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Compressive response of a closed-cell aluminum foam at high strain rate

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Abstract

Compressive behavior of a closed-cell aluminum has been investigated at high strain rates, utilizing AZ31 magnesium alloy bars as compared to maraging steel bars, to estimate the validity of the mechanical response of the foam. Apparent strain rate sensitivity of plateau stress has been observed and strain hardening occurred during compression at the dynamic strain rate.

Keywords: Closed-cell; Aluminum foam; High strain rate; Compression; Plateau stress

1. Introduction

Recently, there has been keen interest in using lightweight metallic foams for automotive, railway and aerospace applications, where weight reduction, mechanical and acoustic damping capacity are required [1,2]. Metallic foams also have the potential to absorb impact energy when a vehicle crashes either against another vehicle or a pedestrian, since this class of materials exhibits an extended stress plateau. To effectively absorb the impact energy, the materials should deform with a minimized stress oscillation, especially the stress peak at the beginning of deformation which produces a rapid acceleration, which can cause serious damage to the human brain. Thus, accurate evaluation of flow stress is noted to be important in developing a suitable absorber.

Trends in strain rate sensitivity of the plateau stress are divided into two categories, judging from previous articles: one exhibits an apparent strain rate sensitivity, and the other is independent of strain rate. A closed-cell foam, i.e. ALPORAS (solid: Al–Ca–Ti alloy), has been reported to exhibit a strain rate sensitivity [3–7]; on the other hand, Alulight (solid: Al–Si alloy) is independent of strain rate [8]. Very recently, Balch et al. have reported the strain rate sensitivity of compressive stress in aluminum syntactic foams [9]. Thus, the strength and ductility of the solid material, and the morphology of the cell walls, possibly affect the compressive behavior at high strain rates. In this study, the compressive behavior of a closed-cell aluminum (ALPORAS) with different relative densities has been investigated over a wide range of strain rates. Compression tests were conducted at a high strain rate of $\sim 560\ s^{-1}$ utilizing AZ31 magnesium alloy bars (i) to evaluate the engineering stress by two-wave analysis at the end of an input bar contacted with the specimen, and (ii) to compare with the stress by one-wave analysis at the end of the transmitted bar contacted with specimen, and then estimate the validity of the measured compression stress by one-wave analysis and the strain rate sensitivity. The effect of increasing the relative density on the compressive stress in the closed-cell aluminum foam at a dynamic strain rate is also investigated.

2. Material and compression test set-up

A closed-cell foam, ALPORAS, with the chemical composition Al–1.42 Ca–1.42 Ti–0.28Fe (by mass%), was fabricated by a batch casting process; this resulted in a

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relatively high density of 0.155 (denoted as HD-foam). The details of the fabrication procedure have been reported elsewhere [10]. The typical structure of the foam is shown in Fig. 1(a). The average diameter of the cells was measured to be ~2.4 mm according to the method prescribed by ASTM for the measurement of grain diameter in polycrystalline materials [11]. Two foams with a lower density of ~0.106 were also prepared for Ref. [12]. These foams have a larger cell diameter of ~3.74 mm (denoted as LDL-foam), and an intermediate cell diameter of ~3.0 mm (denoted as LDM-foam), respectively. In order to characterize the structures of the foams, an optical microscope was used to measure the apparent edge length (denoted as L) and the thickness of cell walls for any 200 edges.

