

Limit Strain Characterization in an Aluminum Die-Quenching Process

S. DiCecco, M. Di Ciano, C. Butcher, M. Worswick

University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1, Canada

sdicecco@uwaterloo.ca

Abstract. This work examines the nature of the strain distributions and limit strains during die quenching of a 7000-series aluminum alloy sheet. Forming limit experiments using limiting dome height (LDH) specimens were performed under plane-strain loading conditions using a 100 mm hemispherical Nakazima punch. Strains were measured using *in situ* stereoscopic digital image correlation (DIC). Two forming processing routes were examined: (i) an intermediate quench and form (IQF) processing route in which the LDH coupons were solutionized, quenched to a preset temperature, and isothermally formed and (ii) a die-quench (DQ) process where the LDH coupons were solutionized, and quenched and formed simultaneously with room temperature (RT) tooling under non-isothermal conditions. The DQ processing route was devised to understand the formability of the alloy under practical die-quenching conditions, while the IQF route was meant to understand the influence of temperature on the formability of the material. The DQ processing route exhibited the best formability from a localization standpoint; however, it was found that at deformations in excess of 0.5 major true strain, an orange-peel defect was present. The IQF process with room temperature tooling may be comparable to a W-temper forming operation. For these conditions, significant Portevin-Le-Chatelier (PLC) bands were present and the formability was approximately 75% less than for the DQ process. All formability results are summarized and a discussion of the interpretation of forming limits under the diffuse necking conditions associated with elevated temperature forming is presented.

1. Introduction

Stringent fuel economy and emissions regulations imposed on the global automotive sector have put pressure on major automotive manufacturers to reduce vehicle weight while also increasing vehicle safety. To achieve these weight reductions, high-strength precipitation hardenable 6000- and 7000-series sheet aluminum alloys are under consideration for the design of vehicle structural components. These alloys derive their strength from a distribution of fine precipitates within the microstructure that is achieved through a tailored heat-treatment process known as aging. In the T6 temper, heat-treatable aluminum alloys are considered to be at peak strength, but have relatively poor room temperature (RT) formability. To form complex parts and still achieve peak strength, the die-quenching processing route has begun to see considerable interest as a forming operation [1, 2]. Die-quenching of sheet aluminum alloys is detailed by Garrett *et al.* [3] where the formability is mentioned to be improved under die-quenching conditions.

In die-quenching of age-hardenable alloys, the sheet is first heated to a temperature at which the strengthening precipitates dissolve into the microstructure in a process known as solutionizing. The sheet material is then simultaneously quenched and formed in a cooled die system. The fast cooling



rates imparted during quenching prevents precipitation and renders the as-formed part in a supersaturated condition. The part can then be heat-treated to near T6 levels of final strength [4].

Die-quenching of sheet aluminum alloys provides higher levels of formability, relative to cold forming; however, there are very few published studies which quantify the safe forming limit strains of alloys undergoing the die-quenching processing route. Reasons for this deficit in the literature include: (i) the limited industrial application of the process; (ii) the non-isothermal nature of the process; and, (iii) the high-temperatures, strains and strain rates operative in the process that make digital image correlation (DIC) strain measurement techniques challenging.

In the present work, the formability of a developmental 7000-series alloy, referred to herein as D7xxx, was characterized under two different die-quenching processing routes. The first route was an intermediate quench and form (IQF) processing route where the LDH coupons were solutionized, quenched to a preset temperature, and formed under isothermal conditions. The IQF route was applied to understand how the formability of the D7xxx alloy might be limited for each temperature regime in a die-quenching processing route. The IQF temperatures examined were room temperature (RT), 200°C, and 300°C. The second processing route was a die-quench (DQ) processing route where the D7xxx alloy was solutionized, and simultaneously quenched and formed in tooling at RT under non-isothermal conditions meant to mimic a real die-quenching operation at the coupon level. All formability testing was limited to a specimen geometry that yields loading near the plane-strain regime to explore the lower bounds of material formability in the different process routes. Digital image correlation techniques were applied in the formability assessment in conjunction with the ISO12004-2 standard. A second, time dependent, approach was used to assess how the material localizes under different forming conditions. To provide context for the improvement in formability with the two die quenching routes, the formability is compared against the formability of the as-received alloy in a fully-hardened T76 condition.

