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Hot Formability of a 7000-Series Automotive Aluminum Alloy Using Nakazima and Marciniak Tests With Rapid Heating

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Abstract

The 7000-series of aluminum alloys have significant potential for automotive structural lightweighting due to their high specific strength and formability at elevated temperatures. The objective of this study is to characterize the formability of an automotive-grade 7000-series aluminum alloy, designated C7M7, using both Nakazima and Marciniak tests in non-isothermal hot forming conditions. A novel formability test procedure was developed with fast heating using a platen furnace and stereoscopic digital image correlation (DIC) to construct forming limit curves (FLCs) using the Marciniak test. The Nakazima test is commonly used in the literature for formability characterization but has significant process effects such as out-of-plane bending, punch contact pressure, and non-linear strain paths. Friction is challenging to control at hot forming temperatures, and local cooling of the blank by the punch nose can lead to strain paths clustered around plane strain. The advantage of the hot Marciniak test is that friction, punch contact pressure, and out-of-plane bending are avoided resulting in linear strain paths until acute localization. The change in the FLC between the non-isothermal Marciniak and Nakazima tests is evaluated at a forming temperature of 450°C and a nominal effective strain rate of 1 s^{-1}. The limit strains identified using the ISO12004-2 methodology were observed to be conservative compared to the limit strains determined using the so-called linear best fit (LBF) methodology that analyzes the thinning strain rate evolution at the neck location.

1 Introduction

Electric vehicles (EVs) are at the forefront of the demand for lightweight materials as their battery pack adds substantial weight compared to their internal combustion equivalent [1]. The high-strength, lightweight 7000-series of aluminum alloys are excellent candidates for structural lightweighting, but their low room-temperature formability has been a barrier to adoption. Hot-forming processes are required to realize the lightweight potential of these alloys. In hot forming, 7000-series alloys are solutionized at approximately 480°C followed by rapid transfer to the press for stamping in cold tooling. Secondary heat treatments are then performed to artificially age the component to the desired temper. To date, the literature has largely focused on the aerospace grade alloy, AA7075 [2]. Non-isothermal forming with a hot blank and cold tooling is preferred compared to the added complexity associated with high-temperature isothermal forming. The consequence of non-isothermal forming is that the limit strains are rapidly changing with temperature, which governs the work hardening rate and strain rate sensitivity.

In previous studies considering hot forming of 7000-series alloys, the dimensional accuracy in the forming of an AA7075-T6 front side member was studied by Mendiguren et al. [3]. It was found that hot stamping produced better dimensional accuracy compared to W-temper forming of the same sheet in its as-quenched condition. DiCecco et al. [4] characterized the plane strain formability of 7000-series aluminum using Nakazima tests. The hot formability was high and only limited by the onset of significant orange peeling and surface degradation before the limit strains were reached.

Nakazima limiting dome height tests are commonly used to characterize formability at elevated temperatures. Nakazima tests employ a hemispherical punch to deform blanks of different widths and obtain a range of strain paths from uniaxial to biaxial (BX) stretching. Nakazima tests are sensitive to friction, which is difficult to control at elevated temperatures, resulting in necks forming on either side of the punch apex. The out-of-plane bending and punch contact pressure induce non-linear strain paths and higher limit strains compared to the in-plane Marciniak tests [5] [6]. A recent study on the hot-forming of PHS1800 steel by He et al. [7] observed that non-isothermal Nakazima tests promoted double necks due to local cooling of the dome apex by the punch, leading to strain paths clustered around plane strain. In contrast, non-isothermal Marciniak tests employ a cold carrier blank with a central hole that eliminates friction and punch contact at the neck location. The flat punch also brings the strain state closer to in-plane stretching to achieve approximately linear strain paths [8].

One of the significant challenges with hot-forming 7000 series alloys is obtaining a sufficiently high quench rate to reach optimal strength and corrosion resistance [9]. The quench sensitivity governs the industrial process window and infrastructure required to control the part temperature. Harrison et al. [10] reported that hot stamping of an AA7075 B-Pillar to achieve T6 properties required a quench rate greater than 300°C/s. Behrens et al. [11] attributed the quench sensitivity of AA7075 to its copper content. The current study considers a newly developed automotive-grade 7000 aluminum alloy, C7M7, which has a controlled amount of manganese with the intent of reducing its quench sensitivity [12] and expanding the hot-forming process window. The objective of the present study is to develop a non-isothermal formability test procedure to define the hot forming limit curve (FLC) of C7M7. Both Marciniak and Nakazima tests are considered to separate the influence of bending, friction, contact pressure, and non-linear strain paths. Moreover, limit strains detected by the ISO12004-2 method are contrasted with those by the Linear Best Fit (LBF) method based on local strain rate evolution.

