Effect of Initial Temper on the Warm Forming Characteristics of a High Strength 7000-series Al-Zn-Mg-Cu Alloy

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Abstract. In this work, the formability of a developmental 7000-series copper containing aluminium alloy was assessed at room temperature (RT), 150°C, 175°C and 200°C in pre-aged (PA), peak-aged (T6) and overaged (T76) tempers using Nakazima tests with stereoscopic digital image correlation (DIC) strain measurement. The limit strains were identified using a novel curvature-based approach to detect the formation of an acute neck. The tensile mechanical properties in these warm forming processing routes were characterized with and without a paint bake cycle. Finally, a thermo-mechanical tensile simulator was used to evaluate the constitutive response of the PA and T76 tempers as a function of strain-rate and time at 175°C. Formability results found the selected PA temper to have a good room temperature formability and a mild positive response to the selected warm-forming cycles. The T6 and T76 tempers both exhibited increases in formability in response to warm forming. The PA temper had a significant positive response to short-duration warm forming and subsequent paint baking, with the yield strength increasing from 420 MPa to 512 MPa following this thermal cycle. For the T6 temper, the warm-forming cycle showed a trend characteristic of retrogression and re-aging, with the warm-forming cycle dropping the yield strength from 566 MPa to 534 MPa and the subsequent paint-bake re-aging to 554 MPa. The effect of aging during pre-heating prior to warm forming on the warm constitutive response of the PA and T76 tempers was also investigated. Both tempers exhibited rather different aging responses to short-duration thermal cycles. In the PA temper, this manifested as an increase in at-temperature yield strength and loss of hardening rate. In contrast, the T76 temper exhibited a drop in strength since this temper is already over-aged prior to warm forming. Both the PA and T76 tempers showed comparable at-temperature strain-rate sensitivity.

1. Introduction
While the strength-to-weight ratio of 7000-series aluminium alloys is attractive for automotive light weighting applications, the manufacturing of structural automotive components is challenging due to their limited room temperature formability. The 7000-series alloys are also susceptible to stress corrosion cracking (SCC), which must be accounted for via process route design prior to use in automotive applications, e.g. by over-aging as a means to reduce SCC [1], [2], [3]. To address formability limitations, there has been a keen interest in warm forming (WF), [4], [5], [6], [7], [8], [9], as well as hot stamping [10], [11], [12], [13] of high strength 7000-series alloys in recent years. In hot stamping, the sheets are first solutionized by heating above approximately 470°C to dissolve the precipitates, after which they are formed non-isothermally in a cooled die system. In warm forming,
sheets are formed isothermally or non-isothermally at temperatures above approximately 150°C, but below the alloy recrystallization temperature. An advantage of hot forming is the enhanced formability and reduced springback but the parts require a secondary ageing heat treatment to obtain a peak strength T6 condition. An advantage of warm forming is that secondary ageing treatments can be avoided since the material does not require solutionization prior to forming. The starting temper can be selected such that the secondary ageing that will occur during warm forming and the subsequent paint bake cycle can produce a final temper near the peak strength or intentionally over-aged to increase resistance to SCC.

Sotirov et al. [14] have identified formability limits for peak-aged AA7075-T6 sheet and considerable benefit was found for warm forming in the 200°C - 230°C temperature range. Kumar et al. [4] demonstrate that the limiting draw ratio of AW7020-T6 benefits from warm forming up to 250°C, but with significant degradation in the as-formed yield and ultimate tensile strengths after 200°C. In the study of warm formability of AA7075-T6 by Wang et al. [7], a decrease in mechanical properties was observed when warm forming above 230°C which was attributed to precipitate coarsening (over-aging); however, they note some strength loss is recovered during a paint-bake cycle as compared to the as-received material that saw a mild decrease in strength after paint-baking.

