Spall properties of Al 5083 plate fabricated using equi-channel angular pressing (ECAP) and rolling

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Abstract. The spall strength and Hugoniot Elastic Limit (HEL) of aluminum alloy 5083 (Al 5083) are compared for plates fabricated using equi-channel angular pressing (ECAP) and rolling. Al 5083 is a light-weight and strain-hardenable aluminum alloy used for armor plating in military transport vehicles, thus requiring the highest achievable spall strength and HEL. Materials that were processed by ECAP displayed a highly refined grain structure with little texture and a large degree of plastic deformation, whereas subsequent rolling resulted in a textured microstructure with both grains and inclusions aligning along the rolling direction. The spall behavior of Al 5083 was determined using plate-impact gas-gun experiments with rear free surface velocity measurements for a variety of processing conditions involving both ECAP and rolling. The spall strength and HEL increased from that of the as-received material after processing with ECAP. Subsequent rolling further increased the HEL but reduced the spall strength. Rolling also resulted in directional dependence of the spall strength, with the lowest spall strength occurring for impact through the plate thickness and highest spall strength in the rolling direction. The trends in the spall behavior correlate with the size and preferential alignment of manganese dispersoids and iron and silicon rich inclusions that are evolved during processing.

1. Introduction

Aluminum alloy 5083 (Al 5083) is a strain hardenable alloy system that is used for light-weight armor plate in military transport vehicles. Armor plate should have the highest achievable spall strength and Hugoniot elastic limit (HEL) in order to enhance blast and penetration resistance. Previous studies have reported the spall strength and HEL of rolled Al 5083 plate in the H131, H32, and H116 tempers [1-4]. In one case, the spall strength and HEL varied with impact direction, due to the textured rolled plate microstructure [4].

Equi-channel angular pressing (ECAP), also known as equi-channel angular extrusion (ECAE), is a processing method that can produce a highly refined, sub-micron, grain structure in metals and alloys [5]. ECAP involves pressing a billet through an angular die, with no change in cross-sectional area after pressing through the die. Processing using ECAP yields a unique and highly refined...
microstructure. The small grain sizes produced from ECAP strengthen the material through the Hall-Petch effect, while also maintaining low temperature ductility, due to the ease of grain boundary sliding [5].

ECAP has been used to produce highly refined grain structures in large aluminum plates and in Al 5083 in particular [6,7]. In the present work, large Al 5083 plates were processed using both ECAP and post-ECAP rolling. The effects of the unique microstructure produced by ECAP on the spall strength and HEL are examined and compared to that for a standard rolled Al 5083 plate.

2. Experimental Procedure

2.1. Materials

The as-received Al 5083 was obtained as a rolled plate in the H321 temper, indicating strain hardening and a partial annealing treatment. The composition of the alloy is 4.0-4.9 wt.% Mg and 0.4-1.0 wt.% Mn, in addition to trace elements. Magnesium gives the alloy its strain hardening capability, while manganese forms dispersoid phases that refine the grain structure.

In addition to the as-received plate, three other sample types were tested corresponding to different degrees of processing with ECAP and rolling. The first of these samples was only processed using ECAP, with no subsequent rolling. The ECAP billets were large plates (15.2 in. x 15.0 in. x 3.2 in.) that were given four passes through the die at 250°C with subsequent turning by 90° about the through-thickness normal between each pass. This processing technique has been shown to yield a uniform grain structure throughout the large plate with a grain size of ~400 nm [7]. Two other sample types were processed similarly using ECAP followed by varying degrees of rolling. One sample was first warm rolled at 150°C to 55% thickness reduction followed by cold rolling at room temperature to give a further 20% reduction. The final sample type was processed with ECAP followed by cold rolling at room temperature to 30% thickness reduction.

The density (ρ) and sound speeds (C) of each sample type were measured for calculation of the spall strength, HEL, and elastic constants. Sound speed measurements were performed using ultrasonic testing as described in a previous work [4]. Table 1 lists the longitudinal wave speed, shear wave speed, bulk wave speed, shear modulus, bulk modulus, elastic modulus, and Poisson’s ratio (C_L, C_S, C_B, G, K, E, and ν respectively) along each direction of the four sample plates.

Table 1. Measured sound speed, density, and elastic constants for all Al 5083 samples. The samples were tested along the short transverse (ST), long transverse (LT), and longitudinal (L) directions for rolled specimens. The samples processed using ECAP only were tested along the two ECAP directions and through the plate thickness. The data represents a 95% confidence interval in all cases.

