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Title: Effects of Thermomechanical Processing on the Resulting Mechanical Properties of 6101 Aluminum Foam

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Effects of Thermomechanical Processing on the Resulting Mechanical Properties of 6101 Aluminum Foam

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Abstract

Porous materials represent a tremenous weight savings for light-weight structural applications. The fabrication path can play a critical role in the resulting properties. High porosity aluminum was fabricated in a number of ways. The starting material was a cast 6101 aluminum that had a relative density of 9.8%. The cast aluminum block was compressed by uniaxial, biaxial, and triaxial densification. Uniaxial compression was done at room temperature and 200°C. Biaxial compression was achieved by unidirectional rolling at room temperature and 200°C. Triaxial compression was done by cold isostatic pressing at 3.4, 6.7, and 34 MPa (0.5, 1.0, and 5.0 ksi). Metallography and mechanical test specimens were machined from the processed bars. The mechanical properties showed that the relative yield strength depended both on relative density and processing temperature.

Introduction

It has been long realized that foaming materials is an effective means for improving some properties while not dramatically affecting others. For example, an obvious driving force for using porous materials is a reduction in density, however, thermal conductivity can remain fairly high in foamed materials (see, for example, Figure 1.3 in reference [1]).

The goal of the program being pursued at Los Alamos is the production of a 30-60% relative density beryllium aluminum foamed material. The principal production path (and not the alternate path described in this paper) being pursued at Los Alamos is the consolidation of powder by hot isostatic pressure (HIP) where the powder is not evacuated under vacuum, but rather the trapped interparticle spacing is under pressure. This powder/pressurized gas compact, now at about 80-90% relative density, would be heated at ambient pressure to allow the argon to swell the compact by creep mechanisms. The resultant foam would be closed pore with approximately 30-60% relative density.

An alternate processing route to the production of a 30-60% relative density porous material is the densification of a less dense, e.g., 10% relative density, material. It is the purpose of the work detailed here to examine how different processing routes would affect the density achieved as well as the resulting mechanical properties. Since beryllium processing imposes daunting fabrication as well as safety issues, an aluminum was chosen first as a surrogate for the beryllium. Ultimately, beryllium and beryllium/aluminum porous structures are the goal.

Materials and Methods

Cast Aluminum Foam

A 10% relative density foam was obtained from ERG, Inc. The block was approximately 100x300x300 mm (4x12x12 in.) with a pore size of ~0.8 mm (20 pores per inch). The foam is nominally an aluminum 6101 alloy (Al-0.6Mg-0.5Si) with an as cast microstructure.

Processing

The cast aluminum foam was subject to three main processing routes, corresponding approximately to uniaxial, biaxial, and triaxial compression. Samples for densification had a minimum dimension any given direction of 25.4 mm (1 inch). Samples were compressed uniaxially in a universal testing machine at two strain rates and two temperatures. The strain rates tested were 0.001/sec and 0.1/sec and the temperatures tested were 25 and 200°C. The foams compressed at 200°C were not processed in a furnace, but rather were put in a furnace at about 225°C for about 30 minutes, quickly transferred to the testing machine, and the compression test was completed in six seconds. Samples were rolled using a standard rolling mill at 25 and 200°C. Here again, the foam was heated in a furnace at about 250°C for 30 minutes, removed, taken to the rolls, and rolled in about five seconds. The rolls were preheated to about 175-200°C. Samples for CIPping were sealed in a polyethylene envelope and subjected to at 3.4, 6.7, and 34 MPa (0.5, 1.0, and 5.0 ksi) isostatic pressure at room temperature. To discern the effect of densification on the resulting mechanical properties, bend tests were performed on selected foams. Samples approximately 8x8x40 mm were cut from densified foams and tested in four-point bending. While it was realize *a priori* that this was likely to be too small a cross section to adequately test a foam, since all the samples would have these dimensions, we felt some qualitative comparisons might be made.

Results and Discussion

Compression of As-cast Foam

The two properties of interest when looking at the foams at lower magnification are the relative density and uniformity of densification. The relative densities for all the foams processed are given in the Table below.

