The results of a recent research program indicate that austenite particle size refinement is an important contributor to the enhanced stability of retained austenite.

Bainitic Stabilization of Austenite in Low Alloy Sheet Steels

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The beneficial role transformation plasticity plays in the uniform ductility of microalloyed sheet steels was firmly established by the definitive tempering experiments of Gil Speich.1,2 Recent work supporting this role has demonstrated that effective stabilization of retained austenite can be achieved by employing an isothermal bainitic transformation after intercritical annealing.3,4 The result is a “triple-phase” ferrite/austenite/martensite microstructure. This paper further explores the relationship between austenite stability and mechanical properties. The mechanical property objectives of this research are a 3 percent flow stress between 75 and 100 ksi, along with a uniform ductility between 20 and 30 percent under plane-strain tension (Figure 1).

The austenite stability is quantified by determining the temperature at which the mode of retained austenite transformation changes from stress-assisted to strain-induced. This temperature is above the Ms temperature and is known as the M\text{st} temperature (Figure 2). Below this temperature the retained austenite transforms to martensite via pre-existing nucleation sites. Above this temperature and up to Ms (above which no martensite is produced), martensite is nucleated at both preexisting and predominantly new nucleation sites produced by the plastic strain. These temperatures are stress-state dependent.5,6

The reversal of the yield strength temperature dependence at the Ms temperature allows for an easy technique to determine this temperature in fully austenitic steels. In steels with small volume fractions of retained austenite, a more sensitive technique is employed to measure the temperature dependence of microyielding.7,8

Two factors affecting the retained austenite stability also have been studied. The enrichment of austenite with carbon is an acknowledged technique to stabilize retained austenite. In these experiments, a second factor (retained austenite pool size) was demonstrated to provide a significant stabilizing effect. This is predicted by the statistical transformation kinetic model developed by Olson and Cohen.9 The model is based on the distribution of potencies of nucleation sites in austenite for the transformation to martensite. Smaller retained austenite pools contain lower potency nucleation sites and require greater total driving force for nucleation.

**EXPERIMENTAL PROCEDURE**

Two steels were produced at the Inland Steel Research Laboratory as 100 pound (45.36 kg) vacuum degassed ingots (Table 1). The ingots were milled to remove surface scale and hot rolled to a thickness of 0.29 of an inch (7.366 mm). Next, 0.035 of an inch (0.889 mm) was milled on each side of the hot band to remove the decarburization.

**Table 1 Compositions of the Two Steels Produced by Inland Steel Research for This Test**

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
<th>P</th>
<th>S</th>
<th>N</th>
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<td>0.2700</td>
<td>0.8100</td>
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<td>0.0390</td>
<td>0.0070</td>
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<td>0.0043</td>
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<td>1.2200</td>
<td>1.5200</td>
<td>0.0500</td>
<td>0.0020</td>
<td>0.0030</td>
<td>0.0008</td>
</tr>
</tbody>
</table>

This is an update of a paper presented at the ISS Gilbert R. Speich Symposium held in October 1992 in Montreal, Quebec, Canada.
layer, resulting in a final thickness of 0.221 of an inch (5.613 mm). The hot band then was cold rolled to a final thickness of 0.067 of an inch (1.702 mm), a 69.7 percent reduction.

The cold rolled material was machined to the required specimen size prior to heat treatment. This was done to avoid transformation of retained austenite to martensite because of the machining forces. It also avoided any localized tempering due to the heat generated during machining.

The heat treatment cycles (Figure 3) were conducted in two neutral salt baths. The intercritical annealing bath was held at 1,418°F (770°C), where experiments in a fluidized bed showed that the microstructure was 50 percent austenite after a five minute anneal. The isothermal transformation bath was at 752°F (400°C). Following heat treating, all specimens were quenched in an ice brine solution. The majority of the analysis was completed on the 0.26 percent C-1.22 percent Mn-1.52 percent Si steel.

