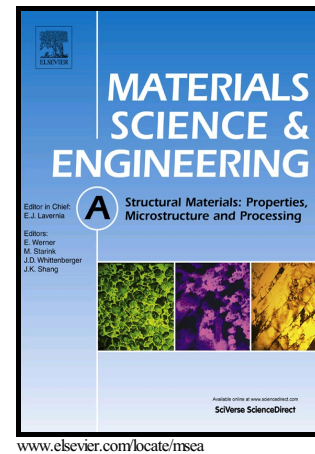


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Effect of Strain Path on Forming Limits and Retained Austenite Transformation in Q&P 1180 Steel

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Abstract

Forming limits and retained austenite (RA) transformation in Q&P 1180 steel are quantified as a function of plastic strain levels for three different strain paths. In-plane uniaxial tension testing was performed in a standard test frame, while limiting dome height tooling was employed for out-of-plane biaxial and plane strain tension experiments. Sheet specimens were tested incrementally for each strain path, and the RA content at each level of strain was measured using electron backscatter diffraction (EBSD). The biaxial tension strain path resulted in the greatest effective strain prior to necking at 0.355, compared to 0.123 for plane strain and 0.142 for uniaxial tension. EBSD measurements for various levels of plastic strain reveal a clear dependence of RA rate of transformation on strain path for the three linear strain paths that were employed in this work. Thinning strains appear to provide a slightly better correlation to RA transformation than effective strain levels, where biaxial tension achieved the greatest level just prior to necking, followed by plane-strain tension, and then uniaxial tension.

Introduction

Steel alloys have undergone significant development over the past 10 years with particular effort directed toward achieving a good balance of strength and formability. The emergence of advanced high strength steels (AHSS), with ultimate tensile strengths (UTS) of 600 – 1500 MPa, has played a significant role in the lightweighting activities of most automakers. Dual phase (DP), transformation induced plasticity (TRIP), and hot-stamped boron alloys are examples of AHSS that have been integrated into the body-in-white (BIW) structure. Lower strength alloys continue to be used, because AHSS formability is not sufficient to form the complex shapes that are needed for some parts of the BIW. Even so, the trend has been toward the use of high strength steels that promote lighter structures through downgauging [1].

Dual phase (DP) steels have microstructures composed of various fractions of ferrite and martensite, depending on the alloy. The ferrite provides ductility, while the martensite increases strength roughly proportional to its quantity in the microstructure. Commonly used alloys include DP 590, DP 780, and DP 980. All three alloys have microstructures of ferrite and martensite, but the phase fractions are different for each one. DP 590 has a mixture of approximately 80% ferrite and 20% martensite; DP 780 has 60% ferrite and 40% martensite; and DP 980 has 40% ferrite and 60% martensite. Exact phase fractions vary from supplier to supplier. In general, ductility in DP steels tends to be limited by fractures that initiate by decohesion at the interfaces between the martensite and ferrite phases. These fractures at the level of the microstructure are induced by inhomogeneity in strain between hard and soft phases [2]. This is a contrast to the classic ductile failure mode that can be observed in a single-phase alloy like IF steel, where micro-void growth and coalescence are the mechanisms that facilitate crack initiation.

Bainitic steels were developed in order to achieve a good combination of strength and ductility, beyond what was possible with DP steels. These alloys have a smaller contrast in hardness between the various phases present in the microstructure than is true with DP steels [3, 4]. When retained austenite (RA) is combined with bainite, ferrite, and some martensite the resulting material is referred to as

transformation induced plasticity (TRIP) steel, where the volume fraction of RA can reach 20% [5]. Lower alloy versions of this material are called TRIP-assisted bainitic ferritic (TBF) steel if the RA portion of the microstructure is smaller, usually about 10% or less [6]. TBF steels have slightly more carbon and significantly more silicon than DP steels. The higher silicon content is needed to minimize the formation of cementite during the transformation of austenite to bainite [7]. Chemistry and thermomechanical processing give TBF steels a microstructure composed of bainitic-ferrite laths, with finely dispersed RA in between the laths [8]. When TBF steel is deformed plastically, much of the RA transforms to martensite, thereby increasing the hardening rate and overall formability of these alloys, compared to DP steels having similar levels of tensile strength. In addition to the beneficial effect of austenite transformation to martensite, TBF steel ductility is increased because the tendency for strain localization around hard phases in the microstructure is lower than for DP steel, since its ability to distribute strain across different phases in the microstructure is greater. Compared to other AHSS like DP steel, TBF alloys are more formable, as measured by total elongation in a tension test, and have a higher work hardening rate. For example, TBF 980 has a strain hardening exponent (n) of 0.22, versus 0.15 for DP 980 [9]. Higher n correlates to better strain distribution in a press forming operation, where complex strain paths are typical.

RA plays a role in the new quenching and partitioning steels (Q&P), where the partitioning step allows for diffusion of carbon from martensite to surrounding RA phases [10-12], thus reducing the hardness of the martensite and creating less tendency for localization around hard phases during plastic deformation. In addition to the carbon enriched austenite and low carbon lath martensite, the microstructure contains some ferrite and bainite [13] since the partitioning temperature is usually in the bainite transformation region and the annealing step can often start in the intercritical range, thus yielding a certain fraction of ferrite after final quench [14]. RA is often credited with increasing ductility in various AHSS alloys; therefore, its effect on forming limits and its transformation rate as a function of strain level was studied. Electron backscatter diffraction (EBSD) was used to identify RA volume fraction in Q&P 1180 steel sheets as a function of plastic strain. Three different strain paths were employed to quantify their effect on RA transformation rate. Limit strains for each strain path, and a corresponding forming limit diagram, were also generated for this sheet alloy.