At present, there is not a clear indication of which initial temper should be used for 7000-series warm forming, for automotive applications. This research investigates the (i) warm formability and (ii) final property characteristics, such as strength and ductility, of a developmental 7000-series alloy, designated herein as AA7xxx, for three different initial tempers comprising (i) a pre-aged (PA) temper, a peak-aged (T6) temper and (iii) an over-aged (T76) temper. The isothermal formability of each temper was characterized at room temperature (~23°C), 150°C, 175°C and 200°C under near plane-strain loading. Tensile samples were extracted from the flanges of the PA and T6 samples after warm forming to understand the effect of the forming process on the subsequent mechanical properties with and without a 30 minute, 177°C simulated paint-bake. In parallel with the formability experiments, the warm constitutive response of the PA and T76 tempers is characterized at 175°C, as a function of time at temperature and strain-rates relevant to the forming experiments to provide insight into the observed formability trends. Based on the culmination of these tests, final recommendations are made for the warm forming of this developmental AA7xxx alloy.

2. Testing Methodology and Analysis Techniques

2.1. Material

The starting sheet material used throughout this study was a 2 mm thick, developmental 7000-series aluminium alloy, designated AA7xxx, by Arconic in the T76 condition. The T76 is an overaged temper which imparts improved stress corrosion cracking (SCC) resistance [2], [3]. The nominal composition for the developmental AA7xxx alloy is given in Table 1.

Table 1 - Nominal composition of AA7xxx, in wt %.

| Alloy   | Cr | Cu  | Fe  | Mg  | Mn  | Si  | Ti  | Zn  | Zr  | Other | Al |
|---------|----|-----|-----|-----|-----|-----|-----|-----|-----|-------|----|
| AA7xxx | <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. |

To produce the pre-aged (PA) and peak-aged (T6) tempers, a batch of the AA7xxx alloy was solutionized at approximately 473 °C for 10 minutes in a fluidized sand furnace (FB-08C Fluidized Bath Furnace, Techne®), water quenched, and subsequently aged. The aging process for the PA temper [10], [15] was a two-step process of 48 hours of natural aging at room temperature followed by 4 hours at 100°C of artificial aging in the fluidized sand furnace. The T6 (peak aged) treatment was taken as a single step 24 hour aging process at 120°C. Between any lulls in heat-treating, samples were held in dry ice (-78.5°C) to prevent unintentional aging.

Representative stress-strain curves for the PA, T6 and as-received T76 tempers are included in Figure 1. The PA temper shows significant work hardening, with a yield strength (YS) of 419 MPa ultimate tensile strength (UTS) of 524 MPa at a uniform elongation (UE) of 18.2%. In the T6 peak-aged
condition the YS and UTS increase to 507 MPa and 566 MPa, respectively, but the UE decreases to 14.1% as the overall work-hardenability decreases and the stress-strain curve becomes flatter relative to the PA condition. In the overaged T76 condition, the work-hardenability further decreases and the strength (494 MPa/524 MPa YS/UTS) and UE (8.8%) also decrease relative to the T6 condition. In the overaged T76 temper, there is a distinctive flat region after yielding not observed in the PA and T6 tempers. Fribourg et al. [16] have explored this behaviour in detail for AA7449, an Al-Zn-Mg-Cu class alloy, and showed that this flat region after yielding emerges and becomes more prominent as the extent of overaging increases. This trait is thought to be associated with the transition from shearable to non-shearable precipitates with overaging.

Figure 1 – Representative stress-strain curves of AA7xxx in the PA, T6 and T76 tempers, tested along the rolling direction.

2.2. Limiting Dome Height Testing and Analysis
Formability characterization of the PA, T6 and T76 tempers was undertaken at room temperature (23°C), 150°C, 175°C and 200°C. Testing was accomplished using a double-acting hydraulic press with tooling heated by closed-loop controlled embedded heater cartridges, as described in [9] and [17]. The specimens were heated in-situ, with typical heating curves measured at the specimen flanges plotted in Figure 2c). The initial heating rate corresponds to the placement of the specimen within the tooling. At approximately 60 seconds, the tooling is closed, and the clamping load is applied, giving rise to an increase in heating rate, followed by asymptotic heating to the target test temperature. A minimum of three repeated LDH tests were completed for each test condition.