Tensile tests were conducted on an Instron 4206 machine at a crosshead speed of 0.1 inch/minute (0.254 cm/minute), for a strain rate of 0.033/minute. The strain was recorded using a standard Instron extensometer. M₄[uniaxial tension (UT)] measurements were conducted on a Gleeble 1500, also at a crosshead speed of 0.1 inch/minute (0.254 cm/minute), for a strain rate of 0.847/minute at the temperatures indicated. The microyield load was measured at a strain of 0.16 percent using a transverse LVDT. The M₄(UT) determination was made using the Bolling-Richman single-specimen technique. All of these specimens were made to ASTM specification A 370 for a longitudinal sheet specimen.

The plane-strain specimens were based upon the design of Corrigan (Figure 4). The specimens were marked using a Vickers DPH tester at 500g prior to testing, in order to confirm that the plane-strain constraint was followed. The strain was measured using a point micrometer at the completion of the test.

The volume fraction of retained austenite was determined by x-ray diffraction (XRD) using the relationship determined by Miller, and then compared with NIST-certified standards. The carbon content of the austenite was determined via lattice parameter measurements using the relations of Ruhl and Cohen, and Ridley, Stuart and Zwelling. The specimens used for XRD analysis were taken from tensile specimen grip ends. The analysis was conducted with a Mo K (alpha) x-ray tube in a Scintag XDS 2000.

Metallographic specimens also were taken from the tensile specimen grip ends. These specimens were polished down to a 1 micron diamond paste finish. A two component tint etchant, consisting of 2 grams of sodium metabisulfite dissolved in 100 milliliters of distilled water, was mixed just prior to use with 4 grams of picric acid dissolved in 100 milliliters of pure ethanol. The etching time was 15 seconds.

**THEORY**

The first step in the research program was to obtain stable retained austenite at room temperature. The technique used to achieve this was an intercritical anneal to form approximately 50 percent austenite (770°C), followed immediately by an isothermal transformation (IT) heat treatment in the upper bainite region. Holding at the IT temperature [752°F (400°C)] permitted the transformation of some of the austenite to bainitic ferrite.

A high-silicon content was used to inhibit cementite precipitation. The manganese in the steel served the dual purpose of slowing the austenite to ferrite transformation, while increasing the stability of the retained austenite. Since cementite precipitation is inhibited by the silicon in the steel, the carbon rejected by the bainitic ferrite enriched the remaining austenite and helped to stabilize it.

Another stabilizing effect on the retained austenite is a small particle or pool size, as noted by Rigsbee, as well as by Cech and Turnbull. The stabilizing effect of a small particle or pool size also is explained in the kinetic model developed by Olson and Cohen. Another prediction of the Olson and Cohen model is the stress-state dependence of M₄. Compared with uniaxial tension, a more stable retained austenite is required for a material to be
deformed under plane-strain tension, as in the stretch forming of sheet. The uniform ductility can be increased by transformation strain hardening if the retained austenite has the optimum level of stability.\textsuperscript{19, 20}

In this study the effect of the stability of the retained austenite upon the uniform ductility under uniaxial and plane-strain tension was studied. The effects of carbon content and the particle size of the retained austenite were correlated with the austenite stability.

RESULTS
The mechanical properties of the steel were studied in three ways:
(1) Uniaxial tension test
(2) Plane-strain tension test
(3) Uniaxial tension $M^\circ$ measurements

The uniaxial tension tests are especially useful for comparing these results with other published data. The uniaxial tension tests also provide a convenient way to monitor the influence of thermomechanical processing on the stability and volume fraction of the retained austenite.

The ultimate mechanical property objectives of this research are specified for plane-strain tension as the stress-state encountered at the site of failure in sheet steel forming. The $M^\circ$ (UT) measurements show more explicitly and quantitatively the increased stability of the retained austenite with increasing IT times. XRD analysis of the specimens indicated that the stability of the retained austenite was of greater importance to the mechanical properties than the volume fraction of the retained austenite. XRD analysis also showed the effects of carbon content and, indirectly, size, upon the stability of the retained austenite.

