Thermomechanical Simulation of Hot Rolled Q&P Sheet Steels

Quenched and partitioned (Q&P) steels are one family of steels that has received some recent interest for high-strength automotive applications. Previous Q&P steel research has usually focused on cold rolled and annealed products. In the current study, the thermomechanical profile was modified such that Q&P simulations were developed to characterize material as if it might be produced directly from a hot strip mill.

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Advanced high-strength steels (AHSS) are becoming increasingly important, with particular interest for automotive structures. Quenched and partitioned (Q&P) steels are one family of AHSS that have received attention. Q&P steels were developed with the intent of creating a microstructure that contains martensite and enhanced levels of retained austenite. Similar to transformation-induced plasticity (TRIP) steels, the retained austenite contributes to work hardening. The novelty of Q&P processing is the partial transformation from austenite to martensite by cooling to a predetermined quench temperature, followed by a partitioning step in which carbon migrates from supersaturated martensite into austenite.[1–3]

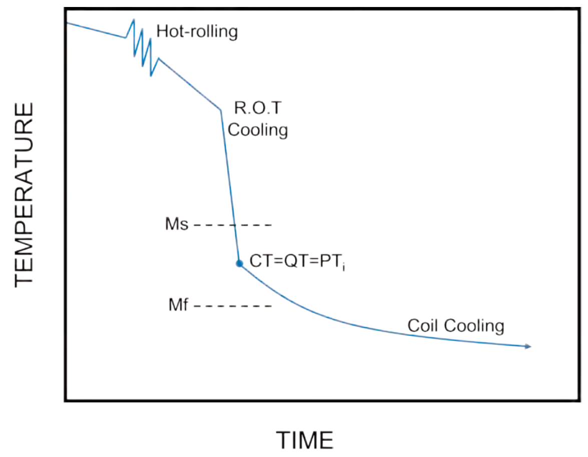
Significant research has been performed in the area of cold rolled Q&P steels, where the Q&P treatment would be applied during annealing or hot-dip coating after cold rolling.[2] To make Q&P steel more broadly applicable, a hot rolled Q&P application might also be of interest. Previous research by Thomas, et al.[1,3] characterized microstructures and properties after Gleeble® simulations of a hot strip mill runout table and coil cooling in a 0.19 C, 1.59 Mn, 1.62 Si steel. In this processing concept, following the schematic thermal profile shown in Figure 1, the coiling temperature is intended to serve as the "quench temperature," defining the martensite fraction, while at the same time controlling the thermal energy available for partitioning. The microstructures observed in this study revealed that simulated coiling temperatures (CT) between 20 and 250°C created dual-phase steel microstructures, coiling temperatures between 200 and 325°C created primarily Q&P microstructures, and coiling temperatures between 300 and 425°C created primarily bainitic TRIP microstructures.[1,3] The processing simulations did not include rolling deformation, and started with intercritical annealing, followed by coiling in an attempt to simulate hot rolled sheet microstructures. The work presented in this article thus represents an extension of the work performed by Thomas; with the acquisition of a new Gleeble 3500 thermomechanical simulator, hot torsion deformation could be performed prior to simulated runout table and coil cooling, allowing a more complete simulation of hot strip mill processing.

This work aimed to compare the effects of hot deformation with the results of Q&P hot rolled sheet simulations obtained without deformation. Gleeble samples were subjected to torsion to simulate rolling, helium quenching to simulate water cooling on the runout table to various selected coiling temperatures, followed by a simulated coil cooling over several hours.