2. Testing Methodology and Analysis Techniques

2.1. Material

The D7xxx alloy in the as-received condition has measured yield strength and ultimate tensile strength values of approximately 486 MPa and 521 MPa, respectively. The nominal sheet thickness of the material was 2.0 mm and the nominal composition can be found in Table 1. In general, this D7xxx alloy has a lower Cr content and higher Zr content than AA7075, for example, which leads to lower quench sensitivity, as demonstrated by Omer *et al.* [5] for the same lot of material. The constitutive response of this alloy and a detailed investigation into die-quenching process routes and heat treatments without the influence of deformation can also be found in Omer *et al.* [5].

Table 1. D7xxx nominal chemical composition (wt. %).

Alloy	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Zr	Other	Al
D7xxx	<0.04	1.3-2.0	<0.08	1.2-1.8	≤0.4	≤0.06	≤0.06	7.0-8.0	0.08-0.15	0.15	Bal.

2.2. Limiting Dome Height Testing

In die-quench formability testing, limiting dome height (LDH) specimens were first solutionized to 470°C for a minimum of 10 minutes in a convection oven and then immediately transferred to the press used for forming limit testing. Following solutionization, the LDH specimens were subjected to two different processing routes illustrated in Figure 1: (i) an intermediate quench and form (IQF) processing route where the blank was first cooled to the tooling temperature by clamping the blank between the heated dies prior to isothermal forming and (ii) a die-quench (DQ) processing route where the blank was immediately transferred to tooling at RT, clamped, and formed non-isothermally. Under the IQF route, the temperatures examined were room temperature (~23°C), 200°C, and 300°C. The different IQF forming temperatures were explored in an attempt to quantify the formability of the D7xxx alloy under different, known, temperatures after it had been solutionized. Conversely,

formability under the DQ route was measured to better mimic a real die-quenching processing route; however, it was not possible to track the temperature change of the specimens during the forming stage of the DQ route. Transfer to the tooling and clamping of the blank was approximately 7 seconds and resulted in a $\sim 60^\circ\text{C}$ drop in blank temperature prior to forming. The transfer process was manually performed, but repeatability of the transfer and clamping time was good and generally did not exceed 10 seconds. The formability of the as-received alloy in the fully hardened T76 temper was determined as a baseline for comparison with the formability of the DQ and IQF processes.

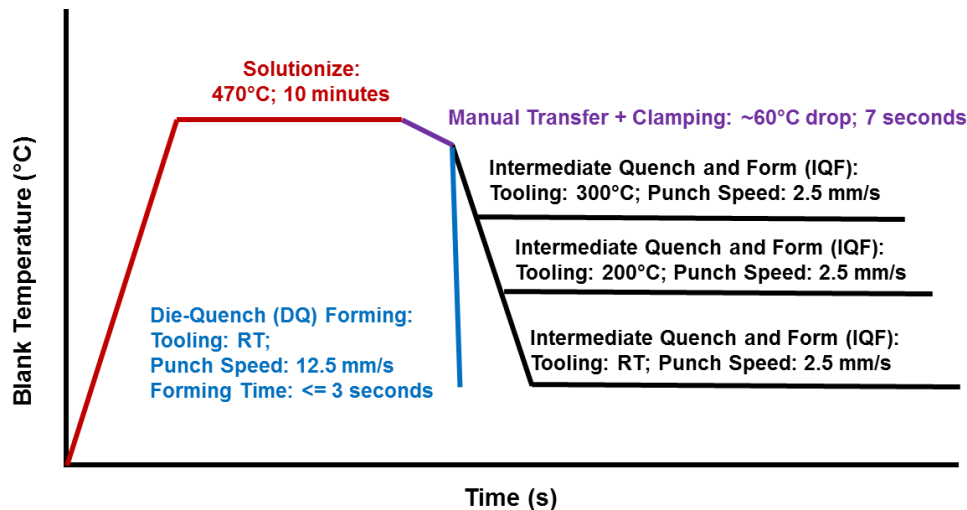


Figure 1. Die-quench processing routes for formability assessment.