Uniaxial Tension Test
The general trend of the ultimate tensile strength is to decrease as the IT time increases (Figure 5). A log-log plot of the true stress versus true strain flow curves at various IT times (Figure 6) shows that the curves are almost parallel. This allows for an easy way to model the effect of IT time:

$$\sigma = \sigma_0 (1 + Ke^n)$$

The “K” parameter is a function of IT time and provides a way to judge the effectiveness of the thermomechanical processing. This will be used in future modeling of the effects of IT time upon mechanical properties.

The amount of uniform elongation increases rapidly at first, and then levels off after IT times of two minutes and greater (Figure 7). This phenomenon is attributed to unstabilized austenite transforming to martensite at short IT times. At longer IT times it decomposes to ferrite and bainitic ferrite, which then can stabilize the remaining austenite. As the IT times increase past the retained austenite peak, the volume fraction of retained austenite is decreasing continuously due to decomposition. Meanwhile, the stability of the remaining retained austenite is increasing continuously because of carbon enrichment and decreasing pool size. This result is discussed later.

Yield strength increases slightly with IT time (Figure 7), due to the greater strength of the bainitic ferrite produced by the decomposition of the austenite, as compared with marginally stabilized retained austenite, which decreases the initial strain hardening rate as it transforms and induces early yielding. As the IT times increase to two minutes, the martensite formed from retained austenite is increasing in carbon content and, hence, strength. After two minutes the retained austenite has effectively reached its maximum carbon content, and additional increases in yield strength are due to increasing volume fractions of bainitic ferrite.

The 3 percent flow strength is relatively unaffected by increasing IT times. The increase in bainitic ferrite and the greater stability of the retained austenite as the IT time increases, apparently offsets the greater amount of martensite formed at small strains after short
IT times, due to the reduced stability of the retained austenite (Figure 7). Similar to Figure 1, a plot of uniform elongation under uniaxial tension, versus the 3 percent flow stress for the two steels undergoing the same thermomechanical processing (Figure 8), shows the effect of composition upon these properties. The plot defines a band of possible properties for each composition as a function of time, and demonstrates a beneficial effect of higher Mn content.

**Plane-Strain Tension Test**

The plane-strain tension test showed the sensitivity of the retained austenite to the stress-state. A similar increase in uniform ductility was experienced during plane-strain testing, with increasing IT time (Figure 7). However, the ductility was slightly lower, which can be attributed to the lower retained austenite stability in the plane-strain stress state.

Before the volume fraction peak of retained austenite, the retained austenite is of insufficient stability to provide much mechanical stability, i.e., delay the onset of localized necking. After the volume fraction peak, a substantial reduction [approximately one-half (Figure 9)] in the volume fraction of the retained austenite occurs at four minutes IT time, without a corresponding increase in retained austenite stability.

The next IT time studied (five minutes) shows a marked increase in mechanical stability. This is due to the significant increase in retained austenite stability. However, the increased stability is not from an increase in percentage carbon in the retained austenite (Figure 9), which levels out after about two minutes IT time. The increased stability is attributed to the smaller size of the retained austenite pools (Figure 10).

**M₆₇(UT), XRD and Metallography**

The M₆₇(UT) results, when combined with the XRD analysis and metallography results, are very informative. As expected, the M₆₇(UT) tests show a decrease in M₆₇(UT) temperature with increasing IT time (Figure 9). The XRD analysis results use lattice parameter measurements¹⁴,¹⁵ to provide both the volume fraction of retained austenite and carbon content. These results indicate that the maximum carbon content is achieved at about two minutes IT time, while the retained austenite volume fraction peak occurs at three minutes IT time.

Prior to the peak, insufficient carbon has diffused into all of the nonuniform austenite to stabilize it against transformation upon cooling to ambient temperature. After the peak in volume fraction of retained austenite, and since the carbon content is approximately constant, it is expected that the excess carbon is precipitated as cementite. Previous research⁶ has found carbides precipitating after four minutes in similar alloys. Transmission electron microscopy is planned to determine definitively if that is the case in this study.