Experimental Procedures

The sheet material to be evaluated was 1.25mm Q&P 1180 steel, produced by Baosteel (and provided by General Motors). The nominal composition of this alloy is 0.2wt% C, 1.5-3.0wt% Mn, and 1.0-2.0wt% Si. Tension testing of this material provided an approximate yield strength of 1000 MPa and ultimate tensile strength of 1180-1220 MPa. Tensile specimens followed the full-size ASTM E8 standard for sheet materials.

An Interlaken hydraulic press was used for plane strain and biaxial tension experiments, with standard limiting dome height (LDH) tooling, including a 100mm diameter punch. The press had a maximum clamp load of 334kN and maximum punch load of 223 kN. Tooling with small lockbeads was used to restrain the blanks, where the beads were small enough to prevent breaking the sheet, but large enough to provide restraint, as seen in Figure 1.

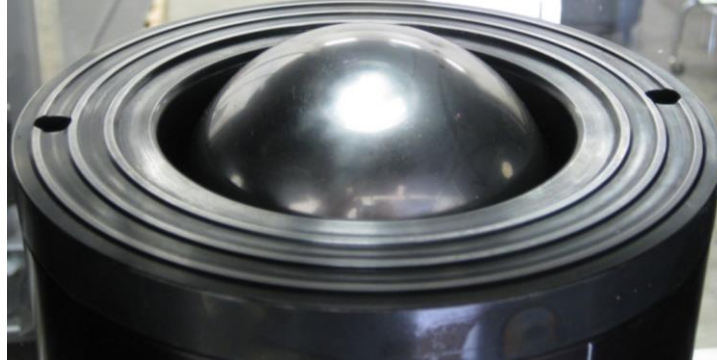


Figure 1. Tooling used for plane strain and biaxial tension experiments.

Strain was measured by coating the surface of each specimen with a white paint suited for bonding to bare metal. Black paint was then applied to the specimen surface to give a random speckled pattern. An Aramis Digital Image Correlation (DIC) [15] system was used to measure the surface strains during testing.

For biaxial tension, sheets that were 200mmx200mm were used to create a fully clamped specimen. For the plane strain specimens, the standard procedure of testing different blank widths and plotting punch failure height versus width was performed, with the width corresponding to the minimum height being chosen. In this case, the width that provided a plane strain fracture was 70mm. Mineral oil and thin Teflon sheets were used as lubrication between the punch and the Q&P 1180 sheets (see Figure 2).

Sheets were strained to fracture in uniaxial tension, plane strain tension, and biaxial tension. Then the displacement that resulted in fracture in each case was used to compute incremental displacements of 25%, 50%, and 75% of failure (in terms of displacement boundary conditions, not strain) for each strain path, as seen in Table 1.

Table 1. Displacements used for deformation experiments on 1.2mm Q&P 1180 steel.

Percent of Failure Displacement	25%	50%	75%	100%
Biaxial Tension (punch displacement – mm)	7.9	15.9	23.8	31.8
Plane Strain Tension (punch displacement – mm)	5.5	11.0	16.6	22.1
Uniaxial Tension (crosshead displacement – mm)	3.0	6.1	9.1	12.1

After the sheet stretching experiments were completed, specimens were removed from the formed sheets by wire EDM, mounted, and polished for EBSD. The portions of sheet that were removed for microscopy were those in the region of eventual fracture. Mounted specimens were then prepared by sanding with grits of 400, 600, 800, 1200, and 1200 fine. The specimens were electropolished using electrolyte comprised of 25 ml perchloric acid and 75 ml butanol in 125 ml methanol at 20 V and 10 °C for 20 seconds.

The EBSD data were acquired on a square scan grid using an accelerating voltage of 20 kV, a working distance of 17 mm, tilt angle of 60 (with 10-degree tilt built into the clamps on the stage) at a magnification of 8000X, a scan size of 17.5x17.5 μm^2 , and a step size of 80 nm.

Phase identification was obtained using OIM analysis software [16]. When diffraction patterns are indexed there can be several possible orientations which match the diffraction bands in the pattern.

OIM software ranks these orientations (or solutions) using a voting scheme. The confidence index value is then based on the results of this voting scheme and ranges from 0 to 1, where 0 represents no votes for an orientation and 1 represents 100% of the votes. In a prior study, by Wang and Speer [10], RA was identified by EBSD scan with results accepted that had a CI of greater than 0.05. This produced good results compared to x-ray diffraction (XRD), where the EBSD volume fraction was less than the XRD volume fraction, but within about 3% in the worst case. Therefore, the same CI criterion was used in the present work, with the additional requirement that grains composed of less than 3 points were also removed. This filtering method was necessary to reduce noise from the phase identification process, as will be shown in the results section.

Results and Discussion

Tension testing of the Q&P 1180 sheet yielded total elongations of about 15% for three tension tests. Engineering stress-strain curves for this material are shown in Figure 2.