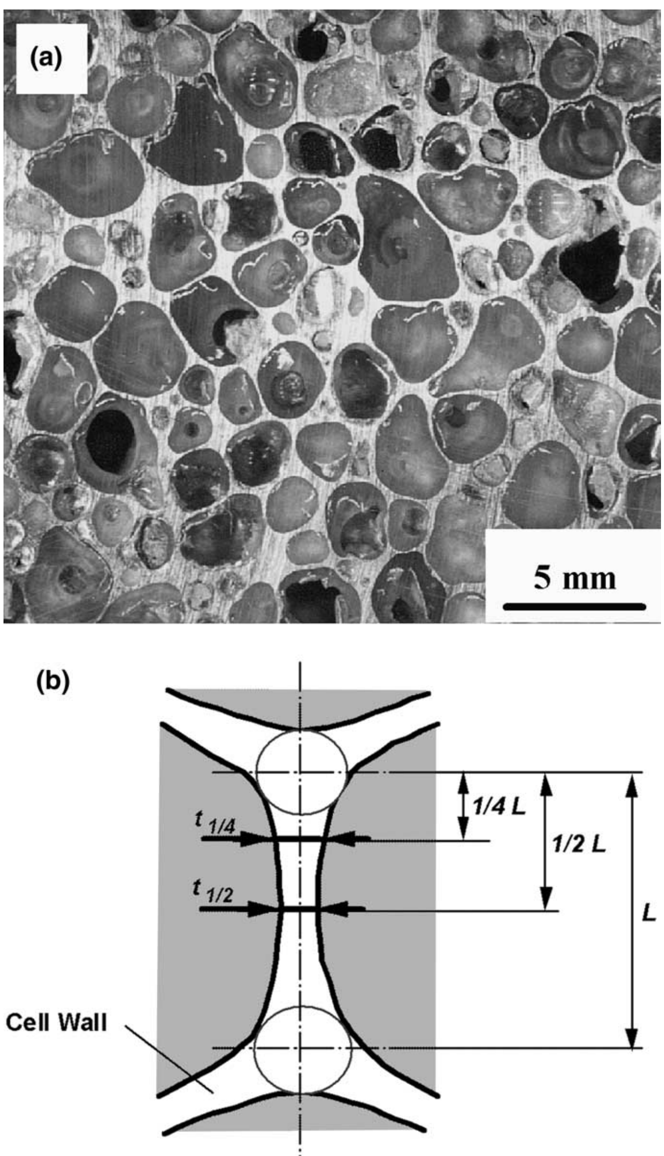

Fig. 1. (a) Microstructure of the present closed-cell foam (ALPORAS) with a relative density of 0.155, and (b) schematic illustration of the cross-sectional structure.

The schematic illustration for the structural characterization is shown in Fig. 1(b). As shown in this figure, the thickness was estimated for two points at $1/4L$ and $1/2L$. The average values of the measured edge length and wall thickness are summarized in Table 1. It was found that the measured edge length of HD-foam was noticeably reduced, while the thickness was identical to that in LDL-foam. The aspect ratio of the wall thickness against the edge length is also estimated in Table 1. It is noted that the aspect ratio in HD-foam was higher than in LDL-foam and LDM-foam on average, which enhances the membrane stress of cell walls.

Specimens were cut from the fabricated foam with dimensions of $16 \times 16\ \mathrm{mm}^2$ in the cross-section and 11 mm in height. Compression tests at a dynamic strain rate of $\sim 1000\ \mathrm{s}^{-1}$ were performed using a split Hopkinson pressure bar (SHPB). The SHPB used at higher strain rates consisted of a maraging steel bar with a diameter of 16 mm. To evaluate the larger specimen, a plate attachment of maraging steel with a thickness of 5 mm and a face of $18 \times 18\ \mathrm{mm}^2$ was fixed at the end contacted to the specimen. Dynamic compression tests were also performed at a strain rate of $\sim 600\ \mathrm{s}^{-1}$ utilizing a SHPB equipped with 23.4 mm diameter AZ31 Mg–3 Al–1 Zn–0.2 Mn (by mass%) bars that improve the signal-to-noise level for low strength materials, as compared to the maraging steel bars, to estimate the validity of the mechanical response of the foam.

3. Mechanical response detected by Mg alloy bars

The impedance of the magnesium alloy bar is lower than that of the maraging steel bar, and therefore the stress waves, e.g. incident, reflected and transmitted waves, detected in the SHPB can be evaluated in the same order of the force; e.g. Gray et al. have demonstrated the compression test of polymeric materials with AZ31 alloy bars [13]. Examples of stress waves detected through the dynamic compression test of the foam are shown in Fig. 2 as a function of time. In the figure, σ_i, σ_r and σ_t denote the amplitude of the incident, reflected and transmitted stress waves that propagate in the incident and transmitted bars, respectively. ε_i, ε_r and ε_t also denote the elastic strain resulting from each stress wave. The determination of the stress–strain behavior of a material being tested in a Hopkinson bar is based on the principle of one-dimensional elastic-wave propagation within the pressure loading bars [14]. The strain rate of the specimen sandwiched between the incident and transmitted bar can be calculated by Eq. (1). The strain is also calculated by the integration of the strain rate in Eq. (2):

$$\dot{\varepsilon}(t) = \frac{C_b}{l_s}(-\varepsilon_i + \varepsilon_r + \varepsilon_t), \tag{1}$$

$$\varepsilon(t) = \int \dot{\varepsilon}(t)\mathrm{d}t, \tag{2}$$

Table 1
Measured average value of edge length and wall thickness of the present foam with different cell sizes [12]

