Sheared Edge Formability Characterization of High Strength Aluminum Alloys at Room and Elevated Temperatures using Hole Expansion Tests

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Abstract. High strength 6000- and 7000-series aluminum alloys have significant potential for automotive light weighting due to their high strength-to-weight ratios. Alternate thermal processing routes and warm forming operations with rapid heating to 150 - 300°C are being explored to expand their forming process windows. While the constitutive and formability behavior of these alloys at elevated temperatures is an active area of research, limited data is available on their sheared edge stretchability, particularly under elevated temperature forming conditions. To this end, the influence of cutting clearance on the edge fracture limits of two precipitation hardening alloys, AA6013-T4 and AA7075-T6, and a non-heat treatable AA5182-O were first investigated at room temperature using the conical hole expansion test. A 12% clearance was found to be suitable for the three materials and used to process the hole expansion samples prior to warm forming. Microhardness tests were used to characterize the depth and severity of the shear affected zone (SAZ) for the AA7075-T6 before and after the warm forming cycle. The forming temperature was found to increase the hole expansion ratio by approximately 400%, 150%, and 520% for the AA5182-O, AA6013-T4, and AA7075-T6 respectively relative to the room temperature tests. The edge stretchability during W-temper forming of the AA6013 and AA7075 at room temperature was also assessed. It was observed that W-temper forming negatively influenced the hole expansion of AA6013 by approximately 30% relative to the T4 condition. Conversely, the hole expansion ratio for AA7075 when formed in W-temper increased by over 35% with respect to the T6 temper.

1. Introduction

The need for lighter and fuel efficient vehicles has driven the increased adoption of high strength 6000- and 7000-series alloys in the automotive stamping industry. However, additional heat treatment and elevated temperature forming processes are often necessary to enable formation of complex parts since...
these age hardenable alloys have limited ductility at room temperature [1]. One approach is to solutionize and quench the material followed by immediate cold forming in the ductile W-temper [2]. Although promising, the W-temper is unstable at room temperature due to natural aging such that the time between quenching and stamping becomes critical. Alternatively, heating the material in the T4 or T6 temper to temperatures above 150°C and warm forming has been found to enhance the material ductility and part depths considerably for 5000- and 7000-series alloys [3]. On the contrary, limited improvements in forming depth and limit strains have been observed in general during warm forming of 6000-series alloys [3, 4]. The available literature has mainly addressed the drawability and stretchability of high strength aluminum alloys. Studies focused on sheared edge formability of these materials at room or elevated temperature have been scarce despite hole punching followed by extrusion being commonplace in automotive panels. Several studies have been conducted with regards to dependence on cutting clearance for 5000- and 6000-series aluminum at room temperature wherein a gap equal to 20% of the sheet thickness or lower was identified to be appropriate [5, 6]. The effect of heat treatment and warm forming on sheared edge stretchability remains unexplored.

The objective of the present study is to evaluate the influence of cutting clearance, hole expansion temperature, and W-temper forming on sheared edge fracture limits of aluminum alloys using the conical hole expansion (HX) test. Three commercial aluminum alloys are studied: a non-precipitation hardenable AA5182-O, and two heat treatable alloys, AA6013-T4 and AA7075-T6. The room temperature sheared edge formability was first characterized to select the best cutting clearance for each material. Blanks with a 10 mm diameter central hole were then prepared by either drilling and reaming or punching, after which the hole expansion test was conducted at elevated temperatures of 250°C, 300°C and 175°C for the AA5182-O, AA6013-T4 and AA7075-T6 samples, respectively. In addition, the sheared edge stretchability of AA6013 and AA7075 at room temperature were also characterized in the W-temper condition. Finally, the severity of work hardening near the edge after punching and before the forming cycle were characterized for AA7075-T6 using microhardness tests to correlate with the hole expansion capabilities at room and elevated temperature.

2. Materials and Experiments

2.1. Mechanical Properties

The room temperature tensile mechanical properties of the three materials at a strain rate of 0.001 s⁻¹ are listed in Table 1. The AA5182-O sheet was supplied in the annealed condition while the AA6013 and AA7075 were provided in the T4 and peak-aged T6 tempers respectively. The plasticity response characterization of the same lot of AA5182-O and AA7075-T6 was performed in prior work by the authors [7, 8].

| Material | Thickness (mm) | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) | Uniform Elongation (%) | Total Elongation (%) |
|----------|----------------|----------------------|---------------------------------|------------------------|----------------------|
| 5182-O   | 1.5            | 146                  | 302                             | 20.6                   | 25.7                 |
| 6013-T4  | 2.0            | 156                  | 314                             | 20.8                   | 30.6                 |
| 7075-T6  | 2.0            | 483                  | 566                             | 11                     | 16.0                 |

2.2. Hole Processing Techniques

Circular holes of 10 mm diameter were punched with three different cutting clearances (c) of 5%, 12%, and 19% with respect to the sheet thickness. The 10 mm hole size was chosen in accord with the ISO16630 standard [9]. A 203.2 mm diameter blank was positioned on lifter springs with its edges in contact with guide stops on the tooling to ensure accurate positioning of the hole during cutting. The
holding force and strip removal was achieved via a punch stripping system with steel springs designed for compact space requirements as shown in Figure 1 (b). Monarch Klir 2 cutting oil was applied on the specimen surface before punching to minimize burr formation. The punching speed was set to 125 mm/s and conducted at room temperature for all test conditions considered. The dimensions and the punching tool setup are depicted in Figure 1. Additional samples were also fabricated by drilling a hole of 9.5 mm followed by reaming to the final 10 mm diameter to consider the baseline material condition with minimal strain hardening at the edge.