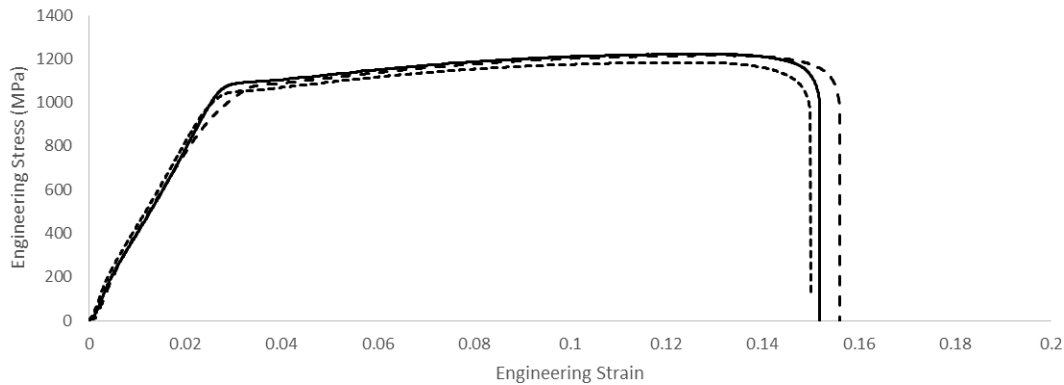
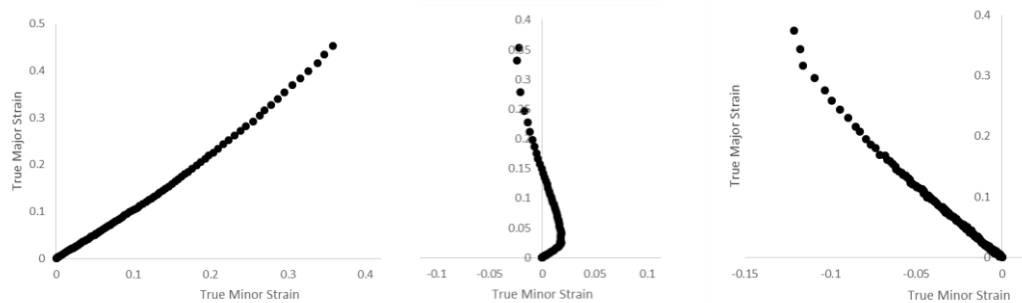


Figure 2. Engineering stress-strain curve from tension testing results of 1.25mm thick Q&P 1180 steel (an extensometer was not used, so elongation is approximate). Full size ASTM E8 specimens were employed.

Engineering stress-strain curves are not included for the plane strain and biaxial strain paths but plots of the DIC-based strain paths for each case are shown in Figure 3. The raw DIC results appear to overestimate strain, because DIC strain values are taken from regions of peak strain in the sample, even after necking has begun to occur in these regions. There is not an easy way to determine, from the major and minor strain plots alone, whether a sheet has started to neck. The process for identifying the point of necking is described below.



(a) (b) (c)

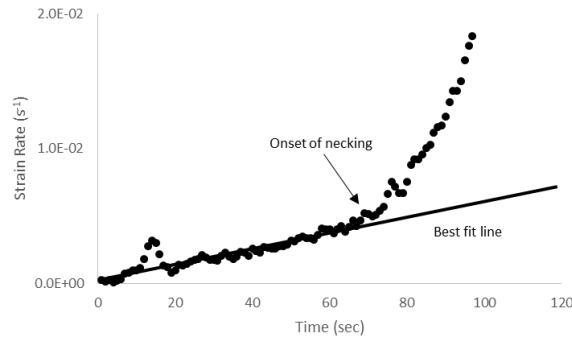
Figure 3. Strain paths from DIC measurements for (a) biaxial tension specimen, (b) plane-strain tension specimen, and (c) uniaxial tension specimen.

The plots from Figure 3 show that biaxial tension and uniaxial tension strain paths are reasonable in terms of the true major/minor strain ratios. For example, the biaxial tension strain plot has a 1:1 ratio between major and minor strains throughout the test, while uniaxial tension displays an approximate 2:1 ratio (where minor strain is negative). For plane-strain tension, the initial strains are slightly positive biaxial, then tend toward plane strain, then later become a bit more uniaxial in nature. However, these deviations are minor, and as will be shown, the point at which necking occurs is actually very close to plane strain.

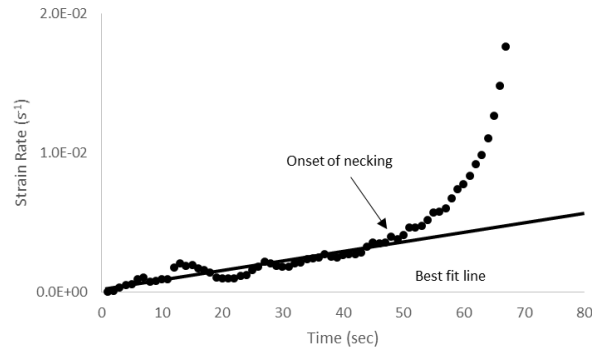
As mentioned, all of these plots have terminal strains that are much greater than the “limit” strain of the material because they include strain values that occur after necking. In order to determine the true limit strains from the DIC strain data, the strain rate was plotted for the entire test and acceleration in strain rate caused by necking was identified. The strain rate was computed at the eventual fracture location, for all of the data from each test, using the following approach:

$$\dot{\varepsilon}_1(j) = \frac{d\varepsilon_1}{dt} \approx \frac{\varepsilon_1(j+1) - \varepsilon_1(j-1)}{2\tau}$$

