while the bainite evolved (Fig. 1). Prior to the experiments, the gage sections of

Table 1 – Chemical composition of the 40CrMnMoS 8-6 steel studied. The data shown represent the minimum and maximum values obtained from various samples.

Element	C	Cr	Mn	S	Pb
Mass content in %	0.33 0.34	1.71 1.75	1.42 1.45	0.055 0.062	0.003 0.004
Element	**Si**	**Ni**	**Mo**	**Nb**	**Fe**
Mass content in %	0.27 0.28	0.10 0.11	0.13 0.14	0.002 0.004	Balance