The specimen geometry used in this work was a 76.2 mm “dog-bone” type geometry meant to approximate a plane strain loading condition [6]. Specimens were machined in the long transverse direction. A hemispherical Nakazima punch was utilized for all formability testing with a 100 mm diameter. Flat dies were used for clamping with an applied load of 300 kN. Lubrication during testing consisted of 2 to 4 Teflon sheets attached to the punch. The punch was operated at 2.5 mm/s for the IQF routes and as-received testing. For the DQ processing route, the punch speed was 12.5 mm/s in an effort to better replicate a practical die-quenching operation. In IQF testing, tooling was maintained at the desired temperature using a closed-loop PID system with in-die heater cartridges. Testing was completed on a custom triple acting press at the University of Waterloo [6].

2.3. Forming Limit Analysis Procedures

Forming limit strains were determined from each LDH test using the ISO12004-2:2008 standard [7]. Following the standard, strain values and the corresponding coordinates were extracted perpendicular to the crack location for all images of each individual LDH test. A minimum of 3 repeats were analysed for each test condition. It should be noted that the elevated temperature forming and the punch speeds in this work exceed what is specified by the ISO standard that is only strictly valid for forming at 25°C and punch speeds of 0.5 to 1.5 mm/s. The ISO approach was not originally developed for die-quenching formability analysis; however, it serves as a benchmark to compare formability against that of other known alloys and processing routes.

A time dependent approach for sheet metal formability assessment has been proposed by Martinez-Donaire *et al.* [8]. In the Martinez-Donaire *et al.* (MD) approach, the major true strain-rate distribution is tracked over the length of an LDH specimen with the assistance of DIC techniques. Within the localized necking region of the LDH specimen, the strain-rates are seen to increase up to failure. Conversely, outside of the localized region, strain-rates are observed to increase up to a peak strain-rate (PSR) value, after which the strain-rates are observed to decrease. In the MD approach, the image (or time) that the peak strain-rate value occurs outside of the necking region is considered the “safe”

image. On the safe image, the maximum principal strains are considered the forming limit strains for the analysed LDH specimen. When the MD approach was implemented in the current work to the same dome specimens analysed using the ISO12004-2 approach, it was observed that outside of the necking region, the peak strain-rate occurred at different times for different points along the length of each specimen on either side of the crack, *i.e.* no unique safe image could be determined, as shown in Figure 2(b). Because no unique PSR time could be identified, the MD approach was not used directly for forming limit strain assessment. Instead, the presence of various PSR times was interpreted as a measure of the necking behaviour of the D7xxx alloy under the different forming routes and was used to identify the transition from diffuse to localized necking. This interpretation of the MD approach was applied to representative LDH tests for the as-received alloy at RT, for the DQ processing route, and for the IQF processing route at 300°C.

For the implementation of the MD approach, only ± 8 mm along the specimen length from the crack location was examined, referred herein as ‘section length’. The major true strain rate was used. To compute the time derivatives of the major true strain at each point along the specimen, a b-form smoothing spline [9] was fit through each time-series of major true strain data points along the section length. A monotonically increasing constraint was imposed on all splines. The major benefit to using the spline approach was that a clearer interpretation of the results was possible without loss in quality of the original dataset. This MD analysis procedure was automated using a computer function developed in Matlab Version 2013a.