Densification of the as-cast foam by uniaxial compression is shown in Figure 1. The three conditions shown are room temperature at strain rates of 0.001 and 0.1/sec and 200°C at a strain rate of 0.1/sec. Increasing the strain rate from 0.001 to 0.1/sec increases the yield stress, σ_{pl}*, from about 1.2 to 1.8 MPa. This result, however, is highly questionable. Monolithic aluminum is not strain-rate sensitive at these rates, and there is no reason to believe that the porous material is. More likely is that some imperfection (e.g., particularly large voids or weakened cell walls) existed in the foam tested at 0.001/sec, thus lowering the σ_{pl}*.

The effect of increasing the temperature from 25 to 200°C at constant strain rate lowers the yield stress from about 1.8 to 1.0 MPa. The yield stress is approximately 1-1.5 MPa for the conditions tested here. A calculation of the theoretical yield stress based on the relative density is given by: [1]

$$\frac{\sigma^*_{pl}}{\sigma_{ys}} \approx 0.3\left(\frac{\rho^*}{\rho_s}\right)^{1.5}.$$

With σ_{ys} equaling approximately 55 MPa for 6101 Al in an overaged condition, [2] this yields

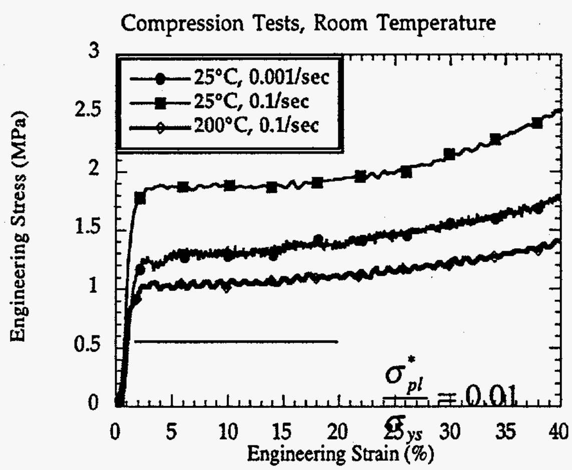


Figure 1. Compression tests of as-cast foamed aluminum.

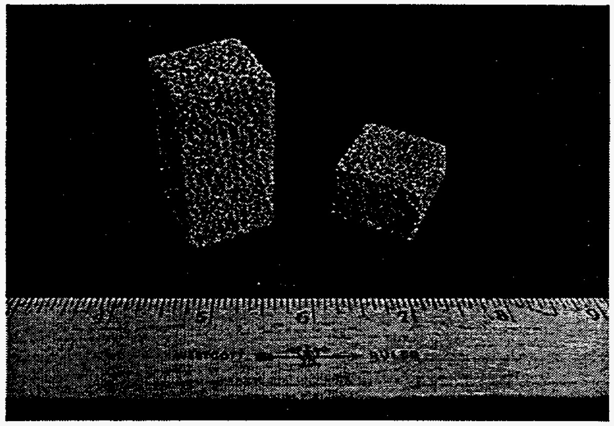


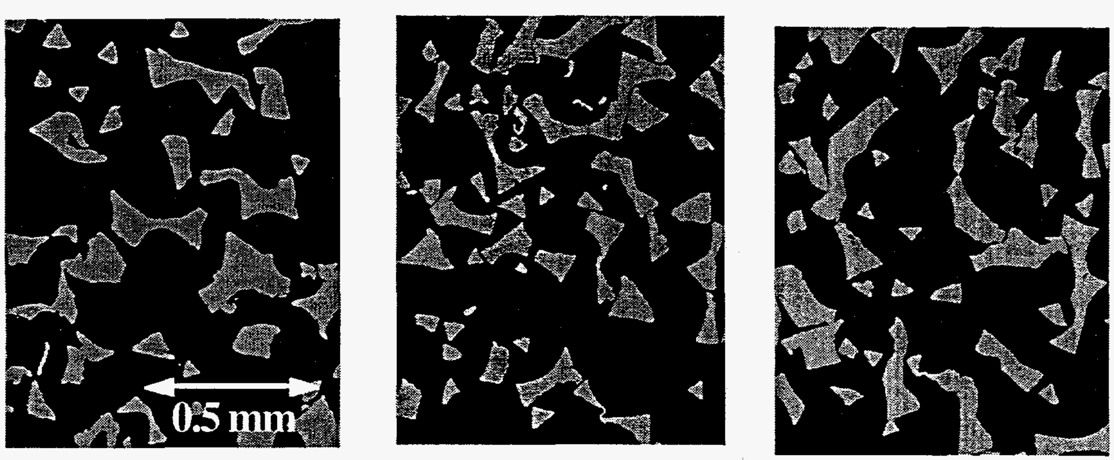
Figure 2. As-cast and compressed foams.