![Figure 1](image)

**Figure 1.** (a) Schematic of the punching process, and (b) punching tool at the University of Waterloo.

### 2.3. Conical Hole Expansion at Room and Elevated Temperatures

The Fast Forming System (FFS) developed at the University of Waterloo and shown in Figure 2 was employed to perform the warm hole expansion tests [11]. The FFS system utilizes an ABB® robotic arm to maneuver the specimen from the loading station to the contact furnace and the hole expansion tooling. The specimens were heated to the forming temperature rapidly before removal and transfer to press by the robot within approximately 12 seconds. The forming temperature chosen for the materials and corresponding heating times in the furnace are tabulated in Table 2. The hole expansion temperature for each alloy was selected based upon the literature and/or prior Nakazima dome test results that resulted in good sheet forming limit strains. Thus, the temperatures chosen for each material may not necessarily be the most favorable in terms of maximizing the sheared edge fracture limits.
Figure 2. Fast forming system developed at the University of Waterloo [11]. (a) Tooling setup and (b) blank heating and handling system for warm hole expansion tests

Table 2. Blank forming temperature and heating time in contact furnace prior to hole expansion. The tools are heated to the same temperature as the specimens to facilitate a near isothermal test condition.

| Material   | HX temperature (°C) | Contact furnace temperature (°C) | Hold time in contact furnace (s) |
|------------|---------------------|----------------------------------|---------------------------------|
| AA5182-O   | 250                 | 300                              | 7                               |
| AA6013-T4  | 300                 | 350                              | 10                              |
| AA7075-T6  | 175                 | 220                              | 8                               |

The conical punch had a minimum and maximum diameter of 4 mm and 40 mm, respectively, with a taper angle of 60° in accordance with the ISO16630 standard. The hydraulic binder imposed a clamping force of approximately 400 kN on the specimen. No lubricant was applied to the punch or the specimen before the tests due to its potential breakdown at elevated temperatures. After sample placement, the binder and die clamped the specimen and moved downward in concert at a speed of 1.0 mm/s to extrude the hole while the punch was stationary. Hole deformation was continuously captured using two high speed stereo cameras having a frame rate of 750 frames per second and equipped with Sigma® macro lenses with 105 mm focal length. The test was terminated as soon as a through-thickness crack was detected in the monitoring system. Subsequently, the first image that showed the crack was identified and the corresponding hole geometry was evaluated using the ImageJ software. A schematic of the conical hole expansion tooling and a recorded image of an AA5182-O sample at the first appearance of a through-thickness crack are shown in Figure 3. The room temperature hole expansion tests were performed on an MTS formability press with a clamping force of 640 kN in dome test tooling without lockbeads. The tests were conducted without any lubricant to be in line with the elevated temperature cases. Details regarding the tooling, test setup and data acquisition are discussed in Noder et al. [10]. A minimum of five repeats were conducted for each test condition.
Figure 3. (a) Schematic and dimensions of the tooling employed in the FFS for warm hole expansion tests, and (b) a representative image of an AA5182-O sample at instant of through-thickness crack after punching with 12% clearance and hole expansion at room temperature.

The average inner hole diameter at fracture, $D_{inner}^f$, was determined from four measurements of the image at fracture and used to evaluate the hole expansion ratio (HER) defined as

$$HER(\%) = \frac{D_{inner}^f - D_0}{D_0} \times 100$$

where $D_0$ is the initial hole diameter equal to 10 mm.

The HER represents deformation under a non-linear strain path due to the initial compression of the inner hole edge when in contact with the conical punch before gradually transitioning to uniaxial tension [12]. Conversely, the outer hole edge remains in a uniaxial tensile stress state throughout the test and is utilized to determine the fracture strain from the initial and final diameters [10, 12]. The average major and equivalent strain in terms of the average outer diameter at fracture ($D_{outer}^f$) are

$$\varepsilon_{eq}^f = \varepsilon_1^f = \ln \left( \frac{D_{outer}^f}{D_0} \right)$$
3. Results and Discussion

3.1. Edge Sensitivity to the Cutting Process at Room Temperature (RT)
The effect of cutting process and punching clearance on the room temperature HER and fracture strains for the studied materials are depicted in Figure 4. The AA5182-O and AA7075-T6 samples were found to be relatively insensitive to the cutting clearance. Interestingly, the measured HER for AA6013-T4 samples after shearing with 12% clearance was significantly higher at 46% compared to the other two punching conditions. A cutting clearance of 12% was then selected for the W-temper and warm forming conditions. All three alloys were moderately sensitive to the cutting process since the HER of the reamed specimens was at least 50% higher than that of the corresponding edges sheared with 12% punch-die clearance.