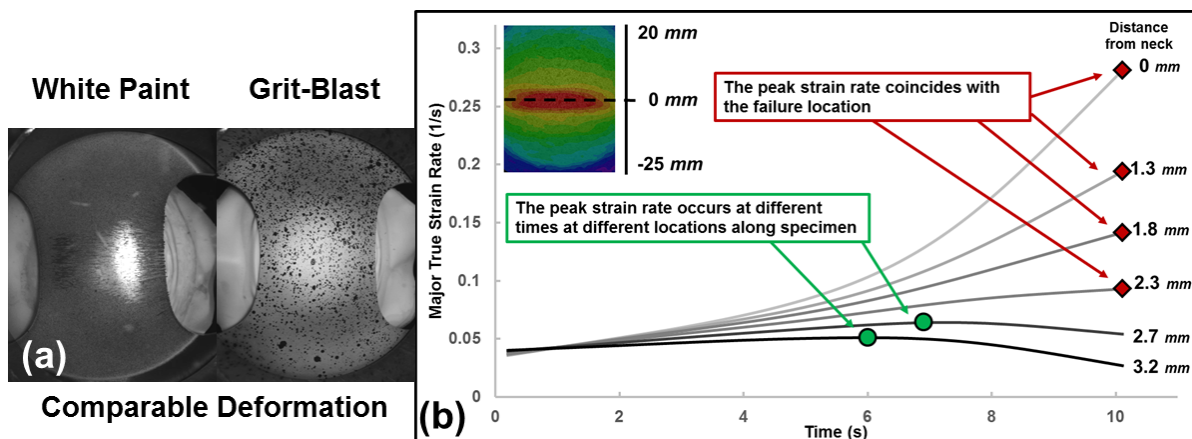


Figure 2. (a) traditional (showing loss of paint) and grit-blast speckle patterns for DQ process with similar deformation and (b) the MD approach applied to D7xxx showing different PSR times.

2.4. Image Acquisition and Post-Processing

Two synchronized cameras were operated to capture the dome deformation during LDH testing. The cameras were operated at frame rates of 40 fps and 140 fps, respectively, for the punch speeds of 2.5 mm/s and 12.5 mm/s, which translated to approximately 16.0 images/mm and 11.2 images/mm, respectively. A single LED light source was used to illuminate the blanks during testing.

Image processing was performed using the Correlated Solutions software program Vic-3D v7. Relevant analysis parameters in Vic 3D v7 consist of: (i) step size, (ii) subset size, and (iii) strain filter. The product of the step size and strain filter size is a type of spatial averaging parameter [10], while the subset size is mainly used for tracking pixel changes between images. In this work, the strain filter was kept to the minimum value of 5 pixels, and the step size was maintained at 4 pixels. The subset size was varied between 35 to 55 pixels, as necessary, based on some observed variations in speckle size post-solutionization. The image pixel density was approximately 11 pixels/mm.

A unique approach to speckling was implemented in this work to allow for DIC analysis without significant degradation in the speckle pattern when exposed to high temperatures and large strains. Typically, temperature resistant paint is used for the background and random speckle pattern in

elevated temperature LDH testing. During testing, it was found that temperature resistant paint could not remain adhered at 400°C under large strain, as shown in Figure 2(b). To overcome this restriction, a grit-blasting technique was used to generate a sufficiently dull background to provide contrast against the black speckle pattern in place of the background paint (white). This speckling technique was found to perform sufficiently well at large strains compared to the conventional approach, as shown in Figure 2(b). A similar benefit to grit-blasting was realized in the work of Boba *et al.* [12].

3. Results and Discussion

3.1. Formability Results

The major true safe strains for all processing conditions were computed from LDH tests using the ISO12004-2 standard and are included as a function of temperature in Figure 3(a). The as-received alloy in the T76 temper tested at room temperature demonstrated the lowest formability of all the processing conditions ($\epsilon_1 = 0.12 \pm 0.01$). The D7xxx alloy tested under the IQF processing route at room temperature had formability of $\epsilon_1 = 0.19 \pm 0.01$ and was approximately 58% better than the alloy in the as-received condition.