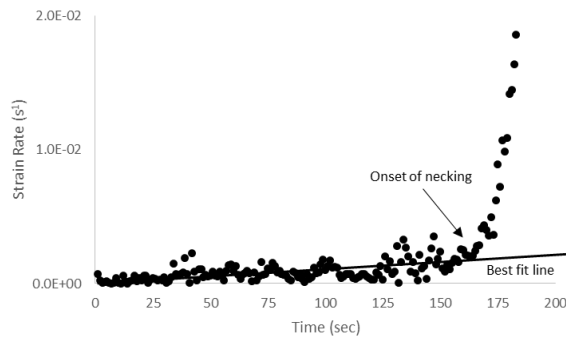
where $\dot{\varepsilon}_1$ is the strain rate in the major direction, ε_1 is true strain in the major direction, τ is the period between frames, and j is the frame number from the DIC analysis. In this case, the period between frames was approximately 1 second. Plots of strain rate vs time for each strain path are shown in Figure 4.



(a)



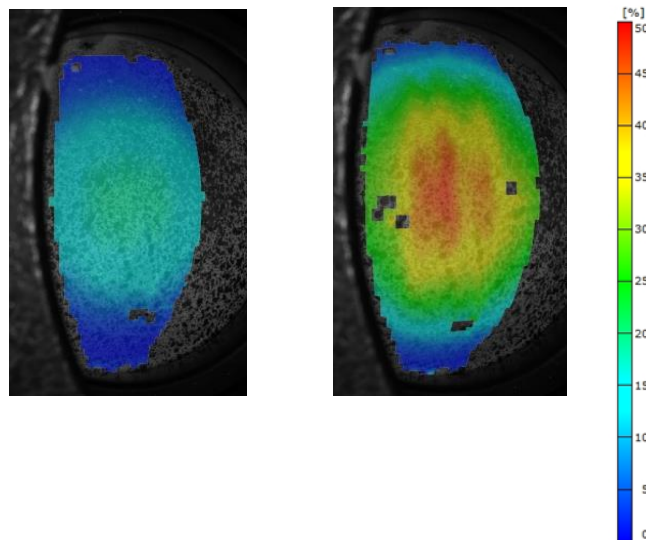
(b)



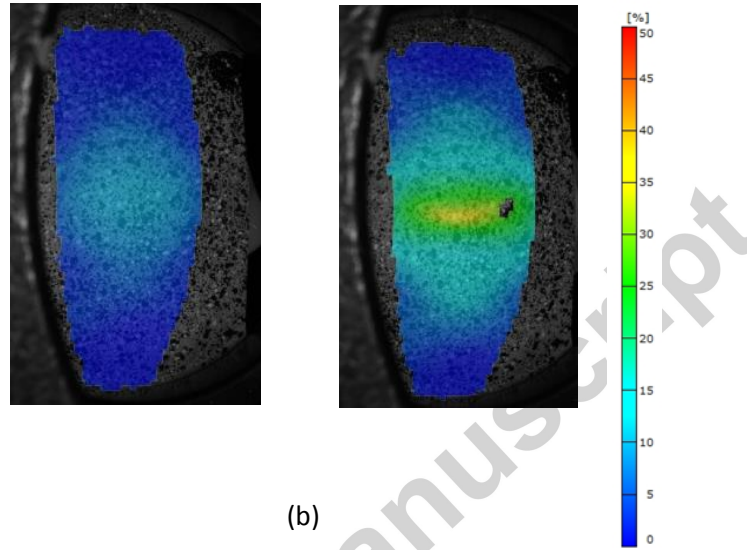
(c)

Figure 4. Onset of necking identified by divergence of strain rate at eventual fracture location for (a) biaxial tension, (b) plane-strain tension, and (c) uniaxial tension.

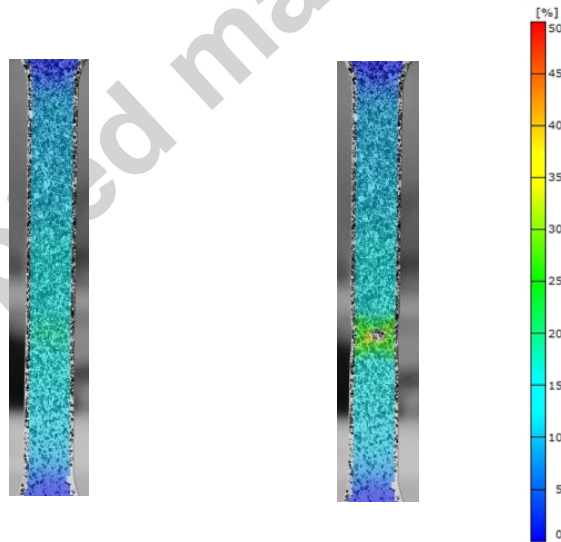
When the strain rate increases rapidly and diverges from a best-fit line of the linear portion of the curve, then the onset of necking is considered to have occurred at the point of divergence. The corresponding true major strain at this point is then taken as the limit strain for the material, for the particular strain path imposed. DIC strain patterns taken at the onset of necking and for the moment before fracture are shown in Figure 5.



