Measurement temperature increment of open-celled cellular Zn-22Al-2Cu alloy

R Guzmán¹ and A Santos¹
¹ Universidad Pontificia Bolivariana Seccional Bucaramanga, Colombia.

E-mail: rolando.guzman@upb.edu.co

Abstract. Thermo-mechanical properties of cellular materials, “metallic foams” make them very attractive in a variety of engineering applications. During plastic deformation of closed-cell metallic foams, part of plastic work is converted into heat. The generated heat increases may be quantified using an infrared camera measuring radiation emitted on the surface of the metallic foam. Experimental tests were carried out under quasi-static loading conditions using Zn-22Al-2Cu (zinalco) foams featuring different pore sizes, and densities between 30% to 50% maintaining constant volume. The goal of this study was to analyse the effect of heat generation during quasistatic compression of metallic foams at constant strain rate. Some conclusions on the mechanical behaviour were obtained in terms of temperature increase, the nominal stress-strain curves and relative density.

1. Introduction
The cellular materials offer excellent attractive combinations of mechanical properties [1-5]. Therefore, these materials have a potential of use in various structural applications, mainly in the automotive, aerospace and aeronautic industries [6-11]. The growing interest in the use of these materials is due to their high stiffness rigidity for a certain density and also due to their high capacity of absorbing energy under low stress values [6]. As a result of this absorption of energy, they are used more, in applications such as the protection of the interior space of the airship against impact. The cellular materials require a deep comprehension of their thermo-mechanical behaviour under static and dynamic conditions. During deformation of a solid, a part of mechanical energy is stored as internal defects, a part is dissipated for micro-structural changes as dislocations or phase transformation and the rest is converted into heat [12-17]. The last part changes the temperature field of the material loaded. This phenomenon depends of the material studied, the initial temperature, and the strain rate used during the test.

2. Experimental procedure
The test devices consist of three equipments: testing machine, infrared camera, and dark chamber [17].

2.1. Materials
Alloy Zn-22Al-2Cu is an eutectoid Zn-Al based with copper addition. Its thermo mechanical properties, as a solid, are listed on Table 1 [18].

Micrographs of the Zn-22Al-2Cu (zinalco) foams used are show in Figure 1. All specimens had cubic shape geometry, each of dimensions 1.5cmx1.5cmx3.5cm with different pore sizes, and densities between 30% to 50% maintaining constant volume. Table 2 shows properties of tested
coupons. Bulk density was calculated measuring the mass of each coupon then dividing it by the known mass of a block made out of the solid material.

### Table 1. Mechanical and thermal properties of the Zn-22Al-2Cu alloy.

| Material       | α (K⁻¹) | K (W/mK) | Cp (J/KgK) | E (Gpa) | Tm (K) | ρ (Kg/m³) |
|----------------|---------|----------|------------|---------|--------|-----------|
| Zn-22Al-2Cu    | 25x10⁻⁶ | 125.5    | 1000       | 90      | 694-754 | 5.3x10⁻³  |

![Figure 1. Micrographs of cellular materials (metallic foams).](image)

### Table 2. Properties of tested materials.

| Sample | Mass (Kg) | Vol free (cm³) | Bulk density (gr/cm³) | Relative density (ρ' / ρ) |
|--------|-----------|----------------|-----------------------|---------------------------|
| Nº1    | 13.111    | 5.447          | 1.665                 | 0.300                     |
| Nº2    | 14.563    | 5.178          | 1.848                 | 0.342                     |
| Nº3    | 14.813    | 5.132          | 1.881                 | 0.348                     |
| Nº4    | 15.457    | 5.013          | 1.963                 | 0.363                     |
| Nº5    | 16.154    | 4.883          | 2.051                 | 0.379                     |
| Nº6    | 16.141    | 4.886          | 2.050                 | 0.379                     |
| Nº7    | 16.007    | 4.911          | 2.033                 | 0.370                     |
| Nº8    | 17.441    | 4.645          | 2.215                 | 0.410                     |
| Nº9    | 18.665    | 3.456          | 2.370                 | 0.438                     |
| Nº10   | 19.124    | 4.333          | 2.428                 | 0.449                     |
| Nº11   | 20.098    | 4.153          | 2.552                 | 0.472                     |
| Nº12   | 21.387    | 3.914          | 2.716                 | 0.500                     |