σ_{pl}/σ_{ys} of about 0.55 MPa. The yield stresses here are about two times higher. However, the exact condition of the as-cast foam has not been determined and is the subject of continuing research. An overaged condition is assumed; however, something between peak aged and overaged is certainly possible. The densification strain (not shown in Figure 1) was approximately 50-60%.

Table. Resulting relative densities from the various processing paths.

Process	Conditions	Process Temperature (°C)	Relative Density (percent)
Uniaxial Compression	0.001/sec	25	23
	0.1/sec	25	27
	0.1/sec	200	29
Rolling	30% reduction, one pass	25	11
	30% reduction, six passes	25	11
	65% reduction, two passes	25	18
	65% reduction, six passes	25	19
	65% reduction, one pass	200	23
CIP	3.4 MPa	25	20
	6.7 MPa	25	31
	34 MPa	25	50

Occasionally compression of the foams from 50.8 mm to 18 mm caused a slight buckling, Figure 2. Although all three foams were compressed the same amount, slight differences in the relative densities were measured. We have not determined whether this is due to a sampling error or whether the effect is genuine. The desification of the foams was rather uniform, Figure 3. Although slight differences in densities were measured, this difference is likely due to sampling error rather than an intrinsic difference.



25°C 0.001/sec
23% density

25°C 0.1/sec
27% density

200°C 0.1/sec
29% density

Figure 3. Densification microstructures of the uniaxially compressed foams.

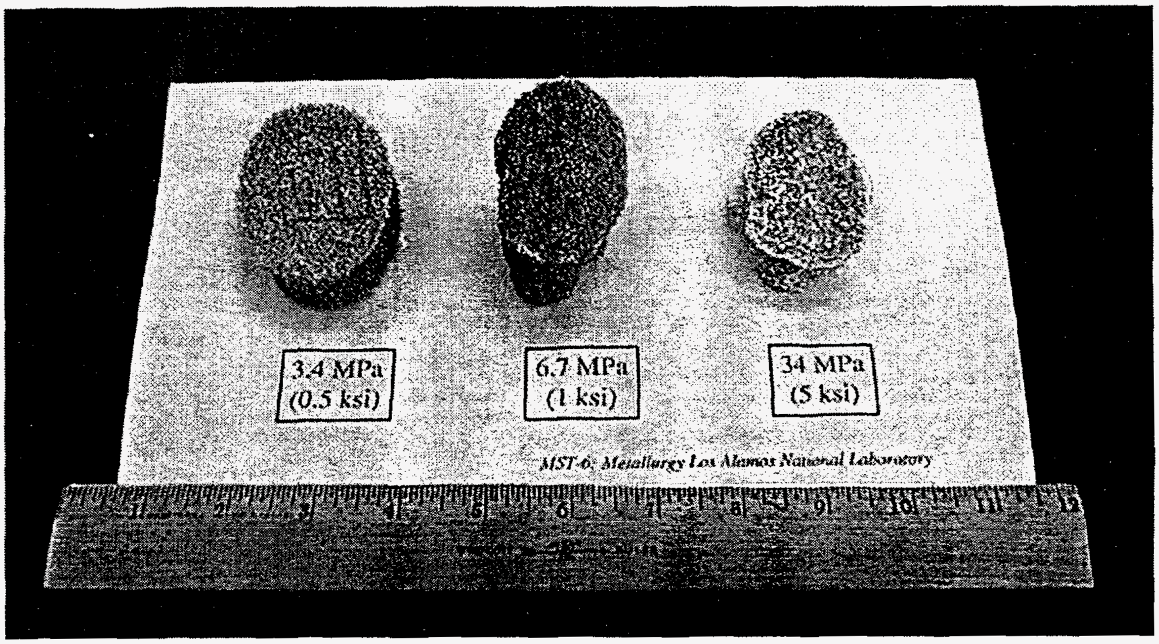
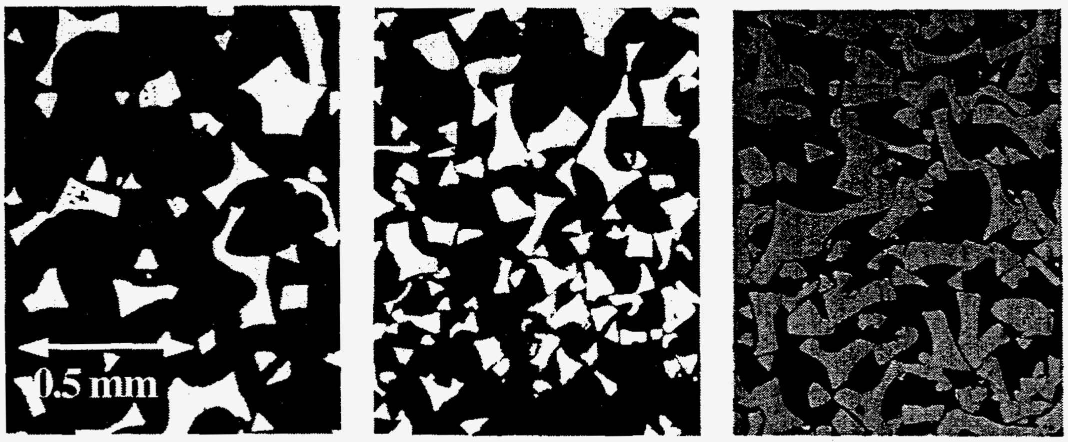