2 Methodology

2.1 Marciniak and Nakazima Tests

The formability test procedure begins with a robotic transfer system loading the blanks into a platen furnace set to 473°C for rapid heating. The blank undergoes the process history in **Figure 1a**, reaching the target solutionization temperature of 473°C after 3 minutes, and is then held for 5 minutes. To limit cooling of the blank during its transfer from the furnace to the tooling, a radiative heating element was installed into the robot's blank holder. The approximate temperature at the start of forming was 450°C at the end of the profile shown in **Figure 1b**.

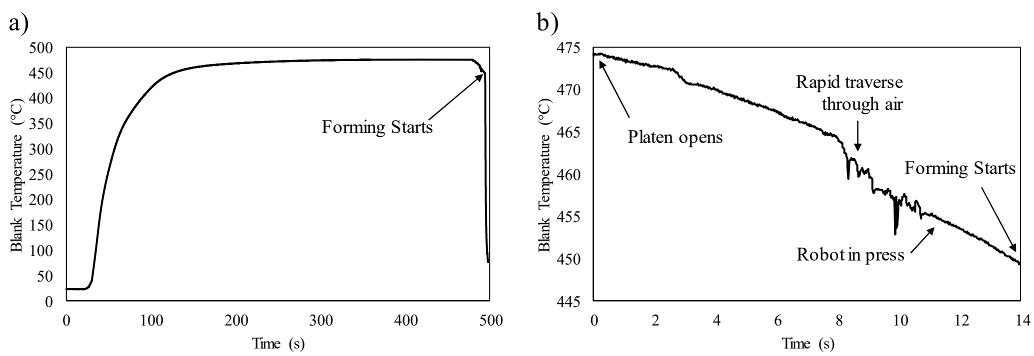

***Figure 1**: a) Thermomechanical process history with change in temperature and time, forming start temperature. b) Blank temperature during transfer.*

The Marciniak and Nakazima tooling was installed into a 900-ton Macrodyne press, shown in **Figure 2a**. Four repeat blanks with the geometry of **Figure 2b** were formed and quenched for every width in **Table 1** on room temperature tooling with a nominal punch velocity of 12 mm/s that corresponded to an average strain rate of 1/s. The tooling dimensions are shown in **Figure 2c, d**. The 101.6 mm diameter punches were stationary, with the forming stroke performed by moving the knurled die-ring downwards. The binder load was 400 kN, and the carrier blank was 2 mm thick mild steel with a central 34 mm hole. Four layers of PTFE film were placed between the punch and carrier in the Marciniak tests and between the punch and blank in the Nakazima tests.

Deformation of the blanks was measured using in-situ stereoscopic digital image correlation (DIC) with Photron AX100 cameras and 60 mm lenses running at 250 frames per second. The strain fields were measured using Correlated Solutions® DIC Vic3D software with a virtual strain gauge length (VSGL) of 2 mm and a virtual strain gauge size (VSG) of 47 pixels. The step, filter, and subset sizes were 3 mm, 7, and 29 mm, respectively.

Table 1: *Selected specimen widths for both Nakazima and Marciniak tests.*

	Specimen Width (mm)								
Nakazima Test	40	60	80	-	120 (FLC_0)	-	160	180	-
Marciniak Test	40	60	80	100	120 (FLC_0)	140	160	180	228.6

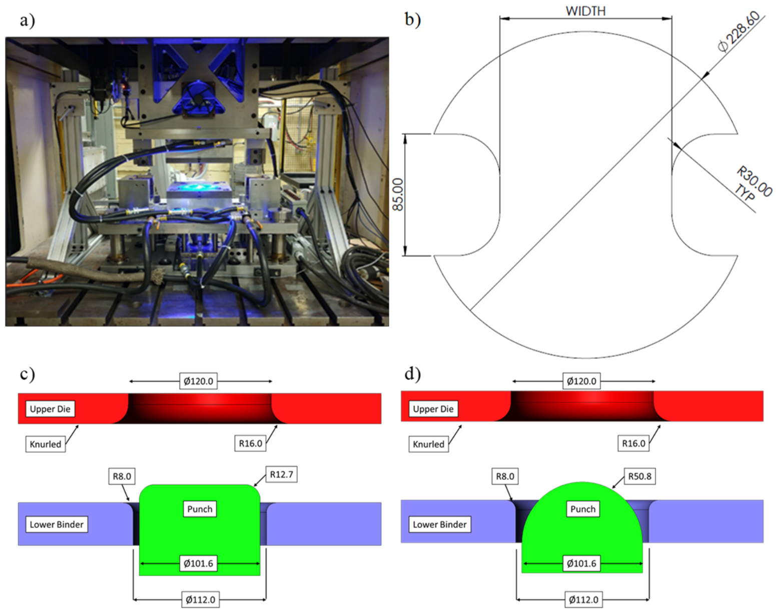

Figure 2: *a) 900-ton Macrodyne press with fixed punch and moving die. Cameras for DIC mounted in situ. b) Geometry of the specimens used in the Nakazima and Marciniak tests (width dimensions are in Table 1). Tooling layouts for c) Marciniak and d) Nakazima tests (all dimensions in millimeters).*