2.2. *Uniaxial compression*

For quasi-static tests, a universal testing machine was used. The specimen has been deformed at a strain rate of 0.01s⁻¹, and was carried out to a total deformation of 70%. The temperature evolution ΔT(t) and the curve stress-strain, σₐ(εₐ) was measured during the test. The window size defined during the test to measure the temperature was 320x256 pixels with a frequency acquisition of 400FPS. The elastic behaviour of material tested is characterized by a stiffness parameter determined from the
unloading portion an unload-load cycle in the test (3% nominal strain). The end surfaces were lubricated (MoS2) to reduce the frictional restraint.

2.3. Measurement method

The temperature increase of the tested specimen was measured by an infrared camera (IRC). In a radiometrically calibrated IRC, the camera measurement has a linear relationship with the incoming radiance, $L_{\text{in}} = \int L_\lambda (\lambda, T) d\lambda$ in a spectral range in which the camera is sensitive.

$$L_{\text{in}} = \sum_{i=0}^{n} C_i \text{Measurement}^i$$ (1)

The polynomial equation can be generated that converts the measurement “counts” to radiance and vice-versa (see Equation (1)). Figure 2(a) show the experimental values and the best adjusted fit, assuming linear detector response. For the IRC calibration, different images of a black body at different temperatures (0ºC-125ºC) (Figure 2(b)). In order to determine the temperature of the object, $L_{\text{in}} = L_0$ (total out radiance = total incoming radiance in the system sensor) is obtained from the measurement “counts”. Knowing $T_{\text{amb}}$ and the objects emissivity, $L_0$ is obtained. The object temperature is the value of $T$ at which the integral of $L_0(\lambda, T)$ over the camera’s spectral range equals $L_0$. The amount of spectral radiance $L_0(\lambda, T)$ emitted at a particular wavelength, $\lambda$, is given by Planck law (see Equation (2)), which states that for a black body:

$$L_0(\lambda, T) = \frac{C_1 \lambda^5}{\exp\left(\frac{C_2}{\lambda T}\right)-1}$$ (2)

![Figure 2](image.png)

(a) Radiance vs Counts. (b) T vs Radiance; the solid lines are calculation with analytic integrate the Planck law.

The test devices consist of three equipments: testing machine, infrared camera, and dark chamber. Figure 3(a) and Figure 3(b) shows the set up experimental, identifying the specimen, the dark chamber, fixed head and cross head of the universal testing machine (Instron, model 8516).

In the IR remote sensing scenario, shown in Figure 3, the radiance emitted by the atmosphere and the IR system’s intrinsic radiation is considered negligible. Temperature increases are obtained on different pixels located on the surface of "cellular material".
3. Results

Images shown in Figure 4 display a shear failure at 45° observed during the tests. Porous walls exhibit failure when reaching maximum compressive strength. Tension drops significantly due to the sudden collapse of one of more high density layers. Figure 5 shows, as for example, the nominal stress-strain curves, obtained at room temperature for a strain rate $0.01\text{s}^{-1}$ (286K) with a relative density $\rho'/\rho_s = 0.379$.

---

Figure 3. (a) Dark chamber. (b) Infrared camera and dark chamber.

Figure 4. Failure mode of the specimen tested in compression for a strain rate of $0.01\text{s}^{-1}$.
Measurement of incremental temperature (thermal field) associated with plastic strain variations were estimated along one line on the generatrix of the sample. An increasing temperature on the specimen surface was detected during the tests until total failure of the specimen took place. In addition, a rapid temperature increase was recorded just before the failure event and a process of temperature diffusion, was noted just after failure. Figure 6 shows the temperature evolution recorded by IRC technique for a strain rate of 0.01s⁻¹ and a room temperature. The thermal field in Figure 6 shows a strain plastic localization (shear band).