The warm-forming cycle entailed a 3 minute heating time of the blank to the target temperature after clamping, with the blank within 20°C of the targeted temperature during approximately the final 60 seconds of heating. The forming duration at elevated temperature varied as a function of dome height. To minimize variation, all samples were kept at elevated temperatures for 60 seconds from the time testing began prior to water quenching after testing was completed.

A 101.6 mm diameter Nakazima punch was used in the formability testing per the ISO12004-2:2008 standard [18], as shown in Figure 2a), with a corresponding annular Nakazima die set with an inner diameter of 106 mm and die entry radius of 6.35 mm. The formability was evaluated using a near plane-strain dog-bone type geometry with a gauge width of 76.2 mm and entry radius of 20 mm [18] under limiting dome height (LDH) testing. Samples were tested in the transverse sheet direction (TD), i.e. the sheet rolling direction was perpendicular to the sample major axis and major strain direction. A clamping force of 330 kN was applied to prevent material draw-in. The punch speed during testing was
1.0 mm/s and lubrication between the punch and blank interface consisted of 2-3 layers of 0.127 mm Teflon™ film to promote centre fracture.

In the formability testing, the Nakazima samples were tested to failure and stereoscopic digital image correlation (DIC) techniques were used to capture the deformation and corresponding strain fields on the sample surface not in contact with the punch over the duration of each test. A sample strain profile prior to cracking is included in Figure 2b). Deformation of speckled samples was tracked at 140 frames per second using two 4 megapixel FLIR Gazelle Camera Link cameras. The camera, lens and test setup produced a pixel density of approximately 14 pixels/mm. Image analysis was completed using the Correlated Solutions Vic3d© version 8 software package. The following key analysis parameters were used: a subset of 25 – 35 pixels, a step size of 3 pixels, and a Gaussian strain filter of 5 pixels. These analysis parameters influence the minimum strain resolution and control the range over which averaging occurs [11], [19] and thus their effect is more significant in the presence of large strain gradients.

![Figure 2](image_url)

Figure 2 – a) Schematic of Nakazima punched used in limiting dome height testing with b) a 3D strain contour of a dome sample prior to failure. In c), sample time-temperature profiles are included for the heating period of LDH testing, as measured at the specimen flange.

Necking onset, corresponding to reaching the material forming limit, was determined using the acquired DIC data in conjunction with a necking detection scheme referred to herein as the “curvature approach”. Necking is assumed to have initiated once changes in the surface curvature occur due to initiation of an acute neck. The curvature approach applied in this work is termed the Enhanced Curvature Method (ECM) and was built upon the method developed by DiCecco et al. [9], [17]. For comparison purposes, limit strains are also computed using the ISO12004:2-2008 methodology.

2.3. Aging Response of PA and T6 Tempers to Warm Forming Process

Tensile testing was performed on as-thermally processed samples to characterize their response to the various aging treatments. ASTM-E8 sub-sized tensile coupons [20] were machined from the flanges of the warm formed LDH samples in the PA and T6 tempers. The gauge length and width of the sub-sized specimens were 25 mm and 6 mm, respectively. The samples were tested under two conditions: (i) as-extracted from the flanges following warm forming, and (ii) as-extracted with a subsequent simulated paint-bake of 177°C for 30 minutes in the fluidized sand bath furnace. Three repeated tensile tests were completed for each condition.

Tensile testing was completed in the sheet rolling direction on a 100 kN load frame (MTS Criterion 45) and DIC techniques were used to extract nominal strain data, using 25 mm virtual extensometers, from each tensile sample. The crosshead speed for all tests was 0.25 mm/s.
2.4. Warm Constitutive Response of PA and T76 Tempers
Constitutive characterization of the AA7xxx – PA and –T76 tempers was completed at 175°C for nominal strain rates of 0.01/s and 0.1/s. The PA and T76 tempers were chosen since they were expected to exhibit the strongest and lowest response to elevated temperature deformation, respectively.