	High density foam (HD-foam)	Medium density foam (LDM-foam)	Low density foam (LDL-foam)
Relative density; ρ/ρ_{solid}	0.155	0.106	0.106
Average cell size (mm)	2.37	2.88	3.74
Cell edge length; L (mm)	1.76	1.91	2.68
Cell wall thickness			
at $1/2L$; $t_{1/2}$ (mm)	0.133	0.112	0.135
at $1/4L$; $t_{1/4}$ (mm)	0.161	0.132	0.162
Aspect ratio; $t_{1/2}/L$	0.076	0.059	0.050

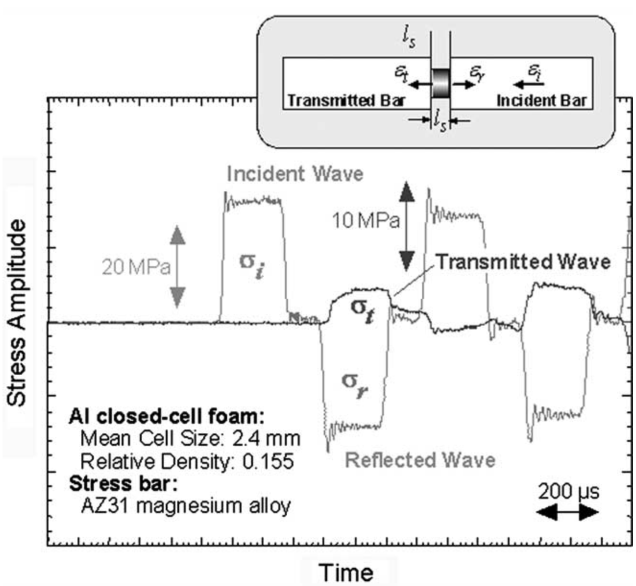

Fig. 2. Monitored stress waves in the present Hopkinson-bar set-up utilizing AZ31 magnesium alloy bars.

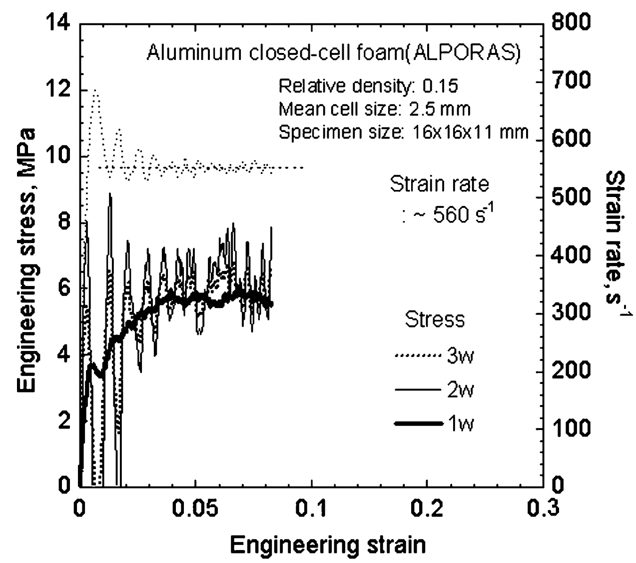

Fig. 3. Variation in compressive engineering-stress calculated by one-wave (1w), two-wave (2w) and three-wave (3w) analysis as a function of strain; the data on the variation in strain rate are included.

