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CONTRASTING THE USE OF CONTACT AND NON-CONTACT DILATOMETERS TO MEASURE FERRITE RECRYSTALLIZATION IN COLD-ROLLED DUAL-PHASE STEEL

L.S. Thomas[1*], K.D. Clarke[2], D.K. Matlock[1]

[1]Colorado School of Mines
1500 Illinois St, Golden, CO, 80401, USA
[2]Los Alamos National Laboratory
PO Box 1663, Los Alamos, NM, 87545, USA

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Abstract

The applicability of dilation data for characterization of heating rate effects on the continuous-heating recrystallization behavior of cold-rolled 1020 (0.2 C, 0.5 Mn wt. %) sheet steel was assessed in both a Gleeble® 3500 and a commercial push-rod dilatometer. Prior to the start of the ferrite-to-austenite transformation, measurements of sample dimension on heating exhibited a change in slope measured by contact dilatometry, which coincided with the start of recrystallization. The degree of the observed slope change depended on degree of cold work, heating rate, and measuring equipment. The specific temperature associated with the slope change was independent of measuring equipment. In contrast, deviations from linearity were not observed for data obtained with the non-contact laser dilatometer. Recrystallization measurements with contact dilatometry appear to be due to recrystallization-induced plasticity, and the significance of this observation is assessed with comparisons between data obtained on the 1020 steel and reported literature data.

Introduction

On heating of cold rolled steels, the extent of recrystallization can be measured in-situ through dilatometry [1-8], laser ultrasonics [9], or by metallographic and microhardness techniques on samples quenched to room temperature from different peak temperatures [8]. In-situ techniques are useful because metallography is time consuming and limited by the number of time-temperature combinations observed. Dilatometry allows continuous in-situ measurement of recrystallization on samples with different initial metallurgical conditions such as cold work, alloy content, and prior microstructure. The effects of variations in heating rate or complicated time-temperature histories, such as combinations of continuous heating and isothermal holds at different temperatures, can also be directly assessed from dilatometer measurements. Furthermore, in studies of the effects of heating rate on other metallurgical processes, e.g. austenite formation in steel, the extent of recrystallization prior to the ferrite to austenite phase transformation can be determined on the same sample used to assess microstructural evolution after austenite nucleation [8].

Dilatometry data can be obtained with a variety of measurement techniques on samples heated by radiation or convection in furnaces, or by techniques such as induction or resistive heating. Typical displacement measuring systems incorporate linear variable differential transformers

[*] Now at United States Steel Research 800 E Waterfront Dr, Munhall, PA 15120

(LVDT), strain-gage based extensometers, or laser dilatometers. Figure 1 shows an example of typical dilation data obtained with continuous heating on a cold rolled 1020 steel [8]. As illustrated by the ferrite + pearlite data below Ac_1 in the absence of a phase change, the sample size increase is linear with temperature according to the thermal expansion coefficient. However, in the presence of a phase change, shown here as ferrite + pearlite to austenite, with austenite nucleation there is a deviation from linearity at Ac_1 on transformation from BCC ferrite to FCC austenite. At the completion of austenite formation (Ac_3), the subsequent linear increase represents thermal expansion of austenite. Because recrystallization does not include a phase change, a deviation from linearity in dilation during continuous heating would not necessarily be expected. However, it has been reported that on continuous heating a deviation during recrystallization is often observed [1-7]. The deviation extent has been found to be influenced by the degree of cold work [1], heating rate [2], orientation to the rolling direction [1], and magnitude of stress applied during dilatometry [3-7]. A deviation consistent with recrystallization was found with stresses as small as 1.6 MPa [4]. The temperature where recrystallization initiates was also affected by heating rate [2] and degree of cold work [1], but independent of applied stress [6]. Tests on low carbon steel which were spheroidized prior to cold rolling exhibited similar behavior during recrystallization which eliminated the possibility of pearlite spheroidization being the cause of the deviation [2].

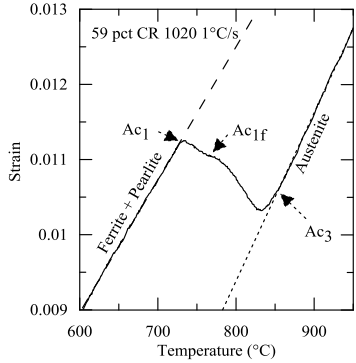

Figure 1. Continuous heating laser dilation vs. temperature curves (strain vs temperatures) for 59 pct. CR 1020 with a heating rate of 1 °C/s. Ac_1 and Ac_3 respectively represent the start and completion of austenite formation. Ac_{1f} is the pearlite-to-austenite finish temperature [8].

Deviations from linear dilation during continuous heating recrystallization experiments have been attributed to several different factors including texture changes [1], dislocation annihilation [1], and recrystallization-induced plasticity [3-7] attributed to accelerated Coble creep [3-5] or preferential movement of defects [6-7].