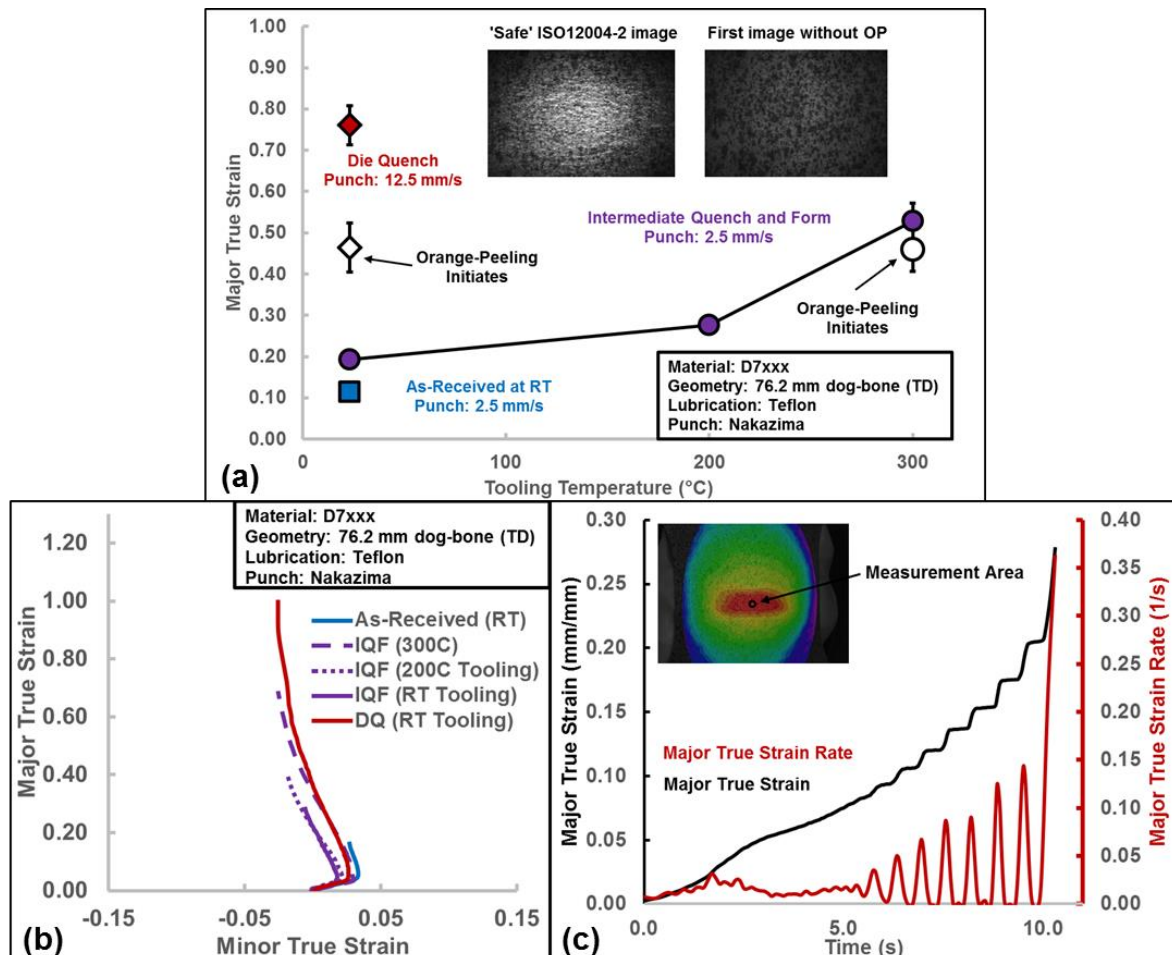


Figure 3. (a) major true limit strains for all processing routes, (b) representative strain paths for all processing routes, and (c) the presence of strain-wave propagation in an IQF specimen tested at RT.

The IQF process at RT demonstrated significant serrated flow-type deformation [13]. This serrated deformation is normally attributed to Portevin-Le-Chatelier (PLC) band propagation, and may have

negatively influenced formability. Figure 3(c) shows that the PLC effect is initially small, but increases with deformation. Omer *et al.* [5] reported the same behaviour in tensile tests of the D7xxx in the W-temper, with the severity of PLC effects increasing with deformation.

For the IQF route at 200°C, the major forming limit strain was computed as $\varepsilon_1 = 0.28 \pm 0.01$, while at 300°C, the major forming limit strain was $\varepsilon_1 = 0.53 \pm 0.04$. From 200°C to 300°C, the increase in formability was approximately 91% and may be attributed to increased strain-rate sensitivity at 300°C. In the DQ processing route, the D7xxx alloy, the major forming limit strain was $\varepsilon_1 = 0.76 \pm 0.05$. Under DQ processing, the temperature-history during the forming operation was unknown other than that the starting temperature was approximately 400°C to 410°C. Factors that might have contributed to the improved formability in the DQ process may include the non-isothermal forming conditions and the initially high temperatures at which deformation was initiated. The strain-paths for all forming operations were relatively consistent and close, but not exactly, plane-strain, as shown in Figure 3(b).