where c_b is the longitudinal wave speed in the loading bar and l_s is the initial height of the specimen. In the one-wave analysis, the specimen stress is directly proportional to the bar strain measured from the transmitted bar. The one-wave stress analysis reflects the conditions at the interface of the specimen-transmitted bar and is often referred to as the specimen "back stress" evaluated in the following equation:

$$\sigma(t) = \frac{AE}{A_s}\varepsilon_t, \tag{3}$$

where A is the cross-sectional area of the loading bar, E is the elastic modulus of the bar, A_s is the initial cross-sectional area of the specimen. In the two-wave analysis, the sum of the synchronized incident and reflected bar waveforms is proportional to the specimen "front stress" as evaluated in Eq. (4) and reflects the conditions at the bar–sample interface:

$$\sigma(t) = \frac{AE}{A_s}(\varepsilon_i + \varepsilon_r). \tag{4}$$

The three-wave stress is simply the average of the two-wave and one-wave stress, as shown in the following equation:

$$\sigma(t) = \frac{AE}{2A_s}(\varepsilon_i + \varepsilon_r + \varepsilon_t). \tag{5}$$

A valid uniaxial stress Hopkinson bar test requires that the stress state throughout the specimen achieves equilibrium during the test and this condition can be checked readily by comparing the one-wave and two-wave stress–strain response. When the stress state is uniform throughout the specimen, then the two-wave stress oscillates about the one-wave stress. The details are described in Ref. [14]. Relations of engineering stress and strain are evaluated in compression with one-, two- and three-wave analysis as shown in Fig. 3. Variation in the strain rate is also shown in this figure. The strain rate oscillates at the beginning of compression, but reaches a steady value of $\sim 560\ s^{-1}$ as deformation progresses. The variations in flow stress evaluated with one-, two- and three-wave analysis are shown in Fig. 3, labelled as 1w, 2w, 3w, respectively. At an early stage of deformation, the amplitude of two-wave stress is huge, but decreases as deformation progresses. It is found that the stress of two-wave analysis oscillates along the result of one-wave analysis. Therefore, the measured stress with one-wave analysis is valid above the strain of 0.03.

Although the compressive stress at the beginning of deformation is invalid because of the lack of stress equilibrium, the stress obviously exhibits a plateau of ~6 MPa above the strain of 0.03.

4. Effect of strain rate on compressive response

The variation of compressive stress in HD-foam is shown in Fig. 4 as a function of engineering strain at various strain rates. The plateau stress detected by the maraging steel bar exhibits a slightly higher value than that by the magnesium alloy bar, corresponding to the deformation at the higher strain rate. The magnitudes of compressive stress detected by the magnesium alloy bar exhibit higher values than those at quasi-static strain rates; in conclusion, it is worth noting that the plateau stress exhibits marked strain rate sensitivity.

The compressive response of HD-foam is shown in Fig. 5, in comparison with the data of a lower density foam (LDM-foam). All the data in Fig. 5 were described by one-wave analysis with the maraging steel bar. Although the flow stress oscillates, the stress plateau region is formed in both foams. The plateau stress of HD-foam is twice as high as that of LDM-foam due to the higher relative density. The flow stress in HD-foam exhibits an apparent strain hardening above the strain of 0.2 in comparison with the result in LD-foam.

As shown in Table 1, the aspect ratio in HD-foam is different from LDM-foam. The structure of a closed-cellular metallic foam is often compared to a tetrakaidecahedra. For relative densities less than or equal to 0.2, the relationship between the relative density (ρ/ρ_s), cell wall thickness (t) and edge length (l) of a tetrakaidecahedral foam with uniform wall thickness is approximated by the following equation [15]:

$$\frac{\rho}{\rho_s} = 1.185\frac{t}{l} - 0.4622\left(\frac{t}{l}\right)^2, \tag{6}$$

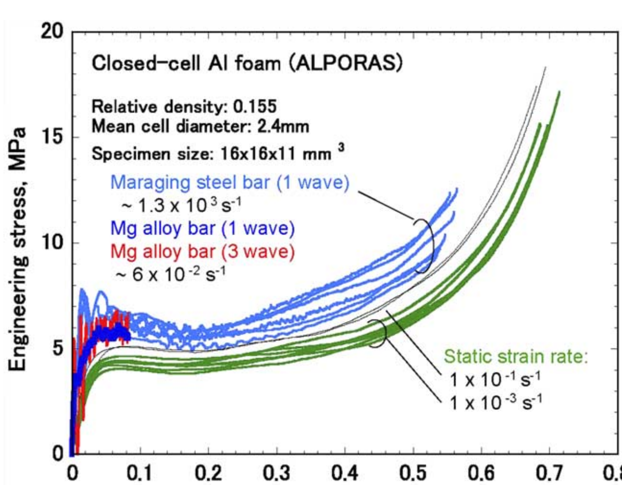

Fig. 4. Compressive response of the aluminum closed-cell foam at various strain rates.