In the present work, potential reasons for deviations from linearity due to continuous-heating ferrite recrystallization prior to austenite formation were systematically assessed for a cold-rolled 1020 steel sheet prepared with two different cold reductions. Dilatometer data were obtained to

compare test systems, methods to measure dilation (contact versus non-contact with lasers), and sample orientations with respect to rolling direction. The contact measurement techniques incorporated an applied stress required to maintain contact with samples while the laser system was stress-free.

Experimental Setup

AISI 1020 steel with a composition (wt. %) 0.199C-0.50Mn-0.006Si-0.013Cr-0.031Al was laboratory cold rolled 39 and 59 pct. to 1.6 mm sheet. Dilation during recrystallization was measured on 75 x 6 x 1.6 mm specimens resistively heated in a Gleeble® 3500, and displacement data were obtained with both a laser and contact dilatometer configured to measure sample width (referenced to the 6 mm dimension) at the location of the control thermocouple. Free floating, "low force" jaws were used so that the jaw setup freely changes size with the specimen. For comparison, data were also obtained with a dedicated commercial push-rod dilatometer configured with an induction heating system and an LVDT displacement measurement system. Samples were 3 x 10 x 1.6 mm, cut parallel to the rolling direction, and held in place with quartz platens.

The applied stress on the samples differed between measurement techniques. The laser dilatometer applied zero stress in the direction of measured dilation. The commercial push-rod dilatometer imposed only the force required to hold the sample between the platens, but the force still resulted in an axial stress during testing. The contact dilatometer used in the Gleeble® 3500 required sufficient force to hold the dilatometer onto the sample, and the contact area of the dilatometer was much smaller than the push-rod dilatometer. While not quantified, the local contact stress was presumed to be greater with the Gleeble® 3500 than the dedicated push-rod dilatometer which applied the contact force uniformly over the sample end. Dilation transverse to the rolling direction was measured by contact and laser dilatometry on the Gleeble® 3500 and parallel to the rolling direction on the push rod dilatometer.

Results

Figure 2 shows representative dilation data based on Gleeble® 3500 and dedicated push-rod dilatometer measurements on samples heated at 1 °C/s. Data which show distinct deviations from the nominal linear thermal expansion dilation in Fig. 2 include dedicated push-rod dilatometer data for 39 pct. CR and 59 pct. CR 1020 and Gleeble® 3500 contact dilatometer data for the 39 pct CR 1020 steel. Also included are two sets of data which superimpose as a single straight line characteristic of thermal expansion of ferrite: data for the 59 pct. CR 1020 from the laser dilatometer and Gleeble® 3500 contact dilatometer data for a reheated sample of the 59 pct. CR 1020 steel which was fully recrystallized prior to reheating. All curves in Fig. 2 are shown plotted to peak temperatures less than Ac_1 (~720 °C). Deviations from linearity consistent with recrystallization are evident for the cold-rolled specimens with both the dedicated and Gleeble® 3500 contact dilatometers. Greater deviation was observed with the 59 pct. CR 1020 than the 39 pct CR 1020, an observation consistent with De Cock *et al.* [1]. Greater deviation was seen with the Gleeble® 3500 contact dilatometer than that of the dedicated dilatometer, interpreted to primarily reflect a higher local contact stress applied by the Gleeble® 3500 contact, even though the sample orientations with respect to the rolling direction differed between the two samples.

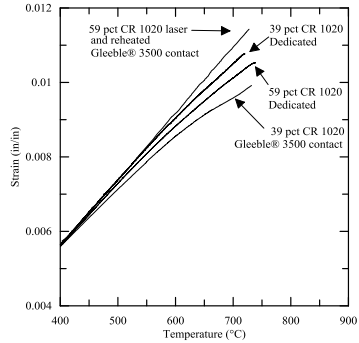

Figure 2. Continuous heating dilation vs. temperature curves for 39 pct. CR and 59 pct. CR 1020 heated at 1 °C/s on a Gleeble® 3500 system and a commercial dedicated push-rod dilatometer. Gleeble data for the 59 pct. CR material are shown for a non-contact laser extensometer superimposed with data on a reheated sample that was fully recrystallized prior to testing.

Figure 3 shows the effect of heating rate (1, 10, and 100 °C/s) on dilation response during recrystallization for the 39 pct. CR 1020 steel. Contact dilatometry with the Gleeble® 3500 and dedicated dilatometer data are shown in Figs. 3a and 3b, respectively. The extent of the observed deviation, interpreted to be associated with recrystallization, decreased with an increase in heating rate. Both figures illustrate that the greatest deviation from linearity is associated with the lowest heating rate, and the recrystallization start temperature (i.e. the point of deviation from linearity) increases with increasing heating rate. Note that laser dilatometer results are omitted from Fig. 3, as the data were linear (consistent with the results in Fig. 2) and independent of heating rate.