From a localization standpoint, the limit strains observed in the IQF process at 300°C and under the DQ processing route may be good indicators for the expected formability in a die-quenching operation for a 7000-series alloy that has sufficient lubrication and temperature control; however, a different type of surface defect was observed for both conditions at lower strain levels. The surface defect can be described as a surface roughening or orange peeling [14] phenomenon, as shown in Figure 3(a). The maximum principal strains at the onset of orange peeling were manually estimated based on visual observation of the change in reflectivity and uniformity of the illuminated surface. Estimates of the strain associated with onset of orange peeling are included in Figure 3(a). It is interesting to note that the approximate strains at which significant orange peeling occurred were similar for the two forming routes. Consequently, the design of an elevated temperature forming operation for the D7xxx alloy might be governed by the surface quality and not the FLC.

3.2. Assessment of Localized Necking Behaviour

Using the modified MD approach, discussed in Section 2.2, the necking behaviour of three forming conditions was assessed in more detail: (i) the as-received alloy in the T76 condition at RT, (ii) the DQ processing route, and (iii) the IQF processing route at 300°C. Results from this analysis are included in Figure 4 for representative test cases from each processing route. Figure 4(a, c, e) include the major strain (**black**) and major strain rate (**red**) distributions at the time of failure and at the peak strain-rate times for each point along the section length. Figure 4(b, d, f) contain the dome heights (**blue**), as measured at the dome apex, for the different PSR times measured along the section length. The dome height at 0 mm on the section length for each processing condition corresponds to the failure dome height. Any points that are equal to the failure dome height experienced peak strain-rate times at the failure time, *i.e.* all of these points were within the localized deformation band at the time of failure. The representation of the dome heights measured for different PSR times along the section length is interpreted as the transition from diffuse to localized necking in the context of the present work.

In Figure 4(b), the necking behaviour of D7xxx in the T76 condition at RT is examined. The small change in dome height (less than 0.8 mm) along the section length for different PSR times shows that the transition from diffuse to local necking is both sudden and happens almost instantaneously at all points outside of the localized necking region. Despite this, there is still a relatively high amount of strain accumulation in the localized deformation band before fracture, as shown in Figure 4(a).

Unlike the D7xxx alloy in the T76 condition at RT, the DQ process and the IQF process at 300°C demonstrate significant, gradual transitions from diffuse to localized necking, as shown in Figure 4(d, f). In both elevated temperature processing routes, there is a large change in the dome height, as measured at the apex locations, based on when the PSR time was reached at different points along the section length. For the T76 condition, the change in dome height over the ± 8 mm measurement range was sudden and less than 0.8 mm; however, for the DQ and IQF processes, the change in dome height was gradual and 8.9 mm for the DQ process and 7.2 mm for the IQF process at 300°C. These observations are in-line with the higher forming trends reported using the ISO standard. It should be noted that in all IQF tests at 300°C, an asymmetry in the major strain distribution was

observed (Figure 4(e)). Interestingly, the asymmetry was also detected using the modified MD approach, as shown in Figure 4(f). The asymmetry may be related to friction or a temperature gradient in the sample; however, further investigation is required.