|                  | C_L [mm/μs] | C_S [mm/μs] | C_B [mm/μs] | G [GPa] | K [GPa] | E [GPa] | ν       |
|------------------|-------------|-------------|-------------|---------|---------|---------|---------|
| As-Received Al 5083-H321: |             |             |             |         |         |         |         |
| ST               | 6.36 +/- 0.03 | 3.20 +/- 0.02 | 5.17 +/- 0.05 | 27.4 +/- 0.3 | 71 +/- 1 | 73 +/- 2 | 0.33 +/- 0.02 |
| LT               | 6.45 +/- 0.02 | 3.16 +/- 0.01 | 5.32 +/- 0.04 | 26.7 +/- 0.2 | 75 +/- 1 | 72 +/- 2 | 0.34 +/- 0.01 |
| L                | 6.45 +/- 0.02 | 3.17 +/- 0.01 | 5.31 +/- 0.04 | 26.8 +/- 0.1 | 75 +/- 1 | 72 +/- 2 | 0.34 +/- 0.01 |
| ECAP 4 Passes:   |             |             |             |         |         |         |         |
| ρ = 2.664 +/- 0.001 [g/cc] |
| ST               | 6.39 +/- 0.01 | 3.17 +/- 0.01 | 5.24 +/- 0.03 | 26.7 +/- 0.2 | 73 +/- 1 | 72 +/- 2 | 0.33 +/- 0.01 |
| LT               | 6.43 +/- 0.02 | 3.18 +/- 0.05 | 5.27 +/- 0.07 | 27.0 +/- 0.9 | 74 +/- 2 | 72 +/- 3 | 0.34 +/- 0.02 |
| L                | 6.41 +/- 0.02 | 3.18 +/- 0.03 | 5.26 +/- 0.05 | 26.9 +/- 0.5 | 74 +/- 1 | 72 +/- 2 | 0.34 +/- 0.02 |
| ECAP + Warm and Cold Rolling: |             |             |             |         |         |         |         |
| ρ = 2.663 +/- 0.001 [g/cc] |
| ST               | 6.36 +/- 0.02 | 3.22 +/- 0.02 | 5.16 +/- 0.05 | 27.6 +/- 0.4 | 71 +/- 1 | 73 +/- 2 | 0.33 +/- 0.02 |
| LT               | 6.44 +/- 0.04 | 3.15 +/- 0.05 | 5.31 +/- 0.10 | 26.5 +/- 0.9 | 75 +/- 3 | 72 +/- 4 | 0.34 +/- 0.03 |
| L                | 6.41 +/- 0.02 | 3.17 +/- 0.05 | 5.27 +/- 0.07 | 26.7 +/- 0.9 | 74 +/- 2 | 72 +/- 3 | 0.34 +/- 0.02 |
| ECAP + Cold Rolling: |             |             |             |         |         |         |         |
| ρ = 2.665 +/- 0.001 [g/cc] |
| ST               | 6.40 +/- 0.03 | 3.20 +/- 0.01 | 5.23 +/- 0.04 | 27.4 +/- 0.2 | 73 +/- 1 | 73 +/- 1 | 0.33 +/- 0.01 |
| LT               | 6.42 +/- 0.08 | 3.17 +/- 0.04 | 5.27 +/- 0.13 | 26.8 +/- 0.6 | 74 +/- 4 | 72 +/- 4 | 0.34 +/- 0.04 |
| L                | 6.47 +/- 0.02 | 3.17 +/- 0.02 | 5.34 +/- 0.05 | 26.8 +/- 0.4 | 76 +/- 1 | 72 +/- 3 | 0.34 +/- 0.02 |
2.2. Plate impact testing
A detailed description of the experimental setup for plate impact testing and the calculation of spall strength and the Hugoniot elastic limit (HEL) is described elsewhere [4]. Symmetric Al 5083 on Al 5083 plate impact was performed on the four differently processed plates using the 80 mm bore single-stage light-gas gun at the Georgia Institute of Technology. The projectiles consisted of sabot with an Al 5083 flyer plate backed with an air gap. Sample targets consisted of 10° tapered disks within Al 5083 surround rings that were designed to prevent 2-D rarefactions from reaching the sample free surface prior to acquiring HEL and spall data. Free surface velocity data was measured from the target sample rear free surface using the VALYN VISAR interferometry system, which uses a 532 nm wavelength laser and has nanosecond time resolution. The spall strength and HEL were both calculated using the sample rear free surface velocity, and the spall strength was corrected for elastic plastic effects using the method of Kanel et al [8].

All four plate materials were tested using two different impact configurations: one where impact was performed through the plate thickness only (using 5 mm thick flyer plates and 10 mm thick samples), and one where impact was performed along all three plate directions simultaneously (using 3 mm thick flyer plates and 6 mm thick samples). Since symmetric impact was used for all experiments and the samples were twice the thickness of the flyer plate, the spall occurred along the mid-plane of the target samples for these experiments.

3. Results and Discussion

3.1. Sample microstructure
As reported previously, processing with ECAP results in a highly refined grain structure with ~400 nm grain sizes [7]. The progression in the inclusion size and distribution after ECAP and subsequent rolling is shown in figure 1. Figure 1(a) shows the microstructure after four ECAP passes, where large inclusions are visible as black particles. Subsequent rolling of this microstructure results in larger inclusions that are often damaged, as shown in figure 1(b). Rolling also aligns these inclusions along grain boundaries, as shown in figure 1(c). Brittle particles such as these are known nucleation sites for spall damage.