Figure 4. Anisotropic compaction of CIPped foams at 3.4, 6.7, and 34 MPa.

Cold Isostatic Pressing (CIPping)

Cold isostatic pressing of the foam did not isotropically compact the foam, Figure 4. Independent of CIP pressure, the resulting shape of the once cylindrical piece was an elliptical cylinder. This may indicate some natural anisotropy present in the foam. To date, we have not kept track of the original thin dimension of the cast plate, but samples were taken such that the original cylindrical axes were parallel to one long direction of the cast block (*viz*., the short direction of the cast block is parallel to the diameter of the cylinder).

CIPping did compact the foams, Figure 5. The lowest pressure we were able to produce, 3.4 MPa, compacted the originally 9.8% relative density foams to 20%. Increases in pressure produced correspondingly higher densities, Figures 5 and 6. Relative density increases dramatically at lower pressures and begins to saturate at the highest pressure, 34 MPa. This would be expected from the way in which foams densify; that is, at low densities, the large volume fraction of porosity does not interfere with the cell walls that are coming closer to each other. Once cell walls begin to impinge, correspondingly higher pressures are required to continue densification of the foam.



3.4 Mpa, 20% density   6.7 MPa, 31% density   34 MPa, 50% density

Figure 5. Compaction of CIPped foams

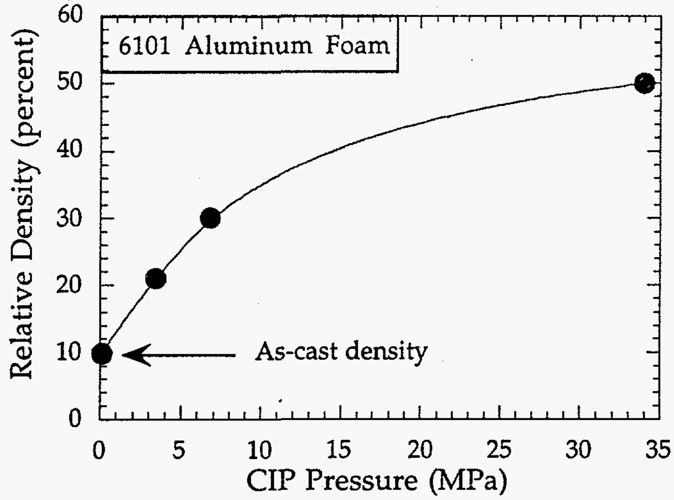
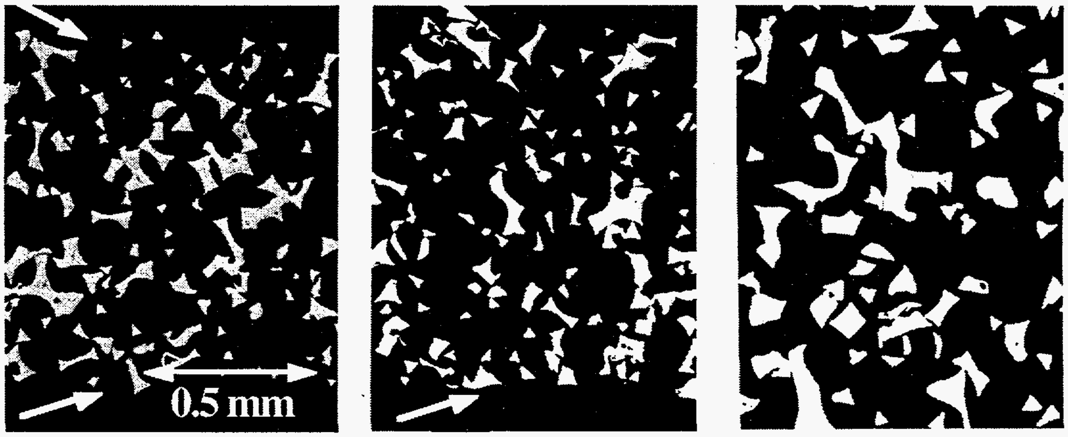


Figure 6. Density vs. CIP pressure for as-cast aluminum foam

Rolling