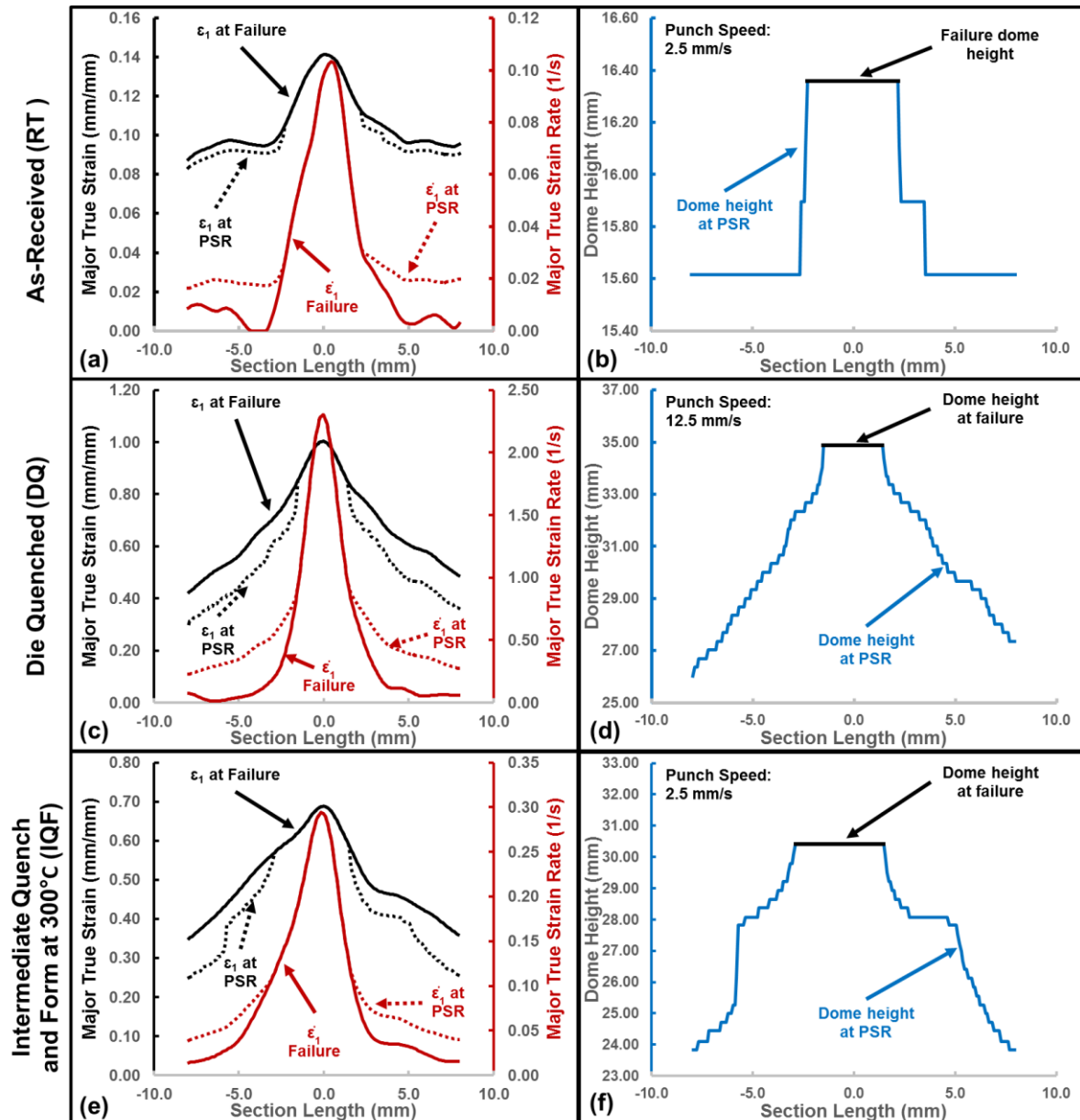


Figure 4. (a, c, e) strain and strain-rate distributions at failure and at measured PSR times; (b, d, f) dome height, as measured at the dome apex, for different PSR times recorded along the section length.

The application of the modified MD approach to the D7xxx alloy under different forming conditions was found to be a useful metric for characterizing necking behaviour of the alloy. More notably, the results from the application of this approach raise the question of what might be considered a “neck” versus a “no neck” condition during elevated temperature, large strain forming operations. With better knowledge of how an alloy transitions from diffuse to local necking, future die design and optimization for complex forming operations using die-quenching might be possible and the application of the current modified-MD approach might facilitate this task.

4. Conclusions

The die-quench formability of a developmental 7000-series aluminium alloy sheet has been investigated under different processing routes for a near plane-strain loading condition. The ISO12004-2:2008 standard was used for formability assessment. It was found that the two conditions which yield the highest forming limit strains are a non-isothermal die-quench processing route and a processing route where the material is quenched to 300°C from the solutionization temperature before forming. Despite the high predicted forming strains under the non-isothermal and isothermal 300°C processing routes using the ISO12004-2 standard, the presence of orange peeling was observed, which may require a reduction of allowable strain for both processing routes.

Using a modified MD approach [8], the transition from diffuse to localized necking was explored for the as-received alloy at room temperature and the two high-strain forming conditions. At elevated temperatures, it was found that the transition from a diffuse to local neck is very gradual, and may blur the boundaries between a “neck” and “no-neck” condition. The analysis presented of the necking response may be relevant in the assessment of die-quench formability based on different design criteria and tolerances. Initial observations from this work have found that die-quenching had a significant positive impact on the overall formability of the D7xxx alloy.

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