Testing was performed using a closed-loop thermo-mechanical simulator (Gleeble-3500, Dynamic Systems Incorporated) with the ability to resistively heat samples up to 10,000°C/s. A modified ASTM-E8 sub-sized tensile sample was used to minimize thermal gradients along the gauge length, in which the grip length was increased to 60 mm and the gauge length was reduced to 20 mm. The sample width was nominally 6 mm. Further sample details are given in [21]. Virtual extensometers using DIC techniques were used to measure strain histories over each test.

The heating profile entailed a linear ramp from room temperature to 175°C over 10 seconds, followed by a hold time at the prescribed temperature, after which isothermal tensile testing was performed. In this work, testing was done with hold times of 5 s and 180 s. The intent of the two hold times was to assess any changes in the elevated temperature constitutive response that may arise from aging prior to forming during heating to the forming temperature 175°C.

3. Results and Discussion

3.1. Formability Results
Major true limit strains as a function of temper and forming temperature are plotted in Figure 3, as well as dome heights measured at the time of failure using DIC analysis, with the PA (red) results in a) T6 (blue) results in b), and T76 (black) results in c). The minor limit strains ranged from 0.016 to 0.030 across all conditions.

The limit strains calculated using the enhanced curvature method (ECM) are represented by the solid bars and the limit strains determined using the ISO12004-2:2008 method (hereafter referred to as the ISO standard) by the dashed bars. For each temper, some disagreement is observed between the quantitative values using the ECM and ISO methods; however, both approaches generally showed the same trends. As such, the following discussion focuses primarily on the ECM limit strains.

![Diagram](image)

Figure 3 – Major true limit strain as a function of temperature for the different AA7xxx tempers: a) PA, b) T6, and c) T76. Solid bars indicate limit strains based on ECM, while dashed bars indicate values from ISO method. Dome heights corresponding to failure are plotted on the same axis in units of mm/100.

In Figure 3, the RT limit strain of the PA temper is approximately 0.21, while the T6 and T76 tempers are lower at 0.18 and 0.12, respectively. These rankings are consistent with the RT work-hardenability trends in Figure 1, in that the tempers with the higher degree of work hardening exhibit the highest RT formability. For the PA temper, the maximum limit strains are achieved between 150°C and 175°C, depending on the limit detection scheme applied. Nevertheless, at 200°C, both limit strain measures show a reduction of formability of the PA temper relative to RT as well as a marked increase in measurement scatter.
The trends in the T6 formability (Figure 3b) roughly mirror those of the PA temper, with the T6 formability improving up to 0.22 major true strain at 175°C before plateauing or degrading at 200°C based on the ECM data. The T76 temper exhibits an improvement in formability from RT to 150°C, from 0.12 to 0.17 major true strain; however, the formability of the T76 temper lies below that of the PA and T6 tempers for all temperatures.

Although the forming limit strains were improved with warm forming for all tempers, the measured dome heights at failure decreased with increases in temperature for all tempers. Comparison of the data in Figure 3 reveals that the dome heights for the PA temper are slightly higher than those for the T6 temper, while the T76 samples had inferior dome heights. The PA temper also offers excellent RT formability which increased by 10% with warm forming at 150°C.

3.2. Secondary Aged Tensile Properties of PA and T6 Tempers Following Warm Forming

Engineering stress-strain curves from tensile samples extracted from the warm-formed (WF) PA and T6 LDH specimens are plotted in Figure 4 for each forming temperature (open symbols). Corresponding data from samples that were paint-baked after forming are also plotted and are distinguished by solid symbols. The room-temperature curves from Figure 1, corresponding to the material condition prior to forming, are replotted for comparison purposes (triangular symbols).