Experimental Procedures

Material of chemical composition shown in Table 1 was used for hot rolled Q&P simulation. The steel was laboratory melted

Figure 1



Schematic Q&P hot rolling thermal profile. The coiling temperature (CT) serves as the quench temperature (QT), which determines the initial fraction of austenite transformed to austenite, and the initial partitioning temperature (PTi), which determines the extent of partitioning that occurs during coil cooling to room temperature.[1]

Table 1

Chemical Composition (wt. %) of the Experimental Steel

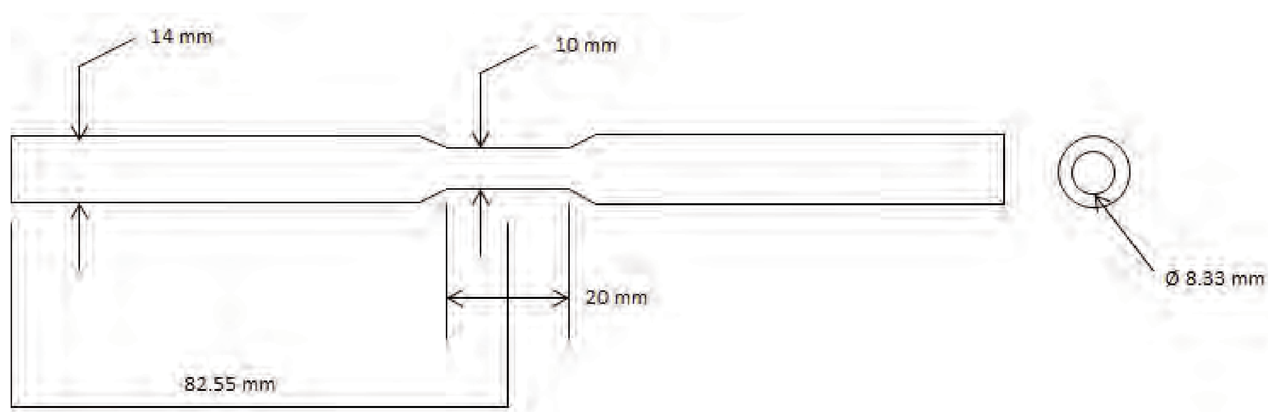
C	Mn	Si	Al	N	P
0.19	1.56	1.61	0.051	0.063	0.008

and hot rolled into a slab about 25 mm thick. This composition was chosen because of its similarity to previous TRIP and Q&P steel studies, and particularly to allow a direct comparison with previous Q&P studies by Clarke[2] and Thomas.[1,3]

Processing was conducted using the Gleeble 3500 thermomechanical simulator at the Colorado School of Mines. The Gleeble samples were machined to the geometry specifications recommended by the manufacturer, Dynamic Systems Inc. (DSI). The specimen geometry is represented schematically in Figure 2. The goal was to simulate rolling, using torsional strains, followed by simulated runout table and coil cooling. Coiling temperatures were selected based on previous simulations by Thomas.[1,3] The experimental matrix consisted of six samples, three with rolling deformation and three without rolling deformation. Following heating and simulated hot rolling, samples of each condition were helium quenched (simulating runout table cooling). The quench was performed in a similar manner for each sample, and the average quench rate was 80, 38 and 31°C/second to desired coiling temperatures of 350, 225 and 150°C, respectively. Then samples were coil cooled using the same thermal profiles employed in the earlier work of Thomas.[1,3] The coiling temperatures were selected to characterize differences in microstructure across a range of coiling temperatures.

The thermomechanical processing schedule is shown in Table 2. The temperature was monitored by a thermocouple welded to the specimen surface at the center of the gauge section. Insulated type-K thermocouple wires were used that could withstand the temperatures experienced during the simulation. Heavier thermocouple wires (0.82 mm in diameter) with insulating sheathing were used to prevent false readings from the heated sample. A sheet spot welder set to 400 psi was used to weld these wires to the specimen. Samples were heated to 1,250°C in one minute and held for 30 minutes to simulate furnace soaking. Samples were then cooled to 1,100°C, the temperature at which roughing deformation began. The strain, the strain rate, times and temperatures at which the sample underwent deformation were based

Figure 2



Schematic illustration of Gleeble® torsion specimen geometry.

