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ScienceDirect
Scripta Materialia 92 (2014) 59–62
Scripta MATERIALIA
www.elsevier.com/locate/scriptamat

Spall and dynamic yield behavior of an annealed aluminum–magnesium alloy

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Received 1 July 2014; revised 12 August 2014; accepted 13 August 2014
Available online 27 August 2014

The dynamic yielding and tensile fracture (spalling) behavior of an annealed aluminum–magnesium alloy is investigated using symmetric plate impact experiments. The Hugoniot elastic limit displays upper and lower yield points, with the lower yield point remaining constant near 0.33 GPa and the upper yield point increasing from 0.38 to 0.48 GPa with increasing peak stress. The dynamic fracture (spall) strength also increases with peak stress from 0.84 to 0.92 GPa.

Keywords: Aluminum alloys; Fracture; Annealing; Grain boundaries; Spalling

Aluminum 5083 (Al 5083) is a lightweight aluminum alloy that can be significantly strengthened by strain hardening [1]. This alloy is used for lightweight armor plates due to its high strength to weight ratio after cold working. Armor plates can fail during service due to projectile impact, in which case dynamic yielding influences the penetration resistance, or due to blast wave impact, in which case dynamic fracture (spall) resistance is important. Therefore, studying the dynamic yielding and fracture behavior of Al 5083 as a function of processing conditions and resulting microstructure is important for producing high-quality armor plate material.

Plate impact testing of strain-hardened Al 5083 has been performed previously to measure the Hugoniot elastic limit (HEL) and the spall strength [2–5], as measurements related to the dynamic yield and fracture strength, respectively. For Al 5083-H131, a heavily cold-worked armor-grade temper, the spall strength and HEL were reported as 0.936 and 0.573 GPa, respectively [2,3]. For Al 5083-H32, another armor-grade temper, the spall strength and HEL were reported as 1.23 and 0.60 GPa in one study [4], while the HEL was reported as 0.40 GPa in a different study [2]. For Al 5083-H116, a similar temper to H32, the spall strength was reported to range between 0.81 and 0.95 GPa depending on plate thickness, while the HEL remained constant at 0.44 GPa [5]. Differences in spall strength values reported by different research groups can partly be attributed to differences in experimental setup. The spall strength of ductile materials can vary with stress duration and strain rate due to changes in impact velocity, impactor material, or impactor or target plate thickness [6–8].

The HEL of ductile materials has also shown thickness-dependent behavior, whereby the HEL rapidly drops to a constant value as the target thickness increases [9–11]. This phenomenon is commonly referred to in the literature as "precursor decay". Precursor decay is also characterized by upper and lower yielding at the HEL, which was first noted by Barker et al. [12] for annealed Al 1060 samples. The upper yield point increased with increasing impact velocity, indicating that the phenomenon is rate dependent. In fact, Nicholas et al. [11] used computer simulations to prove that the precursor decay phenomenon requires a strain-rate-dependent mechanical model. While the physical cause of elastic precursor decay has not yet been ascertained, it is often attributed to the initial high stress required to nucleate dislocations near the impact surface followed by ease of yielding after dislocations have already been nucleated [9]. This explanation accounts for the rapid decrease in HEL as the wave moves away from the impact face, as well as for the upper and lower yielding phenomenon for annealed materials with low dislocation density.

Most plate impact testing of Al 5083 has focused on the strain-hardened tempers that are used for in-service armor plates. One experiment reported the spall strength of Al 5083-O (a fully annealed temper) as 1.6 GPa, which is significantly higher than that for the strain-hardened tempers [13]. In the present work, symmetric plate impact testing, over the stress range of 1.4–5.5 GPa, is used to measure the HEL and spall strength of annealed Al 5083. HEL and spall strength values were calculated using an experimental setup identical to that used for previous experiments on strain-hardened Al 5083-H116 [5].

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http://dx.doi.org/10.1016/j.scriptamat.2014.08.014

Rolled Al 5083-H116 was obtained from McMaster-Carr as a 0.5 in. (~13 mm) thick plate, with a composition of 4.0–4.9 wt.% Mg and 0.4–1.0 wt.% Mn. The H116 temper is heavily cold worked to yield significant strain hardening. An approximately 12 in. × 1.5 in. × 0.5 in. (~305 mm × 38 mm × 13 mm) rectangular slab was cut from the original rolled plate with the long axis of the slab along the original rolling direction. The slab was first annealed at 415 °C (the recommended annealing temperature for Al 5083 [1]) for 10 min to soften the strain-hardened plate, and then stretched to ~3% strain under a strain rate of $\sim 1 \times 10^{-5}\ \mathrm{s}^{-1}$ using an Instron tensile testing machine. This allowed for a uniform state of strain to be achieved in the center of the slab to act as the driving force for grain growth. The ends of the slab were removed after stretching as they were deformed from the clamping mechanism. The center of the slab was annealed again at 415 °C for 24 h to allow significant grain growth to occur.