(a)



(b)



(c)

Figure 5. DIC strain patterns for (a) biaxial tension, (b) plane-strain tension, and (c) uniaxial tension experiments. In each case the image on the left represents the strain just before necking, while the image on the right has the strain level just before fracture.

Using the computed limit strains (from method shown in Figure 4), along with the strains measured for various increments of stretching along each strain path, the forming limit curve was generated for 1.2mm Q&P 1180, as shown in Figure 6.

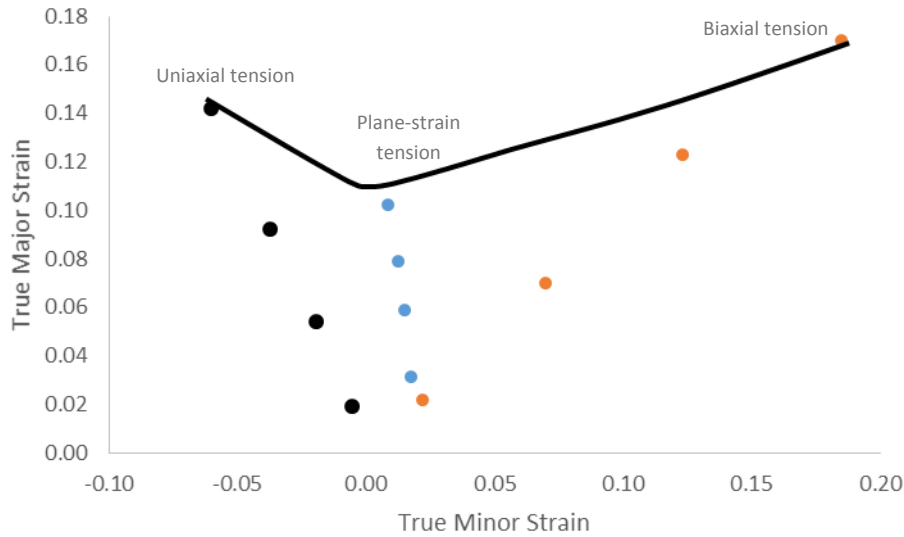


Figure 6. Forming limit diagram for Q&P 1180 with corresponding strain paths. Each data point represents a specimen, and each path required 4 specimens.

Note on Figure 6 that uniaxial tension (black) and biaxial tension (orange) strain paths are linear until the onset of necking, while plane-strain tension (blue) was slightly positive biaxial at low strains, then terminated close to plane-strain. The fourth data point in each case (to create the forming limit curve) represents the limit strains identified from Figure 4. In terms of the effective strain levels corresponding to these limit strains, they are displayed in Table 2 for each strain path.

Table 2. Limit strains for each strain path, along with corresponding effective strain levels.

	Biaxial Tension	Plane Strain Tension	Uniaxial Tension
Limit strains ($\epsilon_{major}/\epsilon_{minor}$)	0.185 / 0.170	0.102 / 0.008	0.142 / -0.060
Corresponding effective strain	0.355	0.123	0.142

Prior work on forming limits for a 1.2 mm Q&P 1180 steel, using LDH tooling and DIC surface strain measurements, exhibited major limit strains of about 0.2 for uniaxial tension, 0.15 for plane-strain tension, and 0.3 for biaxial tension [17]. The prior values are somewhat greater than those presented in the current paper, but show the same tendency, where biaxial tension had the greatest major limit strain, followed by uniaxial tension and then plane-strain tension. After the experiments were completed, specimens were cut from the sheets and mounted for EBSD analysis. Percent RA was measured as a function of effective strain. Four measurements of RA were performed for each strain level, on each specimen. A phase map of the as-received material is shown in Figure 7.

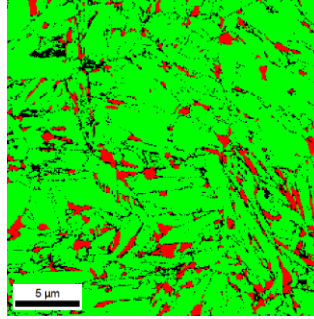


Figure 7. RA (in red) in unstrained Q&P 1180 steel, obtained by phase identification from EBSD scan. For the as-received material the volume percent RA content was 8.7%, as an average of 6 scans.

Phase identification was easier for lower strain levels and more difficult as the point of necking was approached. Dislocation density increases as the material is deformed so the corresponding image quality of the EBSD scans declined at higher strain levels. Therefore, a clean-up method was used to remove patterns that were indexed incorrectly or simply represented bad data. To do this, a new partition of the scan data was created in OIM software in which any point with a confidence index of less than 0.05 was removed and grains with less than 3 points were also removed. This partition was applied to both the austenite and ferrite phases within the scan, and the final phase fractions were based on the remaining points. A visual example of this clean-up procedure is shown in Figure 8, where image (a) is before clean-up and image (b) is after, for a biaxial tension specimen near the point of necking.