2.2 Limit Strain Detection

The ISO methodology for limit strain detection uses a parabolic fitting procedure of the strain distribution across the neck one image prior to fracture, as shown in **Figure 3a** for the 120 mm width Marciniak test. Additional details on the methodology are provided in the ISO12004-2 standard [13]. The linear best fit method of Volk and Hora [14] tracks the evolution of the through-thickness strain rate measured at the neck location. Linear trend lines are fit to the strain rate history to define the regions of stable and unstable thinning. The intersection of the two lines is used to identify the limit strains, as shown in **Figure 3b**.

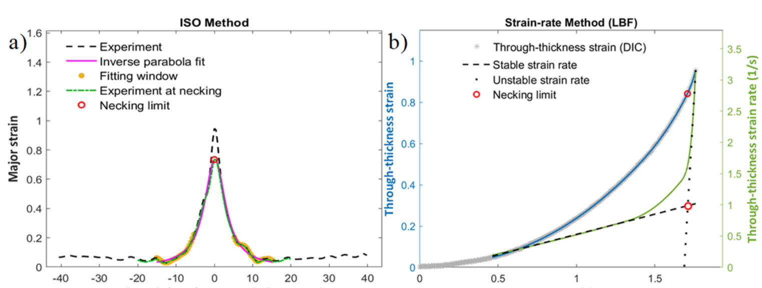

Figure 3: *Comparison of geometrical constructions used with the a) ISO and b) LBF limit strain detection methods. The data used is from a 120 mm width Marciniak test in the baseline condition.*

3 *Results and Discussion*

3.1 Evaluation of Forming Limit Anisotropy

Marciniak tests with a blank width of 120 mm produced a near- plane strain strain path and were used to investigate forming limit anisotropy by conducting tests in the rolling (RD) and transverse (TD) directions of the sheet. The limit and fracture strains determined by the LBF method in **Figure 4** were lowest in the TD, which was then used for all subsequent testing to ensure a conservative FLC.

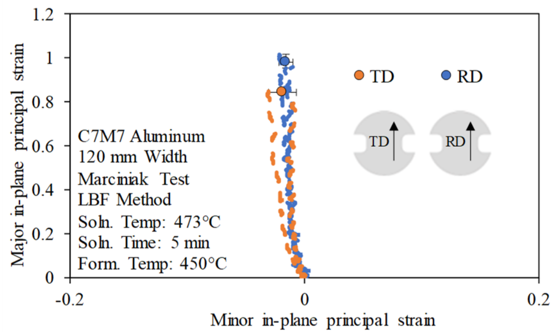

Figure 4: *The limit strains from the Linear Best Fit method in both rolling and transverse directions in a near plane strain state at the baseline process parameters.*

3.2 Forming Limit Curves Using LBF

The principal strain paths and limit strains for the LBF method for both Marciniak and Nakazima tests are shown in **Figure 5**. For the Marciniak tests, localization occurred transverse to the principal stretching direction (TD) for all sample widths smaller than 160 mm, as shown in **Figure 6a**. The neck developed in approximately the diagonal direction for the larger widths of 180 and 228.6 mm in a strain state of near equal-biaxial stretching. The Nakazima tests fractured off-center for all widths except for the biaxial 160 and 180 mm width samples, as can be seen in **Figure 6b**.

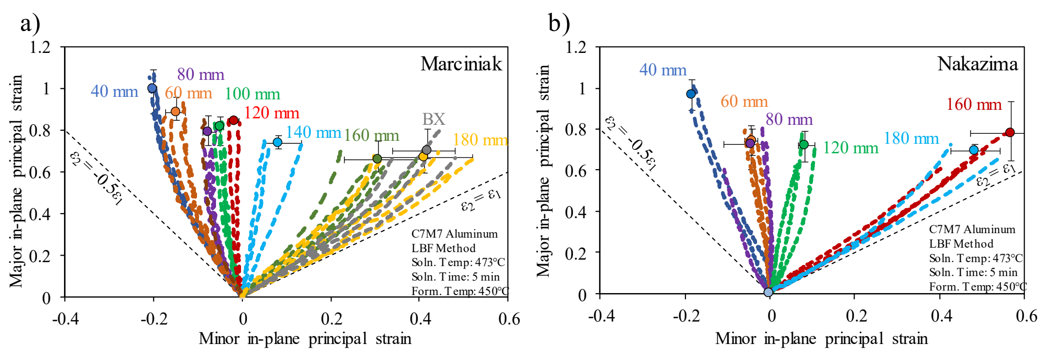

Figure 5: *Measured strain paths of the blanks with varying widths up to necking during non-isothermal hot stamping. The LBF limit strain points are shown for both a) Marciniak and b) Nakazima tests.*

It is interesting to note that the LBF limit strains do not form the typical v-shape of the FLC with the lowest major strain occurring in plane strain. The major limit strains for the C7M7 at 450°C instead vary with the minor strain in an approximately linear manner that is similar to the shape of forming fracture limit curves of ductile materials [15].

