Die Quench Process Sensitivity of AA7050

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Abstract. The current work investigates the sensitivity of AA7050 aluminum alloy sheet to the thermal cycle involved in the die quenching (DQ) process. This entailed the variation of three key parameters in the thermal cycle, namely solutionizing time, transfer time and quench rate, considering both water quenching (WQ) and die quenching (DQ) at various die pressures. Following a lab-grade T6 heat treatment, Vickers hardness (HV-1000) measurements of all test conditions and tensile testing on a reduced number of test conditions were completed. The results showed only limited sensitivity to solutionizing time for the range of conditions tested. Longer transfer times and slower cooling rates both negatively affected final hardness properties, with up to 4% reduction in final hardness relative to the water-quenched T6 condition. Higher cooling rates during die-quenching produced statistically similar final tensile properties to those achieved from water quenching, following a T6 heat-treatment; while slower cooling rates resulted in significant reductions in tensile strength and uniform elongation. Limiting dome height testing of a 101.6 mm dome sample under die-quench conditions produced a major true limit strain of 0.42. The die-quench limit strain compared favourably against the limit strains of the same geometry in the T6 condition at room temperature and 150 °C (isothermal), which were 0.12 and 0.18, respectively.

1. Introduction

One of the more prominent goals of the automotive industry is weight reduction of new vehicles, since this will help to improve fuel economy for traditional combustion powered vehicles as well as increase range of electric vehicles. For this reason, there is continual investigation of new metal forming techniques and new alloys to increase strength and reduce weight. One technique gaining traction is hot forming or die quenching (DQ) of high-strength aluminum alloy sheet. The DQ process is an attractive forming technique because it offers increased formability (i.e. higher forming limit strains) compared to warm forming (WF) [1] and can lead to high strength final parts after aging treatment. The DQ process is well documented for ultra-high strength steels [2]–[3] and 5xxx- and 6xxx-series aluminium alloys [4]–[6]. A more recent candidate for this technique is the 7xxx-series aluminum alloys. For the 7xxx-series alloy class, the DQ process begins by heating the blank to its solutionizing temperature, often near 470 °C [7], using a convection furnace. The blank is transferred from the furnace into a cold die set where it is simultaneously quenched and formed to the final shape. The rapid quenching temporarily

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locks the solutes within the alloy matrix into a state of supersaturation that allows for subsequent aging heat-treatments. The formed part is subsequently subjected to an artificial aging heat-treatment tailored to the desired final strength and corrosion properties.

The focus of this paper is to investigate the sensitivity of the DQ process to various key parameters in the thermal cycle, namely solutionizing time, transfer time and quench rate, and their effect on final properties such as hardness, stress-strain behaviour and formability. Such data is required to help ensure the robustness of the DQ process. The material considered in this research is an aluminum alloy sheet, AA7050 (Table 1), with a nominal thickness of 2.0 mm. This alloy is currently under consideration for automotive structural applications.

Table 1. AA7050 nominal composition, in weight percent [8]

| Alloy   | Zn  | Mg | Cu   | Fe  | Si   | Zr   | Cr   | Mn  | Ti  | Other | Al  |
|---------|-----|----|------|-----|------|------|------|-----|-----|-------|-----|
| AA7050  | 5.7-6.7 | 1.9-2.6 | 2.0-2.6 | <0.15 | <0.12 | 0.08-0.15 | <0.04 | <0.04 | <0.01 | <0.06 | Bal |

2. Experimental Setup

The specimen geometry used for all heat transfer and hardness measurements is shown in Figure 1. A thermocouple was mounted to each specimen using 3M™ High Temperature Aluminum Foil Tape 433. Figure 2 shows the instrumented specimen after it has undergone die quenching, where the blank is cooled between a pair of flat dies at room temperature (RT). Previous work by Omer et al. [9] has demonstrated that the tape does not significantly affect the measured cooling rate. In that study, 3M Kapton tape was used which has a lower thermal conductivity (1.75 Wm⁻¹K⁻¹ at 298.2 K [13]) compared to aluminum tape (237 Wm⁻¹K⁻¹ at 298.2 K [14]).

A Deltech furnace was used to heat the blanks to their solutionizing temperature of 470 °C. An Omega (OMB-DAQ-55) data acquisition system was used to record the temperature histories of the blanks. The time-temperature history for a furnace residency, i.e. total time in furnace, of 13 min is shown in Figure 3. The heating time to the solutionizing temperature was taken as 8 min, giving a resulting time of 5 min at the solutionizing temperature. Furnace residency times of 10.5 and 30 min were also considered, corresponding to times at 470 °C of 2.5 and 22 min, respectively.

Following solutionizing, samples were either water quenched (WQ) or quenched using flat dies, also referred to as die quenching (DQ). The samples were manually transferred from the furnace to the quenching medium or dies. A hydraulic press with cold rolled mild steel flat dies was used to quench specimens using the following pressures 4.5, 6, 15, 22.5, 30 and 60 MPa. The dies were held closed for 10 s at the specified pressure prior to removal of the specimen. Following quenching, samples were artificially aged in a fluidized alumina-sand bath furnace at 120 °C for 24 hrs, corresponding to a standard T6 temper aging treatment [10].