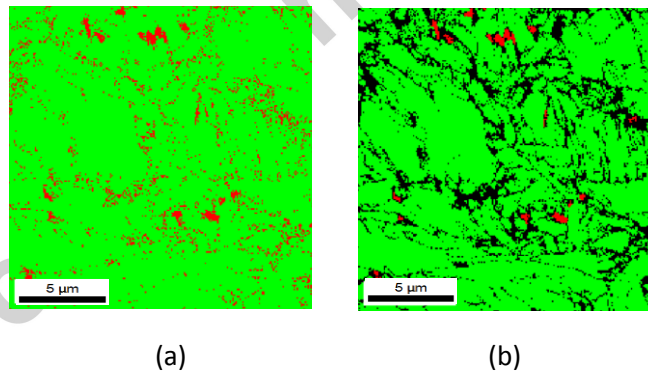


Figure 8. RA content in tensile specimen strained to the point of necking, (a) prior to clean-up (6.5% RA), and (b) after clean-up (1.1% RA).

Using the methods just described, the evolution of RA content corresponding three plastic strain measurement levels prior to the limit strain, and then a fourth at the limit strain, is shown in Figure 9

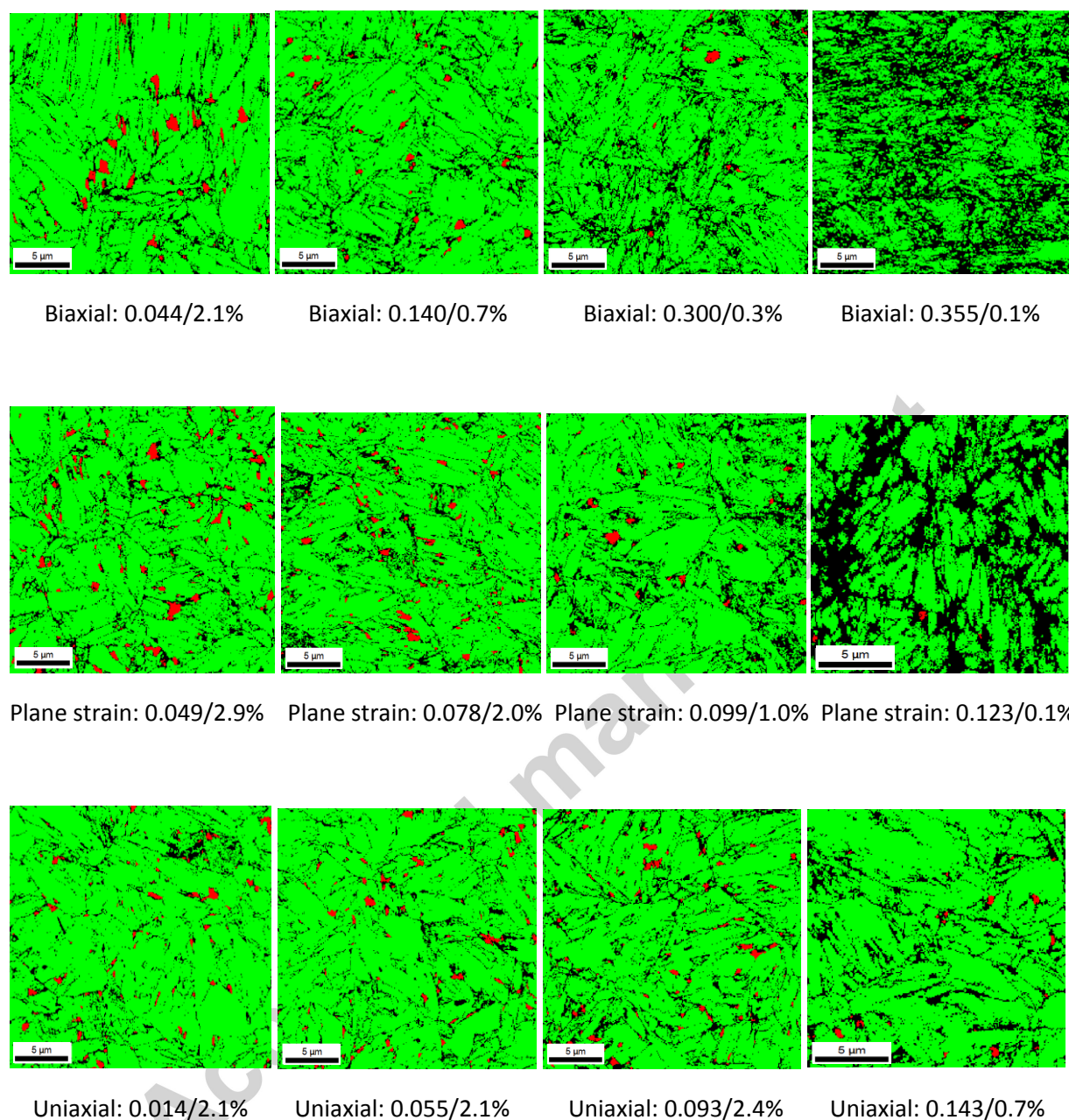
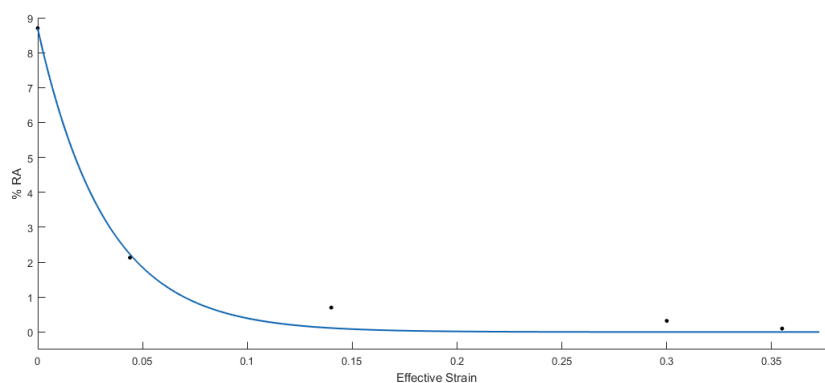
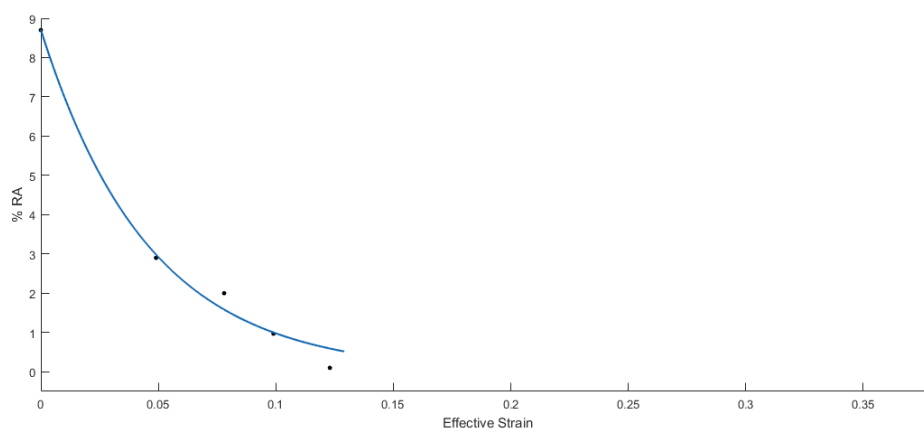