For the PA condition, a decrease of 16 MPa in YS relative to RT is observed in the stress-strain response after exposure to the lowest WF temperature of 150°C (Figure 4a), for which the flanges were at the target temperature for under 120 seconds. After the paint-bake, a significant aging response is observed and the strength of the warm formed PA samples approach that of the RT T6 condition (seen in Figure 4 d-f). The observed drop and subsequent recovery in strength may be indicative of retrogression and re-aging [22] for the 150°C WF+PB cycle.

After WF at the higher temperatures of 175°C and 200°C, the PA temper shows a positive aging response to both WF and WF+PB, in that the strength increases relative to the RT PA condition, while
the ductility decreases. The highest tensile strength of 546 MPa ± 2 MPa is achieved after the 175°C WF+PB cycle, while the strength following the 200°C WF+PB is lower which may indicate overaging during the PA+200°C+PB cycle.

The trends in YS, UTS, UE and TE (total elongation) are summarized in Figure 5 a) – d). After a 200°C forming cycle and paint bake, the ductility in UE and TE of the PA and T6 tempers approximate that of the as-received T76. The yield and tensile strengths also appear to converge towards the overaged T76 properties, although are higher after paint-bake.

From a SCC susceptibility standpoint, the trends towards overaging in the PA temper following the 200°C+PB route may be optimal [2], [3], while offering improved strength, albeit with no formability improvements relative to the lower warm-forming temperatures. The RT and 150°C forming routes, by contrast, offer excellent formability for a 7000-series alloy; however, corrosion studies are required to assess the SCC resistance following this processing route.

![Figure 5](image-url)

**Figure 5** – Effect of the warm forming cycle temperature on the tensile properties of the PA and T6 tempers with (solid symbols) and without (open symbols) a paint bake. a) and b) show trends in yield and tensile strength, respectively. Uniform (c)) and total (d)) elongation capture trends in ductility.

A softening in the stress-strain response of the T6 temper relative to the RT baseline is observed after warm forming (Figure 4 d-f) which is attributed to a retrogression response [16]. This effect is most significant at 175°C, with a drop in YS and UTS of 31 MPa (6%) and 32 MPa (6%), respectively. A positive re-aging response is noted following PB of the T6 samples for all WF cycles, with the most significant re-aging occurring again at 175°C.

With consideration to formability and final strength characteristics, the T6 temper formed at 175°C offers improved formability without a significant degradation in strength from over-aging and is
expected to show improved corrosion performance [3], while offering improved strength relative to the as-received AA7xxx-T76 alloy. At 200°C, the formability benefits are more muted, but signs of over-aging are more prominent.

3.3. Warm Constitutive Behaviour of the PA and T76 Tempers

To further understand the effects of the various starting tempers during warm forming, the engineering stress-strain curves for the PA and T76 tempers from thermo-mechanical testing at 175°C are plotted in Figure 6 a) and b), respectively. The tensile properties, comprising YS, UTS, and UE, are summarized in Table 2. Material rate sensitivity was examined by performing these warm stress-strain tests at strain rates of 0.01 and 0.1/s. In addition, the effect of aging during heating prior to forming was examined by introducing a hold time at elevated temperature prior to isothermal tensile testing. The warm constitutive behaviour of the two starting tempers is dramatically different. The T76 temper begins to diffuse neck immediately after yielding. By contrast, the PA temper exhibits conventional work-hardening at 175°C for all hold times and strain rates.

Figure 6 – Engineering stress-strain response of the PA (a)) and T76 (b)) tempers at 175°C. Note the T76 temper begins to diffuse neck immediately after yielding in figure b). Conversely, the PA temper shows conventional positive work hardening.

Given the lack of work hardening in the elevated temperature T76 data, there is effectively no plastic uniform elongation, and yet the T76 temper positively responded to warm forming. In Figure 6 b), a positive rate sensitivity is observed for each hold time, whereby there is an approximately 7% increase in yield strength from 0.01/s to 0.1/s. This positive rate sensitivity is the driving force for promoting stability during diffuse necking, leading to the formability improvements in the T76 temper with warm forming.