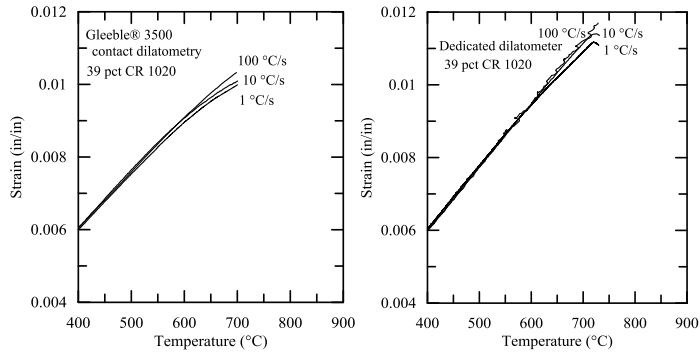

Figure 3. Continuous heating dilation vs. temperature curves as a function of heating rate for 39 pct CR 1020 with (a) Gleeble® 3500 contact dilatometer and (b) dedicated pushrod dilatometer.

At 100 °C/s, the data in Fig. 3a exhibit a slight deviation from linearity while the corresponding data in Figure 3b are linear. A comparison of Figs. 3a and 3b shows that there is a greater difference in strain between 100 and 10 °C/s when testing with the Gleeble® 3500 contact dilatometer than when tested with the dedicated push-rod dilatometer. Dilation measured with the Gleeble® 3500 contact dilatometer had greater deviations from linearity during recrystallization than the dedicated dilatometer at all heating rates, again interpreted to reflect the effects of the presumed differences in contact stress.

Discussion

The observations described above indicate that the measurement of recrystallization with dilatometry only is observed when the measuring system applies a contact stress, an observation that suggests the phenomenon reflects recrystallization-induced plasticity. Based on the dilation data presented in Fig. 3, deviations during recrystallization were not observed with laser dilatometry, i.e. zero stress, and the deviations were greater with the Gleeble® 3500 contact dilatometer than the dedicated dilatometer. The theory of De Cock *et al.,* [1] that texture changes and dislocation annihilation during heating lead to a difference in measured dilation, appears not to be applicable to the material considered here, because deviations in displacement would have been observed with the laser dilatometer. Therefore, any mechanism for a change in strain during recrystallization must include an effect of stress and suggest that recrystallization-induced plasticity mechanisms are responsible for the observed deviations. Proposed mechanisms for recrystallization-induced plasticity include directional diffusion of atoms due to the applied stress [3-5] or directional movement of defects [6-7].

The directional diffusion of atoms model is based on observations of transformation-induced plasticity [10] where plastic deformation of a weaker phase accommodates the applied stress. In the case of austenite formation the deformation was found to occur through sliding of ferrite-austenite interfaces along prior ferrite grain boundaries [11]. As an alternate interpretation, Han and Lee [3-5] created a model based on accelerated Coble creep to explain enhanced grain boundary sliding during recrystallization. In this model it was assumed that diffusion of atoms occurred to the nearest site in the transformed phase. When an external stress was applied, atoms moved to positions to relax the applied stress, therefore accelerating Coble creep. The model fit well with measurements during austenite-to-ferrite and ferrite-to-austenite transformations under different levels of uniaxial compressive stress [11].

The defect-based model evaluates contributions of dynamic recrystallization to the effective flow stress [12]. Dynamic recrystallization models consider nucleation sites such as grain boundaries, dislocations, and other defects rather than direct consideration of atomic diffusion. Dynamic recrystallization may reduce flow stress through similar mechanisms so comparisons between dynamic recrystallization and recrystallization-induced plasticity may be useful in the future. Both models describe the behavior witnessed in the current study. However, none of the authors that provided mechanistic theories for recrystallization-induced plasticity provided compelling experimental evidence supporting their theories. Atom probe and transmission electron microscopy may be able to separate the effects of defect movement and diffusion of atoms to differentiate between the two proposed mechanisms, and both should be considered in future studies.

Summary

Deviations from a linear thermal expansion in sample dimensions were observed during continuous heating of cold-rolled steel with low applied stress. Several explanations have been suggested to explain the observed deviations which are interpreted to be associated with the onset of recrystallization. The concept that the deviation during recrystallization, not apparent in results obtained with the non-contact (i.e. zero stress) laser dilatometer, is due to dislocation annihilation and texture changes appears to be insufficient, as the deviation would be expected to be observed regardless of applied stress. A more reasonable explanation of the dilation deviation during recrystallization is recrystallization-induced plasticity, and possible mechanisms for recrystallization-induced plasticity are accelerated Coble Creep or dislocation motion due to the directional applied stress. More experimental work is required to determine which of these proposed mechanisms is correct.

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