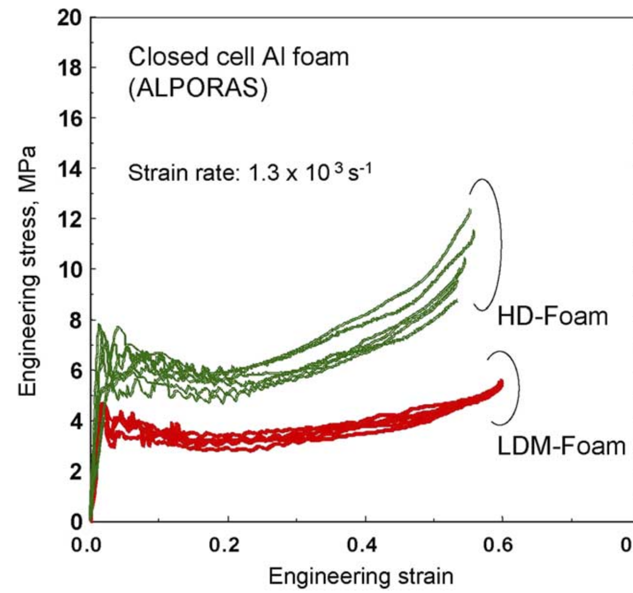

Fig. 5. Engineering stress as a function of strain at a dynamic strain of $1300\ \mathrm{s}^{-1}$, in HD-foam and LDM-foam.

where ρ is the density of the cellular material and ρ_s is the density of the cell wall (solid) material. Substituting the values of $t_{1/2}$ and L in Table 1 into the above equation, the relative densities of HD-foam and LDM-foam are calculated to be 0.0869 and 0.0679, respectively. On the other hand, the measured values of relative density for both foams are 0.155 and 0.106, respectively. Therefore, the mass of 56% for HD-foam and 64% for LDM-foam formed tetrakaidecahedral structure with uniform wall thickness. The resistant strength against the plastic bending at the cell edges in HD-foam is noted to be higher than that in LDM-foam for the higher volume of solid at cell edges. The apparent strain hardening in HD-foam is possibly attributed to be the combination effect of increasing the membrane stress with the aspect ratio and increasing the volume of cell edges.

The variation of relative yield strength of the present foams is shown in Fig. 6 as a function of relative density. Included are the data of a lower density foam (ρ/ρ_s: ~0.062) compressed at strain rates of $1\times10^{-3}\ \mathrm{s}^{-1}$ and $1.4\times10^{2}\ \mathrm{s}^{-1}$ [7]. Plastic collapse of a closed-cell foam was described by Gibson and Ashby using the following equation [1]:

$$\frac{\sigma_{pl}}{\sigma_{ys}} = 0.3\left(\phi\frac{\rho}{\rho_s}\right)^{3/2} + \left((1-\phi)\frac{\rho}{\rho_s}\right), \tag{7}$$

where σ_{pl} is plateau stress of the foam, σ_{ys} is the yield stress of the solid and ϕ is the fraction of solid in the edge. The value of yield stress in the solid (σ_{ys}) was measured (with the bulk specimen) to be 160 MPa at the static strain rate of $1\times10^{-3}\ \mathrm{s}^{-1}$ and 210 MPa at the dynamic strain rate of $1.3\times10^{3}\ \mathrm{s}^{-1}$, respectively. The first term in Eq. (7) denotes the plastic bending of the cell edge, and the second part the plastic stretching of the cell faces. The datum of