The metallography results offer a reason for increasing stability with increasing IT time. The results (Figure 10) show a marked decrease in retained austenite pool size with isothermal transformation, although detailed variations with transformation time are difficult to measure with optical microscopy. Additional analysis is planned using a Tracor Northern Image Analyzer. The austenite (and transformed martensite) is the white phase in Figure 10; the dark phase is the ferrite and bainite. The particle size factor provides additional stability to the retained austenite.

**DISCUSSION**

The effect of stress-state upon the transformation kinetics of austenite to martensite have been well studied. An early model that successfully predicted the change in the M₆₇ temperature was the Patel-Cohen model.⁷ It showed that the M₆₇ temperature was raised by uniaxial tension, raised less by uniaxial compression and lowered by hydrostatic pressure.

A later model based upon the earlier one of Olson and Cohen⁸ was developed by Haebelrouck.⁹ Haebelrouck studied
the effect of stress-state upon the free-energy change due to stress in the driving force term of the Olson-Cohen minimum defect size required for the nucleation of martensite. Haezebrock developed a relationship between stress-state and the mechanical driving force contribution.

An understanding of the relationship between the amount of retained austenite, its stability as a function of pool size and carbon content, and mechanical properties, is critical to properly exploiting the benefits of a triple-phase steel. The specimens with the maximum volume fraction of retained austenite (three minute IT time) did not provide the best mechanical properties at room temperature. A larger carbon content would be required for this steel composition to stabilize approximately 20 percent retained austenite, compared with the specimen with the best mechanical properties and lower retained austenite of approximately 8 percent.

The variation of uniform ductility with test temperature for these two conditions (two-minute and five-minute treatments) is shown in Figure 11, demonstrating the greater ductility enhancement associated with the higher austenite stability at higher temperatures.

Contours of constant uniform ductility versus austenite amount and stability (measured as $T-M_{s}^{o}$, where $T$ is the test temperature) are presented in Figure 12, based on the experimental measurements in uniaxial tension. Consistent with the experience in previous studies of transformation plasticity in austenitic steels, optimum austenite stability for ductility enhancement corresponds to $T-M_{s}^{o} +34^\circ$F ($10^\circ$C), and the contours of Figure 12 are drawn to reflect this. The best properties should thus be achieved with an $M_{s}^{o}$ slightly below room temperature.

Since the maximum carbon content in the retained austenite was reached fairly early (two minutes IT time), a steel with retained austenite of sufficient stability due to small pool size might be developed with a more appropriate composition for commercial use. The decreasing $M_{s}^{o}(UT)$ temperature is due to the decreasing pool size (Figure 10) after two minutes. Prior to that point, a combination of pool size and carbon content affect stability.

The uniform ductility contours of Figure 12 suggest that the desired plane-strain ductility of 20 to 25 percent at a 5 percent flow stress of ~90 ksi could be obtained with only ~5 percent austenite, if sufficient stabilization could be achieved to place the plane-strain $M_{s}^{o}$ temperature at ~10$^\circ$C. Such stability could be achievable through a combination of alloying and austenite size refinement. The reduced requirement in austenite content would then allow a significant reduction in alloy carbon content for improved weldability.

**CONCLUSIONS**

The results obtained in this study emphasize the important role of austenite stability in the enhancement of uniform ductility in triple-phase steels. Superior properties are obtained with only 8 percent austenite, compared with 20 percent austenite when the austenite stability is sufficiently increased toward the optimum.

The results further indicate that, in addition to carbon enrichment, particle size refinement is an important contributor to enhanced stability. Further ductility enhancement should be attainable with relatively modest amounts of austenite, if the $M_{s}^{o}$ temperature can be depressed below ambient.

**ACKNOWLEDGMENTS**

The authors are grateful for inspiring discussions with Professor Gilbert...
Speich during the early stages of this research. Professor Speich died in 1990 and the symposium at which this paper was presented was held in dedication to his memory. This research is supported by Inland Steel Company and the Basic Energy Sciences Division of the U.S. Department of Energy under Grant No. DE-FG02-88ER 45365.

References