Figure 9. RA evolution as a function of strain for biaxial tension (top), plane-strain tension (middle), and uniaxial tension (bottom), as an average of at least 2 scans. In each case the effective strain is indicated on the left, while the average percent RA is on the right. The phase map on the far right, in each case, represents the material near the point of necking (limit strain) for each strain path.

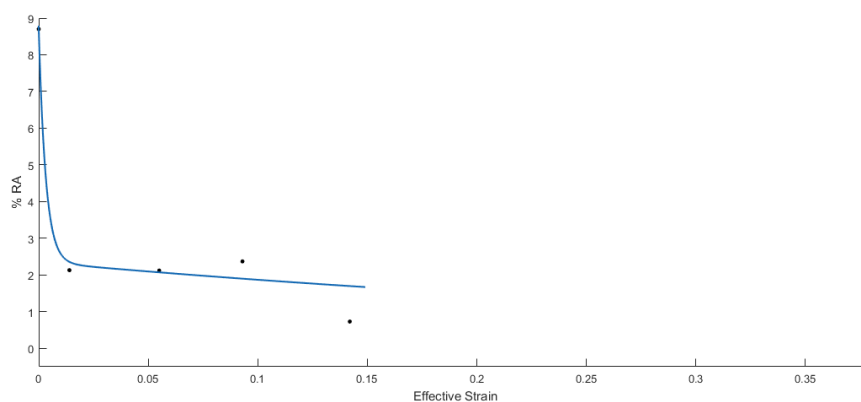
Trends in percentage of RA content relative to strain level are plotted in Figure 10 for three strain paths. Exponential fitting was done with one parameter (using Matlab) for biaxial and plane-strain tension, and with two parameters for uniaxial tension.



(a)



(b)



(c)

Figure 10. Volume percent RA as a function of effective strain for (a) biaxial tension, (b) plane-strain tension, and (c) uniaxial tension. Each point represents the average of two or more scans.

Uniaxial tension produces the greatest rate of conversion of RA as a function of effective strain, but then saturates rapidly at around 2% before dropping below 1% near the point of necking. Biaxial and plane strain tension impose a more gradual, and ultimately more complete, conversion of RA. Since the strain increments were not exactly the same for the three strain paths, interpolation can provide a more direct comparison. Using the exponential fits shown in Figure 9, the RA volume fractions at effective strains of 0.025, 0.05, and 0.075 are shown in Table 3.

Table 3. Percent RA as a function of effective strain level.

Effective Strain	Biaxial %RA	Plane-Strain %RA	Uniaxial %RA
0.025	4.0	5.1	2.2
0.05	1.8	2.9	2.1
0.075	0.09	1.7	2.0

While RA transformation has been related to plastic strains in this paper, the transformation can also be related to a threshold stress [18]. Stress affected transformation would typically occur in higher carbon content alloys, where the austenite has been enriched with carbon and hardened significantly as a result of thermomechanical processing. The carbon content of the current alloy is not especially high at 0.2%. However, because Q&P steels have a partition step in the heat treatment [19], the carbon content of the austenite is likely to be fairly high. Therefore, the relationships that we portray in this paper need to be considered in light of the possibility that transformation may be correlated to local stress levels acting on the RA.