![Figure 1](image_url)

**Figure 1.** Optical microscope images of (a) the sample given ECAP alone, (b) the longitudinal plane of the sample given ECAP followed by warm and cold rolling, and (c) the long transverse plane of the sample given ECAP followed by warm and cold rolling. Large inclusions can be observed after ECAP. The inclusions grow and align along the rolling direction after warm and cold rolling.

3.2. Plate impact experimental results
Plate impact testing was performed at approximately 400 m/s both through the plate thickness and along each orientation of the plate for each of the four specimens described in section 2.1. This velocity is in a range that was previously studied for rolled Al 5083-H116 plate using the same experimental setup [4].
3.2.1. VISAR free surface velocity. The VISAR free surface velocity profiles for impact through the plate thickness and along all three plate orientations are given in figures 2 and 3 respectively. The inset of each figure better displays the trends in the HEL with processing and plate orientation.

Figure 2 clearly shows that processing with ECAP increases the HEL from that of the as-received rolled plate. Subsequent rolling of the plates processed with ECAP results in even larger gains to the HEL - especially for the plate processed using both warm and cold rolling; however, the pullback velocity, a measure of the material’s spall strength, shows a different trend with processing. ECAP alone results in an increased pullback velocity relative to the as-received plate, but rolling in addition to ECAP results in decreased pullback velocity for both rolled specimens measured through the plate thickness.

Figure 3 displays the orientation dependence of both the HEL and spall properties for each specimen. The as-received plate shows the largest difference in the HEL as a function of orientation, with the long transverse direction showing the largest HEL value. This is similar to the HEL trends for Al 5083-H116 [4]. The plate processed using ECAP has a lower HEL value through the thickness than either of the two ECAP directions. Subsequent rolling of the plate results in similar HEL values for each of the three impact directions. The as-received and ECAP specimens show slight decreases in the pullback velocity when measured through the plate thickness, as shown in figures 3 (a) and 3(b); however, there is a much larger decrease in the pullback velocity through the thickness for the samples processed using both rolling and ECAP, as shown in figures 3 (c) and 3(d).

![Figure 2. VISAR rear free surface velocity data for Al 5083 samples impacted through the plate thickness](image1)

![Figure 3. VISAR rear free surface velocity data for Al 5083 samples impacted along all three plate orientations](image2)

3.2.2. Spall strength and HEL values. The spall strength and HEL values were calculated using the free surface velocity data shown in figures 2 and 3. The calculated values are shown for impact through the plate thickness and along all three plate orientations in figures 4 and 5, respectively.

Figures 4 and 5 quantify the trends mentioned in section 3.2.1. For impact through the plate thickness, the highest spall strength value is 0.90 GPa for the specimen processed using ECAP only. Subsequent rolling results in decreased spall strength, despite the large gains in the HEL value. The
largest HEL value is 0.72 GPa for the specimen processed using ECAP followed by both warm and cold rolling.

Figure 5 shows the values of spall strength and HEL as a function of orientation for each plate specimen. The as-received and ECAP samples show little variation in spall strength with all values within the error bars for each orientation; however, the HEL shows some orientation dependence. For the as-received specimens, the HEL ranges between 0.37 GPa to 0.50 GPa, and for the ECAP samples, the HEL ranges between 0.47 GPa to 0.56 GPa. ECAP followed by rolling results in a larger and consistent HEL of approximately 0.7 GPa for any plate orientation; however, the spall strength is drastically reduced through the thickness. The spall strength for the samples processed using ECAP followed by warm and cold rolling drops from a maximum value of 1.09 GPa to 0.72 GPa, and the spall strength for the samples processed using ECAP followed by cold rolling drops from 1.09 GPa to 0.84 GPa.

As shown in figure 1, brittle particles, such as Mn dispersoids and Fe and Si rich inclusions, grow and align along the grain boundaries after processing with ECAP and rolling. Therefore, void nucleation sites are preferentially located along planes perpendicular to the impact direction for impact through the plate thickness and are likely responsible for the reduced spall strength for impact in this direction. As shown in figure 1(a), the specimen processed by ECAP alone does not have a preferential alignment of inclusions, and consequently, shows higher spall strength than the rolled specimens and little orientation dependence.

4. Conclusions
Equi-channel angular pressing (ECAP) is a processing technique that can result in a uniform sub-micron grain structure for large alloy plates. The spall properties of Al 5083 processed using both ECAP and rolling are largely controlled by the alignment and cracking of brittle inclusions during processing. Processing via ECAP alone results in no alignment of particles, causing increased spall strength and HEL with little orientation dependence for either property. However, subsequent rolling
of the ECAP plates results in significant increases to the HEL, but at the expense of the spall strength. The spall strength decreases dramatically through the plate thickness, due to the preferential alignment and cracking of inclusions during the rolling process. Processing via ECAP alone shows promise for increasing the impact resistance of aluminum alloy plates, as this resulted in the best combination of both HEL and spall strength.

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