Table 2

Simulated Hot Deformation Rolling Schedule

Pass No.	1	2	3	4	5	6	7	8
Equivalent strain	1.00	0.36	0.51	0.41	0.33	0.30	0.25	0.10
Temperature (°C)	1,100	1,041	979	955	934	919	908	898
Interpass time (second)	10.0	8.0	4.8	3.2	2.3	1.7	1.3	—
Twist angle (°)	548.3	197.4	279.6	224.8	180.9	164.5	137.1	54.8

on data taken from literature,[4] and the details are presented in Table 2. The twist angle is related to strain using Equation 1:[5]

$$\varepsilon = \frac{0.724a\theta}{\sqrt{3}l} \quad \text{(Eq. 1)}$$

where

ε is the equivalent strain at an effective radius derived by Barraclough[6] as 0.724 of the actual radius, a,
θ is the twist angle and
l is the length of the gauge section.

The effective radius has been derived to minimize the effects of geometry on local deformation conditions and structure, particularly near the surface, for samples of different geometry. After the multipass rolling simulation, the sample was cooled at 1.6°C/second to 750°C to simulate step cooling to form primary ferrite. Approximately 25% primary ferrite was expected to form during cooling through the intercritical temperature range.[7] Then the sample was quenched with helium to the desired coiling temperature of 350, 225 or 150°C. After the quench, a simulation of coil cooling was employed to match typical conditions employed in steel production.[1]

Standard quench fixtures were insufficient to achieve the desired helium quench rates. In order to meet the time/temperature schedule described previously,[4] some modifications were made to the cooling apparatus. The original quench nozzles were too far away from the sample and the valve openings were too wide to provide a sufficent quench rate. Thus, the quench fixture was moved closer to the sample. Brass pipe fittings were used to move a custom-manufactured T-bar quench fixture to within about 25 mm of either side of the sample. The T-bar fixture had small holes (0.40 mm in diameter) drilled every millimeter across the horizontal plane facing the sample. This arrangement ensured uniform quenching of the sample and provided the desired quenching rate.

The rolling schedule shown in Table 2[4] did not allow sufficient time between passes for the Gleeble sample to air cool to the next pass temperature. Therefore, a slow flow of helium was also used to improve temperature control and achieve the desired cooling rates. This flow of helium began during the last minute of the cool from 1,250°C to avoid any undesired thermal fluctuations and remained on until the final quench temperature was achieved. To avoid an undesirable temperature spike caused by abruptly ending the helium flow, the helium flow was gradually turned off (manually) at the end of the final quench.

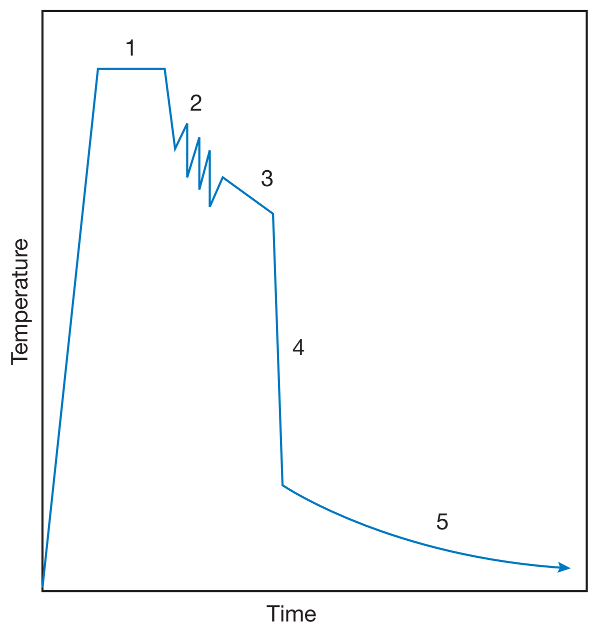
After completion of the thermomechanical simulations, tensile and metallography samples were machined from the Gleeble specimens. The center of the torsion samples was removed by electrical discharge machining (EDM). The outer tubular specimen was used for tensile testing (although the tensile properties were inconsistent due to surface effects and are not reported here), while the material bored from the inner (core) region was used to characterize the microstructure. EDM methods were used in an effort to avoid any excessive heating or plastic deformation that might have resulted from traditional machining methods. Retained austenite fractions were measured by analyzing the outer portion of the bored specimen using x-ray diffraction (XRD), using the analysis methods reported by Thomas.[1] Then, samples were sectioned at the mid-length of the bored section, leaving a circular cross-section, which was mounted and polished. The region near the outer surface of the bored cylinder was examined, as this location was most representative of the microstructure of the tube that received higher torsional strains and was subjected to mechanical testing. Grinding included 240, 320, 420 and 600 grit sandpaper finish, rotating 90° between steps, and polishing was conducted with 6, 3 and 1 μm diamond slurries. The metallographic samples were etched with 2% Nital and observed using scanning electron microscopy (SEM), secondary electron imaging, and compared to previous results from Thomas.[1,3]