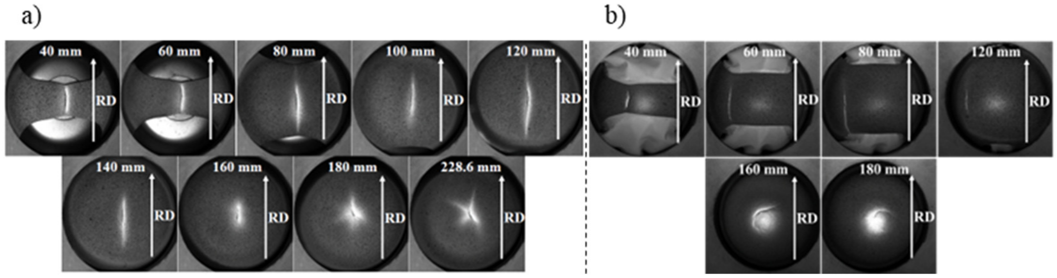

Figure 6: *The image shortly after fracture showing crack propagation from the a) Marciniak tests and b) Nakazima tests. The material is characterized along the transverse direction, perpendicular to the rolling direction (RD) shown in the figures.*

3.3 Comparison of LBF and ISO Methods

The ISO method was developed based on the strain distributions across the neck that develop at room temperature, forming a neck that is typically more acute than at elevated temperature. The LBF method was also developed for room temperature forming, but since it tracks the local thinning rate at the neck location, it may be more appropriate for elevated forming compared to the ISO methodology. It is interesting to note that the LBF limit strains are very similar for both the Nakazima and Marciniak tests, as shown in **Figure 7a**. In contrast, the ISO limit strains in **Figure 7b** show a marked difference between the Nakazima and Marciniak tests. The Nakazima limit strains are significantly higher in biaxial stretching and lower in the drawing region. Typically the limit strains are similar between tests with Nakazima giving higher limit strains due to out-of-bending and contact pressure delaying localization. The unexpected performance of the ISO method may be due to fracture outside of the Nakazima dome apex, which strictly invalidates the method [13]. Future work is required to investigate the significant differences observed between the LBF and ISO limit strain detection methods to determine which, if either, is appropriate for non-isothermal forming.

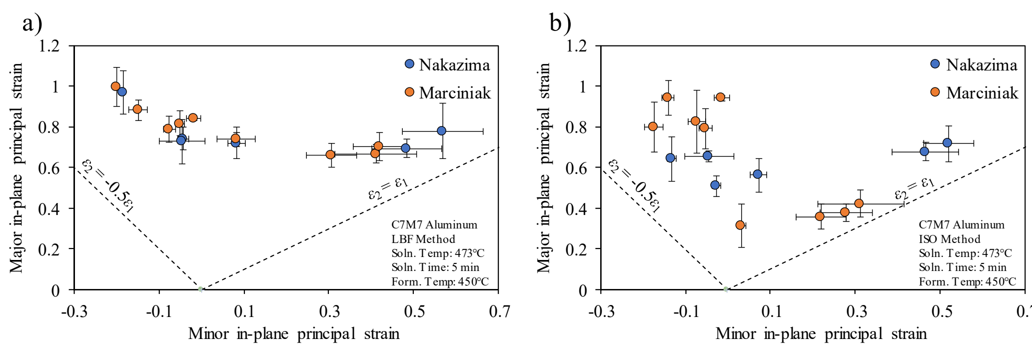

***Figure 7**: Comparison of Marciniak and Nakazima a) LBF and b) ISO limit strains. The average of repeats is plotted with standard error bars.*

4 Conclusion

In this work, the forming limit strains of C7M7, an automotive grade 7000-series alloy, were measured in both Marciniak and Nakazima tests in non-isothermal forming with a start temperature of 450°C. The Nakazima tests showed localization off-center on samples with a width of 120 mm and less, while the Marciniak tests consistently failed in the center for all widths. The limit strains were evaluated using the ISO12004-2 and LBF methods. The Nakazima and Marciniak limit strains were in close agreement according to the LBF methodology with an FLC0 of 0.8. The limit strains determined using the ISO method showed a strong divergence between the Marciniak and Nakazima tests with respective FLC0 points of 0.3 and 0.6. The ISO method seems to be more conservative when compared to the LBF limit strains. However, further work needs to be done to validate these limit strain detection methods in non-isothermal forming conditions.

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