Hardness measurements were taken using a Vickers hardness tester with an indenter mass of 1000 g. Tensile tests were performed to assess the effect of quench rate on strength and elongation. Full-size ASTM E8 specimens machined along the rolling direction were tested at nominal strain-rate of 0.01 /s, measured over a 50 mm gauge length, on an MTS Criterion 45 tensile test frame. Specimens were tested under die quench conditions of 15 MPa and 35 MPa and water quench conditions.
Figure 3. Temperature vs. time for blank heat up, total furnace residency time of 13 min.

Limiting dome height (LDH) testing was performed using a 100 mm Nakazima hemispherical punch. Notched Nakazima specimens machined along the rolling direction with a 101.6 mm sample width were used. This specimen is a modified version of a geometry used by DiCecco et al. [1] with an additional 25.4 mm added to the width to achieve near-plane strain conditions. Four layers of Teflon film were used as lubricant to minimize friction. For LDH testing, specimens were tested under conditions meant to mimic the DQ process. The dome specimens were first solutionized in a furnace for 16 min at 470 °C and then quickly transferred (manually) to the press, clamped, and formed. The tooling was at room temperature and the punch speed was prescribed as 10 mm/s. AA7050-T6 specimens of the same geometry were also tested at room temperature and under isothermal warm-forming conditions of 150 °C at 1.0 mm/s for comparison purposes. The warm forming process and details regarding its application to the AA7050 alloy are discussed in greater detail in the work of Pishar et al. [12].

Strain was measured during tensile testing with stereo digital image correlation (DIC) assistance. A pair of Point Grey GRAS-50S5M-C cameras attached to a pair of Nikon AF Micro 180 mm lens were used for image acquisition. All DIC analysis was done using Vic 3D [11], a commercial DIC software package. A similar set-up was used during LDH testing, except with a pair of 17 mm focal length lenses. During tensile testing, a random black speckle pattern was used with a white base paint. In LDH testing, the white paint was omitted in favour of a dull surface finish generated by sand-blasting with commercial glass bead. The omission of the white paint was done after initial work found the white paint could not withstand deformation at the elevated temperatures experienced in the DQ process.

In DIC analysis, the basic parameters used within the Vic 3D software included a step size of 3 pixels, a strain filter of 5 pixels, and a subset of approximately 35 pixels. Based on the physical test setup, the pixel resolutions were 11 pixels/mm and 15 pixels/mm in the LDH and tensile testing, respectively.

Table 2 provides a test matrix outlining all the test conditions considered. Note that the heat transfer specimens used to assess sensitivity to solutionization time and transfer time were water quenched rather than die quenched prior to aging. Note, also, that a manual transfer process was used between the furnace and quenching operations and some variability exists as a result. A robotic transfer system is currently being implemented to minimize this variability in future work.

| Test Matrix | Hardness | Tensile | DQ Dome |
|-------------|----------|---------|---------|
| Time in furnace | 10.5, 13, 30 min | 14 min | 16 min |
| Time at solutionizing temperature | 2.5, 5, 22 min | | |
| Transfer time | 3, 8, 15 s | < 8 min | ~ 10 s |
| Die pressure | 4.5, 15, 22.5, 30 MPa | 15, 35 MPa and WQ | |
3. Results and Discussion

3.1 Effect of Solutionizing Time
The effect of furnace residency (solutionizing) time on the subsequent aging response is shown in Figure 4. Plotted is the measured hardness as a function of time in the furnace. The time at the solutionizing temperature of 470 °C for each condition is also included. Note that these samples were rapidly (<4s) transferred to a water quench medium prior to aging. It is evident from the figure that no significant change in hardness is exhibited beyond 13 min total time in the furnace. Therefore, all blanks in the subsequent investigations used a minimum total time in the furnace of approximately 13 min; hence, a minimum time of 5 min at the solutionizing temperature (470 °C) before quenching.

![Figure 4](image)

**Figure 4.** Hardness vs. time in furnace during solutionizing. The time at solutionizing temperature is also indicated for each data point. The error bars (inset figure) correspond to the measured scatter for a minimum of 3 repeat experiments per condition.

3.2 Effect of Transfer Time
Figure 5 shows the heat loss that occurs during transfer of the blank from the furnace to the die. The change in cooling rate is attributed to variation in the convective cooling rate as the blank is manually transported in the air. The temperature drops for transfer times of 3, 8 and 15 s were measured to be 11, 23 and 48 °C, respectively.

![Figure 5](image)

**Figure 5.** Temperature vs. time history during 8 s transfer time under convective cooling.
Figure 6 shows the measured hardness after WQ and aging. A slight decrease in hardness is seen as transfer time is increased, from 189 HV for 3 s to 188 HV at 15 s. However, this difference is rather small and falls within the scatter of the measurements. This range of time for transfer of the blank is representative of that achievable in an industrial setting and shows relatively little impact on the properties of the final product.