Results and Discussion

A procedure was successfully developed that simulated the hot rolling and coil cooling of steel using the Gleeble 3500 system. A representative thermal profile is shown in Figure 3. This profile represents the 150°C coiling temperature following multipass deformation. The various steps in the process are indicated by numbered regions, and the boxed inset at the upper right represents the temperature range of hot deformation.

Selected light optical micrographs are presented in Figure 4, showing substantial differences in the size of the prior-austenite grains present in samples with and without deformation. The prior-austenite

Figure 3



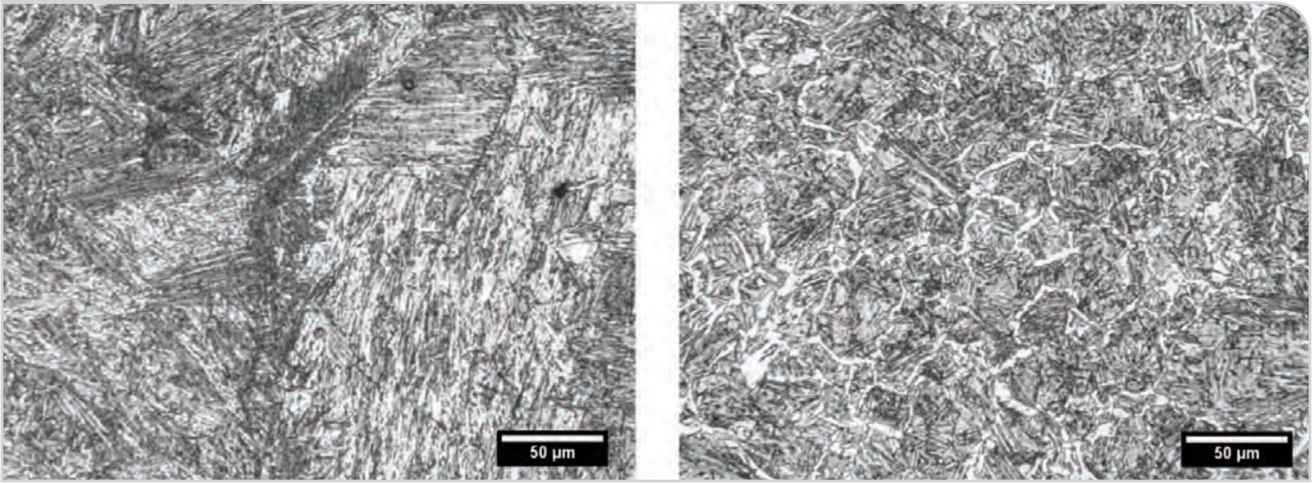
Thermal profile representing 150°C coiling temperature following multipass deformation. Regions 1–5 represent isothermal holding for 30 minutes at 1,250°C, hot deformation over a range of temperatures, controlled cooling to 750°C at 1.6°C/second, helium quenching to the desired coiling temperature, and controlled simulated coil cooling, respectively.

grain size in the simulations exluding deformation were estimated to be approximately 205 μm, while the simulations that incorporated multipass austenite deformation resulted in an estimated prior-austenite grain size of about 30 μm. This behavior is not surprising, as multipass deformation is well known to refine austenite through repeated interpass recrystallization. The deformed samples also exhibit a greater fraction of primary ferrite, resulting from accelerated transformation kinetics associated with austenite deformation/refinement.