Table 2 – Summary of tensile properties for the PA and T76 tempers under warm tensile testing at 175°C. Both tempers exhibit similar degrees of positive strain-rate sensitivity. The underaged temper shows at-temperature strengthening as a function of time at temperature and the overaged alloy, by contrast, decreases in strength with time at elevated temperature.

| Hold Time (s) | Nominal Rate (s⁻¹) | AA7xxx-PA | AA7xxx-T76 |
|---------------|-------------------|-----------|-----------|
|               |                   | YS (MPa)  | UTS (MPa) | UE (%)   | YS (MPa)  | UTS (MPa) | UE (%)   |
| 5             | 0.01              | 328.3 [1.6] | 379.4 [2]  | 11.8 [0] | 399.3 [3.3] | 400.6 [2.7] | 1.3 [0.7] |
| 5             | 0.10              | 347.8 [2.8] | 394.1 [3.2] | 9.1 [0]  | 426.4 [6.3] | 427.4 [6.4] | 0.9 [0.2] |
| 180           | 0.01              | 352.8 [3.2] | 396 [3.9]  | 10.7 [0.9] | 390.6 [4.9] | 392.4 [5.4] | 2.2 [1]   |
| 180           | 0.10              | 373.2 [2.5] | 406.8 [1.8] | 9.2 [0.1] | 414.6 [2.8] | 416.5 [3.8] | 1.4 [0.4] |
For the PA condition, a positive rate sensitivity (increase in strength) of approximately 6% between the 0.01/s and 0.1/s conditions was observed, independent of hold time and the shape of all tensile curves were relatively consistent, per Figure 6a). At temperature, the warm formability (ECM-based data) saw a maximum improvement of only 10% at 150°C and almost no difference to RT at 175°C. In contrast to the T76 temper, the PA temper had strong RT work-hardenability and showed correspondingly good formability. In addition, the PA temper exhibited consistently higher formability than the T76 temper for all temperatures, which is largely attributed to the prominent work-hardening in the PA condition.

For the PA temper, the effect the longer (180s) hold time at 175°C prior to tensile testing is an increase in yield strength of about 24 MPa, compared the shorter (5s) data. This increase is attributed to precipitation strengthening (aging) prior to commencing the tensile test. In contrast, the overaged T76 temper experiences additional over-aging with increases in hold time, and exhibits an at-temperature decrease in yield strength of 9 MPa from a 5 s hold time to a 180 s hold time at a nominal rate of 0.01/s.

4. Conclusions
The warm formability and final strength characteristics of a developmental AA7xxx alloy were assessed in the PA and T6 tempers, as well as a baseline T76 temper as a function of temperature. The PA temper offered the highest room temperature limit strain of 0.21, compared to 0.18 for the T6 temper at RT. The PA temper saw a 10% improvement in formability up to 150°C to reach a limit strain of 0.23, while the highest formability of the T6 temper was 0.22 at 175°C. The overaged temper saw some benefit from warm forming; but was in general the least formable temper for all conditions.

Tensile testing of samples exposed to the warm forming time-temperature cycle was completed with and without a paint bake. It was observed that the PA temper showed a strong positive response in strength to the combination of WF and PB at 150°C and 175°C. With the 200°C WF+PB cycle, the PA temper had tensile properties approaching the baseline T76 properties, indicating this cycle may lead to overaging of the initial PA temper. The T6 temper showed a softening response with warm forming, notably at 175°C, consistent with retrogression and exhibited recovery in strength following the simulated paint-bake.

Warm tensile testing of the PA and T76 tempers at 175°C and corresponding formability results suggest the positive strain-rate sensitivity of the alloy at elevated temperatures may promote stability during diffuse necking, hence the positive WF response of the T76 temper, despite diffusely necking immediately after yielding in uniaxial tension testing at 175°C. Time at 175°C had little influence on the strain-rate sensitivity, but did lead to in-situ aging (strengthening) for the PA temper and coarsening of the T76 temper.

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