Figure 5. Nominal stress-strain curve for Zn-22Al-2Cu foam for a strain rate of 0.01 s⁻¹ (286 K).

Figure 6. Images IRC for a test strain rate of 0.01s⁻¹ and a room temperature.
4. Conclusions
The nominal stress-strain curves show three distinct regions: a linear elastic region at a low strain, a plastic plateau region with stress fluctuation over a wide range of the strain and a third region called the densification region, before fracture. For compressive quasi-static tests for cellular Zn-22Al-2Cu foams, an increment in relative density raises the temperature increment associated to plastic strain. This is because an increase in relative density raises the deformation energy absorbing capacity by the foam.

Both in load-time and in temperature-time relations, oscillations were detected. The appearance of these oscillations can be associated to the wall’s progressive fail in Zn-22Al-2Cu foam. Less porous walls fail when reaching a maximum compressive strength. The tension drop shown is due to the sudden fracture of high density walls.

Pore size affects alloy Zn-22Al-2Cu during compressive strength because smaller pores show a more stable stress flow hence, showing a flat zone in the $\sigma$-$\varepsilon$ curve (Plateau stress). This is reflected in higher energy absorption values. Therefore, it can be concluded that, for energy absorption, for Zn-22Al-2Cu foams with a high density is more effective than the one with a lower density.

Acknowledgements
The authors would like to express their gratitude to Engineering Department of Universidad Carlos III de Madrid and Universidad Nacional Autónoma de Mexico.

References
[1] Banhart J 2000 Progress in Materials Science 46(6) 559-632
[2] Banhart J and Baumeister J 1998 Journal of Materials Science 33(6) 1431-1440
[3] Gama B, Bogetti T, Fink B, Yu C, Claar T, Eifert H, Gillespie J 2001 Composite Structures 52(3-4) 381-395
[4] Hahfuz H, Zhu Y, Haque A, Abutalib A, Vaidya U, Jeelani S 2000 International Journal Impact Engineering 24(2) 203-217
[5] Villanueva G and Cantwell W 2004 Composite Science and Technology 64(1) 35-54
[6] Baumeister J, Banhart J, Weber M 1997 Materials & Design 18(4-6) 217-220
[7] Fuganti A, Lorenzi L, Grønsund A, Langseth M 2000 Advanced Engineering Materials 2(4) 200-204
[8] Stöbener K, Baumeister J, Lehnhus D, Stanzick H, Zöllmer V 2003 Composites based on metallic foams: Phenomenology, production, properties and principles Advanced Metallic Materials: Proceedings of the International Conference ed J. Jerz (Slovakia: Institute of Materials & Machine Mechanic) pp 281-286
[9] T. Bernard, H.W. Bergmann, C. Haberling and H. G. Haldenwanger 2002 Advanced Engineering Materials 4(10) 798-802
[10] Yu C J, Eifert H H, Banhart J, Baumeister J 1998 Materials Research Innovations 2(3) 181-188
[11] Seeliger H W 2002 Advanced Engineering Materials 4(10) 753-758
[12] Rusinek A and Kлепaczko JR 2009 Materials & Design 30(1) 35-48
[13] Rusinek A, Gadaj P, Kлепaczko J R and Nowacki W K 2004 Matériaux & Techniques 92(5-6) 21-30
[14] Rusinek A, Novacki W K, Gadaj P, Kлепaczko J R 2003 Journal de Physique IV 110 411-416
[15] Hodowany J, Ravichandran G, Rosakis A J, Rosakis P 2000 Experimental Mechanics 40(2) 113-123
[16] Netzelmann U, Abuhamad M and Walle G 2005 Journal de Physique IV 125 511-514
[17] Guzmán R, Essa Y, Meléndez J, Aranda J, López F, Pérez-Castellanos J L 2009 Strain 45(2) 179-189
[18] Elizabeth Martínez-Flores and Gabriel Torres-Villaseñor 2011 Hybrid Materials Based on Zn-Al Alloys Metal, Ceramic and Polymeric Composites for Various Uses Edition 1st ed John Cuppoletti (Croatia: Intech open science) Chapter 7 pp 149-170.