The etched microstructures were also viewed at higher magnification using a field emission scanning electron microscope. Results are shown in Figure 5. All microstructures exhibit areas of (predominantly) martensite surrounded by primary ferrite that nucleated on the prior-austenite grains. As mentioned previously, the samples incorporating deformation exhibit a greater fraction of grain boundary ferrite. Figures 5a–d also show areas suggestive of lower bainite between areas of martensite, based on the appearance of fine carbides within the plates or laths (an example is labeled "LB" in Figure 5b). The martensite appears to be associated with thick films of retained austenite, similar to Q&P microstructures observed in previous studies.[1–3]

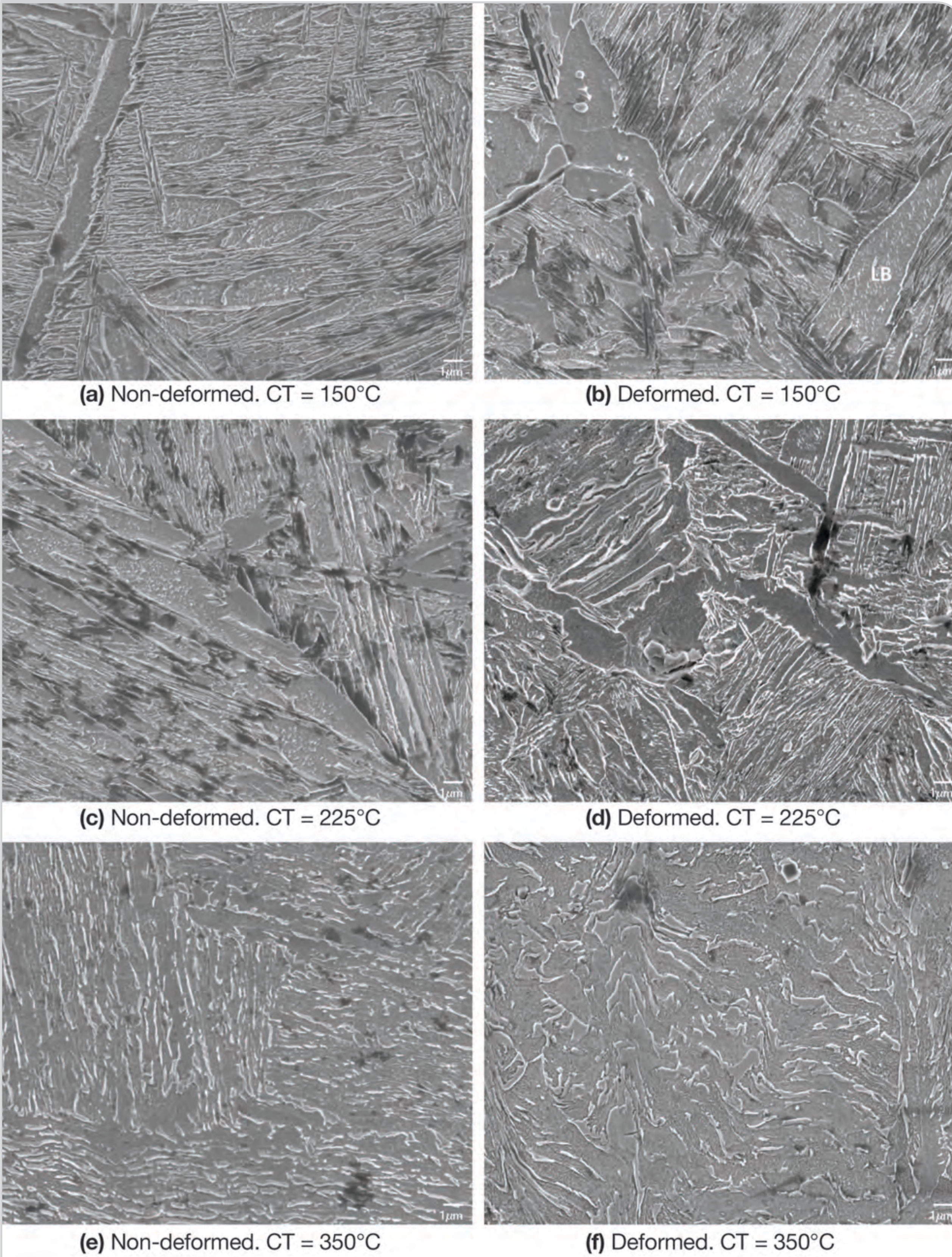
In addition to the effects of austenite deformation on prior-austenite grain size and primary ferrite fraction, the specimens processed using coiling temperatures of 350°C appear to exhibit an interesting influence of austenite deformation on the morphology of the resulting martensite/austenite mixture that is not completely understood. In Figure 5f, there are areas of austenite between bainitic or martensitic martensite laths, and interlath austenite exhibits some curvature. The origin of this morphology is not completly understood, and these observations should be confirmed through additional testing, but are suggestive of an influence of (parent phase) austenite deformation on the morphology of the transformed product phase.