Figure 4. (a) Measured hole expansion ratios and (b) average major fracture strains from RT hole expansion tests of reamed and sheared edges. The error bars denote the standard deviation in the measured data.

3.2. Effect of W-Temper Forming on Sheared Edge Fracture Limits
The AA6013 and AA7075 specimens were solutionized for 30 minutes at 570°C and 470°C, respectively, followed by rapid quenching between flat dies, RT hole punching and extrusion within 6 minutes for the W-temper tests. The comparison of the W-temper hole expansion with the as-received material is shown in Figure 5. The sheared edge formability of AA6013 sheet was found to decrease in W-temper forming by approximately 30% relative to the T4 condition. On the contrary, the HER increased in W-temper forming of AA7075 and was comparable to that of the drilled and reamed test conducted in the T6 temper.
3.3. Influence of Forming Temperature on Sheared Edge Fracture Limits

A significant influence of hole expansion temperature on the edge fracture limits was observed for the three materials, as can be seen in Figure 6 for both reamed and punched holes. The observed HER at 250°C for AA5182-O was at least five times higher than that of the room temperature tests. Fracture was not achieved in the AA5182-O tests at 250°C so the HER of 150% is a lower bound estimate. The sheared edge HER at elevated temperatures was approximately 2.5 and 6.2 times higher than the RT test for the AA6013-T4 and AA7075-T6 samples, respectively. A similar trend is also noted in the fracture strains.

3.4. Hardness Distribution After Hole Punching for AA7075-T6

The reamed and sheared AA7075-T6 specimens were sectioned along the rolling direction (RD) for hardness measurements since through-thickness cracks predominantly occurred in this direction during hole expansion. A few samples were also subjected to a rapid heating cycle at 175°C for 8 seconds after hole processing but prior to sectioning and mounting to gauge the hardness change due to temperature. The specimens were then cold mounted in the puck using a mixture of epoxy resin and hardener (25:3
ratio by weight) due to heat sensitive nature of the AA7075-T6. The microhardness tests were conducted after a resin curing time of approximately 12 hours. One representative sample was considered for each condition. The microhardness measurements were conducted across the SAZ along three lines located at approximately 25%, 50%, and 75% through the sheet thickness, as shown in Figure 7(a). The first indent was placed at approximately 0.15 mm away from the edge while the distance between two consecutive indents was roughly 2.5 times the indenter size or 0.20 mm. A notable SAZ with a hardness gradient near the edge was not observed for the punched specimen at RT with the values comparable to a reamed specimen as shown in Figure 7 (b). This lack of SAZ hardness change is also reflected in the small absolute differences in the HER and fracture strain between the reamed and punched specimens for the AA7075-T6 shown in Figure 4. Treating the specimen to a heating cycle at 175°C after hole punching slightly reduced the hardness but does not explain the significant difference in the sheared edge fracture limits. It is hypothesized that the reduction in the hardness is due to potential over ageing that is accelerated by the deformation induced near the edge despite only 8 seconds of hold time in the furnace at 175°C. The increased sheared edge formability at 175°C is presently attributed to a reduction in the flow stress [11] that delays damage nucleation near the edge.

![Figure 7](image_url)

Figure 7. (a) Vickers hardness (HV0.2) measurements conducted along three lines for an AA7075-T6 sample, (b) average hardness versus the distance from the hole edge for a reamed and punched specimen at RT, and (c) hardness distribution for a punched specimen at RT and held at 175°C for 8 seconds.

4. Conclusions
The sheared edge formability of three different aluminum alloys was experimentally characterized at room and elevated temperature. At RT, the AA5182-O and AA7075-T6 did not exhibit a strong sensitivity to the cutting clearance whereas 12% clearance performed the best for the AA6013-T4. Cold punching and HX of the W-temper at room temperature negatively affected the fracture strains for the AA6013, whereas a fracture strain increase of over 10% was seen for AA7075-W with respect to the peak-aged condition. With respect to the RT sheared edge HER values of 31%, 46%, and 9% for a 12% cutting clearance, the hole expansion capability at elevated temperature were higher by approximately 5.0, 2.5, and 6.2 times for the AA5182-O, AA6013-T4, and AA7075-T6 specimens, respectively. Finally, microhardness tests conducted for the punched AA7075-T6 specimens did not indicate the presence of any hardness gradient within the SAZ and likely accounts for its low edge sensitivity to the cutting process. However, observed hardness distribution could not explain the increase in HER and fracture strain with temperature. Future work will address the influence of other conditions such as pre-aging, hot forming, and stroke rate on the sheared edge stretchability of these alloys.

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