Specimen preparation for microscopy consisted of grinding using 400, 600, 800 and 1200 US grit papers, followed by polishing with 1 μm alumina and 0.05 μm colloidal silica suspensions. The grain structure was revealed by anodizing the sample in Barker's etchant, consisting of 1.8% fluoroboric acid in water, for ~30 s. A Goldstar GP-4303D DC power supply supplied 30 V DC to a stainless steel electrode using a current of $\sim 1\ \mathrm{A\ in.}^{-2}$ ($\sim 0.16\ \mathrm{A\ cm}^{-2}$). Imaging was performed using a Leica DM IRM reverse-stage optical microscope under polarized light. Figure 1 displays the microstructure along each of the three orthogonal slab directions after the final 24 h annealing treatment. The textured microstructure from the original rolled plate is removed by stretching and annealing, resulting in the equiaxed grain structure visible in Figure 1. The mean intercept grain size along any direction in the annealed plate was measured as 34 ± 11 μm.

Table 1 lists the material properties for the annealed Al 5083 plate. The density (ρ_0) was measured using a standard Archimedes setup. The longitudinal and shear wave velocity (C_L and C_S, respectively) were measured through the plate thickness using an Olympus 5072PR pulser/receiver in the pulse echo configuration attached to Ultran VSP-200 and SRD50-5 ultrasonic probes. Ultrasonic data were recorded using a Tektronix DPO 5104 1 GHz oscilloscope. The bulk sound speed (C_B) and the remaining elastic constants in Table 1 were calculated from the measured C_L, C_S and ρ_0 values.

Symmetric plate impact experiments were performed using the 80 mm bore single-stage light-gas gun at the Georgia Institute of Technology. The experimental setup used was the same as that employed for plate impact spall experiments performed on Al 5083-H116 in a previous work [5]. For a detailed description of the experimental setup, the reader is referred to the previous publication. Briefly, aluminum sabots were used to impact 5 mm thick Al 5083 flyer plates onto 10 mm thick target Al 5083 plates. The target samples were tapered discs surrounded by an Al 5083 ring holder designed to ensure a one-dimensional state of strain for the duration of the rear free surface velocity measurements. All flyer and target plates were lapped parallel to <1 mrad of tilt using a 45 μm diamond slurry.

Table 1. Material properties of annealed Al 5083 with a 95% confidence interval.

Material parameters	
Longitudinal wave speed (C_L) [mm μs^{-1}]	6.367 ± 0.003
Shear wave speed (C_S) [mm μs^{-1}]	3.193 ± 0.004
Bulk wave speed (C_B) [mm μs^{-1}]	5.19 ± 0.03
Shear modulus (G) [GPa]	27.2 ± 0.1
Bulk modulus (B) [GPa]	71.8 ± 0.6
Elastic modulus (E) [GPa]	72.4 ± 0.7
Poisson's ratio (ν)	0.332 ± 0.007
Density (ρ_0) [g cm^{-3}]	2.664 ± 0.007

The impact velocity, tilt angle and rear free surface velocity profiles were recorded for each plate impact spall experiment. Impact velocities were measured using four electrically charged metal shorting pins of known spacing. The tilt angle was calculated using four metal shorting pins lapped parallel with the impact face of the target plate. The tilt angle was <1 mrad for each experiment. The VALYN velocity interferometry system for any reflector (VISAR) was used to record the rear free surface velocity profiles. The raw data from the VISAR system was recorded using a Tektronix TDS 784A 1 GHz oscilloscope, which was triggered by the projectile impact with the velocity pins prior to impact with the target.

Symmetric plate impact experiments were performed for impact velocities ranging from 196 to 743 m s^{-1}. The VISAR rear free surface velocity data for the impacted Al 5083 samples is shown in Figure 2.

During plate impact, the compressive elastic precursor wave is the first to arrive at the target sample rear surface, where the rise in free surface velocity is recorded by the VISAR system. The material starts to deform plastically at the HEL, visible in the inset of Figure 2, where the peak elastic stress is reached. The free surface velocity at the HEL (u_{HEL}) is thus related to the dynamic yield strength of the material. The HEL stress (σ_{HEL}) is given by:

$$\sigma_{HEL} = \frac{1}{2}\rho_0 C_L u_{HEL}. \tag{1}$$

Following the HEL region, the plastic compressive shock wave arrives at the target back surface, after which the free surface velocity rapidly rises to the peak velocity.

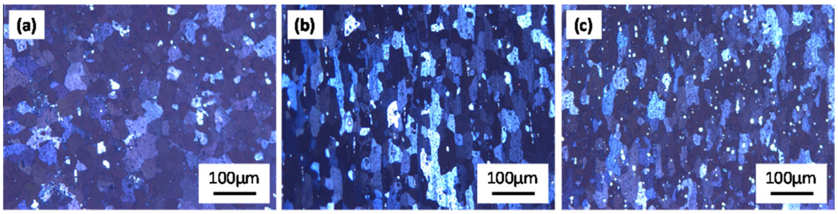

Figure 1. Optical micrographs taken after stretching and annealing the original rolled Al 5083 plate, showing the equiaxed grain structure for planes normal to the former (a) short transverse, (b) long transverse and (c) longitudinal directions. The material was anodized using Barker's etchant and was viewed under polarized light.