Figure 4



Light optical micrographs showing prior-austenite grain size in specimens processed using simulations without deformation (a) or with multipass torsion deformation (b). A quench temperature of 150°C was used in these simulations. Etched with 2% Nital.

Figure 5

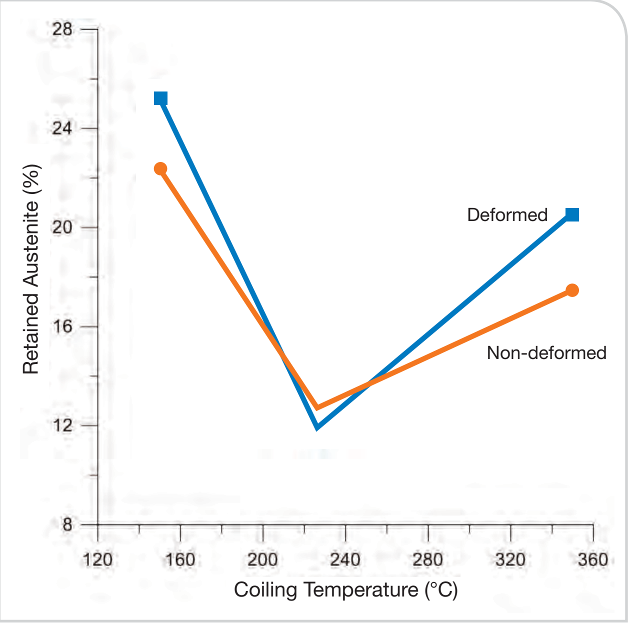


(a) Non-deformed. CT = 150°C
(b) Deformed. CT = 150°C
(c) Non-deformed. CT = 225°C
(d) Deformed. CT = 225°C
(e) Non-deformed. CT = 350°C
(f) Deformed. CT = 350°C

SEM secondary electron images of etched specimens following Gleeble simulation. Samples processed without any deformation are shown in the left column, and samples processed using the full hot strip mill simulation incorporating multipass torsion deformation are shown in the right column. Images from top down represent simulated coiling temperatures (CT) of 150, 225 and 350°C, respectively. Etched with 2% Nital.

X-ray diffraction analysis was performed to quantify retained austenite fractions following Gleeble simulation; results are shown in Figure 6. The retained austenite fractions are similar in the deformed and non-deformed conditions, indicating that multipass deformation of the austenite does not appear to have a profound influence on the phase fractions following the quenching and partitioning steps. A reduced amount of retained austenite was measured for the intermediate coiling temperature (225°C); the reason for the reduced austenite fraction in this condition is not yet apparent.

Figure 6



Retained austenite fractions (volume percent) in samples given hot strip mill Q&P process simulations with and without deformation, for three coiling temperatures.

Summary

A method for the Gleeble simulation of hot rolled Q&P steel was successfully developed and utilized to simulate hot rolling, runout table and coil cooling of sheet steel. The hot rolling simulations yielded interesting microstructures containing substantial austenite fractions in combination with a primarily martensitic matrix. Multipass austenite deformation was shown to refine the prior-austenite grain size and increase the fraction of primary ferrite, and also appeared to influence the morphology of the transformation product in one instance.

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Authors' Note

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