3.3 Effect of Quench Rate
Quenching temperature versus time plots for the different die pressures are shown in Figure 7. These tests were conducted to quantify the relationship between cooling rates and die pressures for the current experimental set-up. The cooling rates indicated in Figure 7 were calculated based on the average of the slopes of the linear fits to the data in the range 400 to 180 °C (T1, T2 in inset) from all repeats for each test condition. The cooling rate is found to be proportional to the die pressure; a die pressure of 6 MPa resulted in a cooling rate of 60 °C/s, whereas for a die pressure of 60 MPa the cooling rate is 191 °C/s. Note that the transfer times seen in the 6 MPa curves are about 2 seconds longer than the other curves, which have a transfer time ranging from 4.8 to 6 seconds; this lag is due to the slower press ramp up which is a result of the lower pressure in the master cylinder. The small variation between the remaining curves is thought to be primarily attributable to the natural variation in manual transfer time between each test, as well as the small difference in ramp up time of the press.
Hardness measurements were taken for die pressures 4.5, 15, 22.5 and 30 MPa and can be seen in Figure 8. The hardness of the material increases from 182 HV to 187 HV for an increase in die pressure from 4.5 MPa to 30 MPa. At 22.5 MPa and 30 MPa the measured hardness is 98% and 99% of the hardness for the water quenched samples, respectively, at the fixed transfer time of 8 s. Thus, given the close match of the hardness of the water quenched specimens vs. the die quenched specimens at 30 MPa, it was assumed that any higher die pressure would generate similar final properties.

![Figure 8. Hardness vs. die pressure. Error bars correspond to the standard deviation.](image1)

3.4 Tensile Test Results

Tensile tests were performed to further examine the effect of the quench rate on final properties. The tensile specimens were quenched at die pressures of 15 MPa and 35 MPa, chosen based on the previous quench rate investigation. The specimens were then artificially aged to a T6 temper. For comparison purposes, tensile tests were also performed on water quenched samples. Figure 9(a) shows the tensile results, comprising the measured yield strengths, ultimate tensile strengths and uniform elongations. The higher pressure DQ samples show strength and ductility that are similar to the WQ results. The lower pressure (lower quench rate) samples exhibit a 3% drop in tensile strength and a 29% drop in elongation, indicating that this alloy is quench sensitive. Note that for the 15 MPa quench rate the tensile strength values exhibit greater scatter which signals weaker repeatability of the process at the lower quench rate.

![Figure 9(a). Engineering stress and strain vs quench method](image2)

![Figure 9(b). Orange peel phenomenon on tensile specimen.](image3)
Figure 9(b) shows that at high strains the AA7050 alloy presents a significant degree of surface roughening, known as “orange peeling”. The observation of surface roughening was seen for all quench conditions studied in this work and is therefore considered independent of the studied quench processes. The observations of surface roughening and the apparent quench rate sensitivity are thought to be texture and grain size dependent and are the subject of ongoing research.

3.5 Dome Testing Results

Figure 10(a) plots the measured limit strains using the plane strain Nakazima specimens. The DQ samples were tested immediately after solutionization and were quenched during testing using room temperature tooling (punch speed of 10 mm/s). The DQ samples revealed a rather high plane strain limit of 0.42 major true strain, as calculated using the ISO12004-2:2008 standard. Limiting dome height tests of AA7050-T6 samples were also tested at RT and under isothermal warm forming conditions of 150 °C. During warm forming, the LDH tooling was maintained at 150 °C with embedded heater cartridges and a closed-loop PID system, and the blanks were heated via contact under pressure with the tooling for approximately 3 min prior to testing at 1 mm/s.

Major true limit strains, as determined using the ISO12004:2-2008 standard, were 0.12 and 0.18 for the RT and 150 °C conditions, respectively. The die-quench formability of the alloy compares favourably with the room temperature and warm forming conditions, yielding improvements in formability on the order of 2.6 to 1.4 times greater forming limit strains, when compared to RT or warm forming at 150 °C, respectively. Figure 10(b) depicts the so-called orange-peel phenomenon during LDH testing; this aspect of the test results will be examined further in future work.

4. Conclusion

The AA7050 alloy exhibited only limited change in hardness with changes in solutionizing and furnace-die transfer time within the test ranges considered. On the other hand, the lower quench rate associated with the low pressure DQ specimens did result in a 4% drop in hardness and 3% drop in tensile strength. Of greater concern is the drop in uniform elongation for the lower pressure DQ samples since this could indicate that fracture resistance is affected by quench sensitivity. Future work will address these issues in more detail. In addition, automated experiments using robotic blank transfer and higher press speeds are planned to ascertain whether the observed quench sensitivity is due in part to the current forming speeds and manual transfer process. Nonetheless, the measured forming limit strains serve to demonstrate the strong potential of this alloy for elevated temperature forming operations.
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