The tensile test results reported in this paper are similar to those seen for a Q&P 980 alloy [10], where both EBSD and x-ray diffraction were used to measure RA content at various levels of plastic strain. Measured RA contents were slightly higher in the prior study, but the slope of the RA content vs true strain curve was similar. Another paper presented results from uniaxial and balanced biaxial testing of a Q&P 980 sheet [20], where RA transformation was more rapid in the biaxial case, as a function of strain, than the uniaxial case. The results of this paper confirm the finding that transformation is more effective, overall, in biaxial tension. We did not find prior work on RA transformation under plane-strain conditions in the literature. But our results show that the transformation level near the point of necking, for plane-strain tension, is about the same as that of biaxial tension. Prior work on similar alloys, like TRIP steels, showed that plane strain tension was slightly more effective at transforming austenite to martensite than biaxial tension [21, 22]. While the aforementioned TRIP steels had compositions and phase fractions (55% ferrite, 28-33% bainite, and 12-17% RA) that were different than the current alloy, the same general tendency was seen: both plane-strain and biaxial tension caused a more rapid transformation of RA with effective strain than uniaxial tension. Another study on TRIP 800 steel found that austenite transformation was more rapid in biaxial tension than in plane-strain tension [23]. In this case the austenite transformation was modeled for different phase morphologies and it was found that greater stress triaxiality correlated with greater transformation rate at a given level of effective strain. This modeling result is confirmed experimentally for the current Q&P 1180 alloy.

When comparing the three strain paths employed in this work, it appears that thinning strains may correlate with RA transformation a little better than effective strain. Rank ordering of the strain paths, with respect to effective strain and absolute value of true thinning strain, just prior to necking, provides the following:

- effective strain (ϵ_{eff}): biaxial tension > uniaxial tension > plane-strain tension
- thinning strain (ϵ_{zz}): biaxial tension > plane-strain tension > uniaxial tension

The data are displayed in Table 4 and Figure 11, where thinning strains are calculated from volume constancy, using the surface strains on each specimen.

Table 4. Volume percent RA as function of effective strains and absolute value of thinning strains at the point of necking.

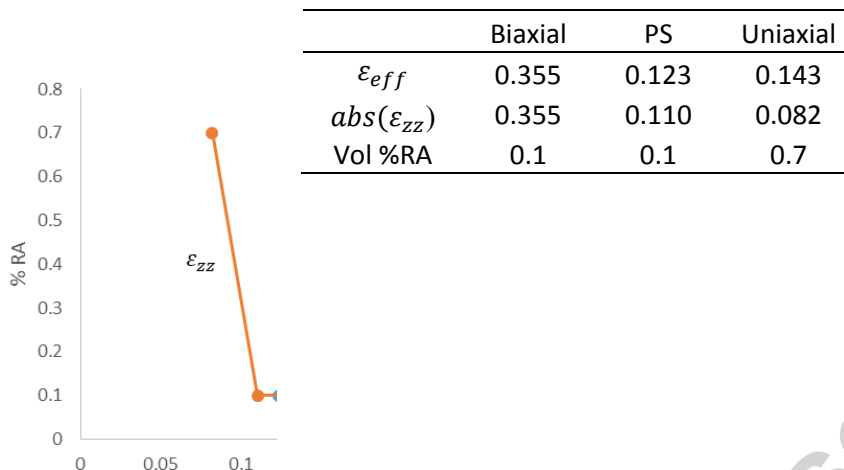


Figure 11. Volume percent RA as a function of effective strains and absolute value of thinning strains, for all three strain paths.

The apparent correlation of thinning strains to RA transformation may be explained by the displacement boundary conditions imposed by each strain path. Uniaxial tension provides the least restraint, because the specimen can freely deform along the major strain direction, while contracting in the minor strain and thickness strain directions. The ability to contract in the minor strain direction slows the thinning process, owing to volume constancy of plastic deformation, so it isn't possible to achieve a uniform thinning strain in uniaxial tension as large as the ones we saw in biaxial or plane-strain tension. Therefore, the strain paths that maximize thinning during uniform straining, namely biaxial and plane strain tension, are the ones that result in the greatest levels of austenite conversion in this sheet alloy.

Conclusions

Forming limits and RA transformation in Q&P 1180 steel were quantified as a function of plastic strain levels for three different strain paths. The biaxial tension strain path resulted in the greatest effective strain prior to necking at 0.355, compared to 0.123 for plane strain and 0.142 for uniaxial tension. EBSD measurements for various levels of plastic strain reveal a clear dependence of RA transformation rate on strain path, for the three linear strain paths that were employed in this work. Biaxial tension was found to be the most effective strain path for transforming RA to martensite, followed by plane-strain tension, and then uniaxial tension. In comparing the strain paths, RA conversion appears to be better correlated to thinning strains than effective strains, where biaxial tension achieved the greatest thinning strain prior to necking (-0.355), followed by plane-strain tension (-0.11) and uniaxial tension (-0.082).

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those of the authors and do not necessarily reflect the views of the National Science Foundation. Sheet materials for the experiments were supplied by General Motors R&D laboratory.

Data Availability Statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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