The densification of the rolled foamed occurred qualitatively in the same fashion as the CIPped samples, that is, at 30 % reduction it increased from 9.8% to 11% dense, while at 65% reduction, the density increased to about 20%, Table. One concern was that the rolling process would densify the surfaces of the foams more and the inner part less. This did not apparently happen, Figure 7. The black strips on the top and bottoms of the left two micrographs represent the top and bottoms of the rolled foams. No higher density at the surfaces is readily apparent. Qualitatively, there is no difference in the microstructure between the samples rolled at 25°C and 200°C, Figure 7.



65% reduction, 13 passes, 25°C

18% density

65% reduction, 2 passes, 25°C

19% density

65% reduction, 1 pass, 200°C

23% density

Figure 7. Densification of rolled foams (arrows indicate the top and bottom rolling surfaces).

Bend Tests

Bend samples compressed at room temperature, (i.e., rolled at 25°C in two and 13 passes and CIPped at 6.7 MPa) with approximately the same density all had very similar stress displacement traces, Figure 8. The sample that had been machined from the bar rolled at 200°C had an appreciably lower curve, while that taken from the CIP 34 MPa material had a much higher curve. The CIP 34 MPa sample can be understood in terms of its dramatically higher 50% relative density. The rolled 200°C curve was an interesting observation; while the relative density was similar to the room temperature samples, it is clear that the higher temperature processing did allow for some recovery to take place.

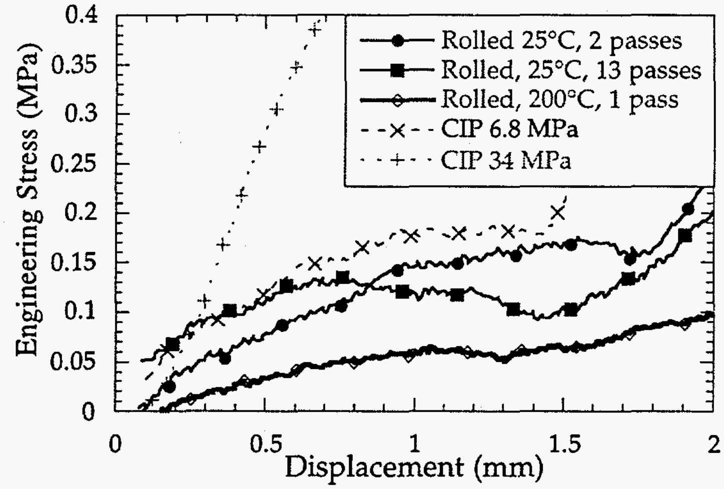


Figure 8. Room temperature bend tests of foams compacted by various methods.

Acknowledgments

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