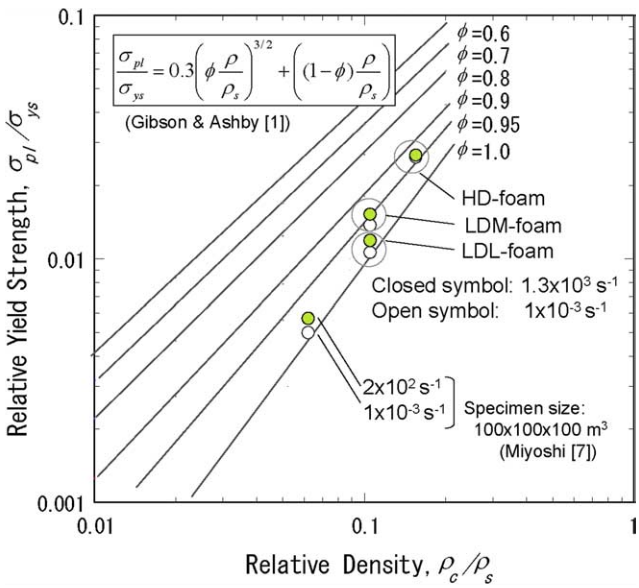

Fig. 6. Variation in relative yield strength of the present foams as a function of relative density; the data for a relatively lower density ALPORAS [7] are included.

the lower density foam [7] is close to the line of $\phi = 1.0$, corresponding to the condition of a open-cell foam. With increasing relative density, the data deviate from the line of $\phi = 1.0$. Since the relative yield strength of the LDM-foam exhibits a higher value than that of LDL-foam, the increase in the aspect ratio of cell wall thickness against cell edge length causes the higher stretching resistance of cell faces. While the relative yield strength at the high strain rate exhibits a higher value than that at the low strain rate, the difference in the relative yield strength increases with decreasing relative density. The apparent increase in the strain rate sensitivity is possibly attributable to the additional effect of gas pressure in the closed cell as described in the previous literature [1]. Further investigations are under way to clarify the gas pressure effect.

5. Summary

Compressive behavior of a closed-cell aluminum (ALPORAS) has been investigated over a wide strain rate range. The compression tests were conducted at a high strain rate of $\sim 560\ s^{-1}$ utilizing AZ31 magnesium alloy bars (i) to evaluate the engineering stress by two-wave analysis at the end of an input bar contacted with specimen, and (ii) to compare with the stress by one-wave analysis at the end of a transmitted bar contacted with specimen. As a result, the engineering stress evaluated by two-wave analysis oscillates along the stress by one-wave analysis; thus the measured compressive stress by one-wave analysis is valid and exhibits a certain strain rate sensitivity. Direct comparison of the engineering stress with the data in a relatively low density foam revealed that an apparent strain hardening occurred during compression at the dynamic strain rate in a relatively higher density foam, resulting in an increase of the membrane stress with the aspect ratio and increasing the bending stiffness with the volume of cell edges. On the other hand, strain rate sensitivity of plateau stress increases with decreasing relative density due to additional effects, such as the gas pressure in the closed cell.

References

[1] Gibson LJ, Ashby MF. Cellular solids, structure and properties. second ed. Cambridge: Cambridge University Press; 1997.
[2] Banhart J. Prog Mater Sci 2001;46:559.
[3] Mukai T, Kanahashi H, Miyoshi T, Mabuchi M, Nieh TG, Higashi K. Scripta Mater 1999;40:921.
[4] Dannemann K, Lankford J. Mater Sci Eng 2000;A293:157.
[5] Paul A, Ramamurty U. Mater Sci Eng 2000;A281:1.
[6] Ramachandra S, Sudheer-Kumar P, Ramamurty U. Scripta Mater 2003;49:741.
[7] Miyoshi T, Mukai T, Higashi K. Mater Trans 2002;43:1778.
[8] Deshpande VS, Fleck NA. Int J Impact Eng 2000;24:277.
[9] Balch DK, O'Dwyer JG, Davis GR, Cady CM, Gray GT, Dunand DC. Mater Sci Eng 2005;A391:408.
[10] Miyoshi T, Itoh M, Akiyama S, Kitahara A. Adv Eng Mater 2000;2:179.
[11] ASTM Designation E 122-82.
[12] Miyoshi T, Itoh M, Mukai T, Kanahashi H, Kohzu M, Tanabe S, et al. Scripta Mater 1999;41:1055.
[13] Gray GT. ASM metals handbook, vol. 8. Metals Park (OH): ASM International; 2000. p. 490.
[14] Gray GT. ASM metals handbook, vol. 8. Metals Park (OH): ASM International; 2000. p. 462.
[15] Simone AE, Gibson LJ. Acta Mater 1998;46:2139.