Elastic response of titanium foams during compression tests and using laser-ultrasonic probing

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Elastic Response of Titanium Foams During Compression Tests and Under Laser-Ultrasonic Probing

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Abstract

This paper presents an evaluation of the elastic properties of titanium foams by two methods: the evaluation of the unloading slopes measured during destructive compression tests and the measurements of the resonance frequencies of foams using laser ultrasound. The results show that the elastic moduli evolve during the compression tests. The values extrapolated at zero deformation can be used to determine the elastic properties of undeformed specimens. Besides, laser-ultrasound technique can be used to bring foam specimens into resonance and to measure the elastic modulus and Poisson's ratio. The values measured by the two methods are in good agreement.

Keywords: Elastic properties, compression, modulus, Poisson's ratio, titanium foams, laser-ultrasound, ultrasound, non destructive evaluation.

1. Introduction

Porous metals are used in a wide range of applications. For some applications (porous coating on orthopedic or dental implants, thin nickel foam strip or porous Ni coating for batteries), the material is not produced into large specimens adapted for the evaluation of the elastic properties using standard compression tests. Besides, since these materials are highly porous, they are highly attenuating and their elastic properties cannot be evaluated using standard ultrasonic propagation techniques.

1.1 Compression tests

A challenge in the evaluation of the elastic properties of small porous specimens comes from the measurement of small deformations on thin specimens as well as the deformation mechanisms of the foams. At the beginning of the tests, non-linear deformation of the foams is observed due to specimen adaptation to the plates of the compression stage due to unparallel specimen faces. Besides, during specimen loading, plastic deformation occurs due to irregularities in the structure and microstructure of the materials (most commercial materials cannot be modeled as a continuous distribution of defect free struts having uniform sections). Thus, the load is generally not uniformly distributed throughout the material and some zones can be plastically deformed while some others remain in the elastic domain. Accordingly, the slope of the compression curves is affected by these simultaneous elastic and plastic deformations.

The elastic modulus can be evaluated by unloading the specimens and evaluating the slope of the elastic recovery. Under those conditions, the elastic modulus is measured at a certain strain [1]. Thus, the measurements are done on plastically deformed and possibly damaged materials. Accordingly, the measured elastic modulus can be different from that of the initial specimens.

1.2 Laser-ultrasonic techniques

The elastic properties of materials can be determined non-destructively by measuring the frequencies of the natural vibration of specimens of simple geometry. Martincek [2] examined the pure elastic response of discs exposed to different vibration conditions. Assuming an isotropic and homogenous material and knowing the dimensions and the resonance frequencies of the specimens, they calculate the elastic modulus. For discs, the elastic modulus can be evaluated using:

$$E = \frac{4\pi^2 f^2 R^2 \rho}{\omega^2} \qquad (2)$$

where f is the natural frequency of vibration of the disc, R is the radius of the disc, ρ is the material density and ω is a constant depending on the Poisson's ratio, the radius and the thickness of the disc (see ref [2] for tabulated data of ω). By measuring the frequencies of the fundamental torsion and flexion modes, it is thus possible to obtain both the elastic modulus and the Poisson's ratio.

Laser-ultrasonic has been developed to provide alternative solutions for the non-destructive evaluation of different material properties and characteristics [3]. The technique can be used to bring solids into vibration. This non-contact method can be used to obtain the pure elastic response since the material is not exposed to plastic deformation during the tests. The technique can be used on small specimens of simple geometry and allow to obtain results along different directions. In addition, the technique can be used on highly sound absorbing material that cannot be characterized using standard ultrasonic propagation techniques.

Thus, the technique is a powerful tool to characterize the structure as well as the properties of some metal foams. The technique has been previously used on titanium foams and results in the range corresponding to the elastic properties of the titanium foams characterized in that study were obtained. However, no correlation with the elastic characteristics evaluated with standard mechanical compression tests has been reported on these specimens [4].

2. Specimen characteristics and measurement setups

Titanium foams were produced using the process described in [5]. Two sets (A&B) of materials were produced using a modification in the starting powder formulation. The modification of the formulation had minor effects on density but no effect on the structure and chemical composition of the foams.

Small discs (10 mm diameter and approximately 5 mm thick) were machined from larger discs (55 mm diameter and 20 mm thick). Due to the material ductility, part of the surface porosity was closed down during cutting with the diamond saw blade. Thirteen specimens (7 of A and 6 of B) were used in the experiments. A typical scanning electron micrograph (SEM) of the microstructure of a foam is presented in Figure 1. The foams have an open cell structure and are permeable.

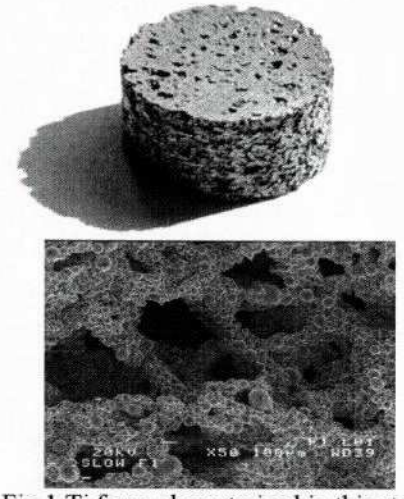


Fig.1 Ti foam characterized in this study (specimen A).

The density was evaluated using the weight and physical dimensions of the specimens. Compression tests were done on a *MTS* 100 kN testing machine using a crosshead speed of 1.25 mm/min. A series of unloading was done at 0.1 mm (2%) of compression and at incremental 0.25 mm (5%) of compression thereafter to follow up the elastic modulus as a function of the plastic deformation.

Laser-ultrasonic measurements were done using a CO_2 high-peak power pulsed laser (80 mJ, 100 ns at 10.6 μm wavelength) for generation of vibration modes, a detection unit based on a continuous 5 mW He-Ne detection laser and a heterodyne Mach-Zender interferometer to probe the small surface displacements (typically of a few nanometers), and a control module to synchronize laser shots and measurement acquisition (see Figure 2). All tests were done with generation and detection laser spots on opposite sides of the specimens. Diameters of laser spots were close to 1 mm, which is much less than the 10 mm diameter of the metallic foam specimens. The specimens were held without stress by polyurethane foam in order to acoustically isolate the metallic foams and allow them to vibrate freely.

Assuming that the foams are isotropic, the elastic modulus and the Poisson's ratio of the specimens can be deduced from the values of the fundamental frequencies of torsion and flexion vibration modes. The lowest natural vibration

frequency is a torsion mode f_{01} that has two mutually perpendicular nodal diameters (see Figure 3). This fundamental torsion mode is preferably excited and detected when the laser impinge off the center of the specimen. The fundamental flexion mode f_{20} has a nodal circle and is preferably excited and detected for lasers beams impinging at the center of the specimen. Figure 4 presents the flexion vibration mode and its corresponding frequency spectrum.

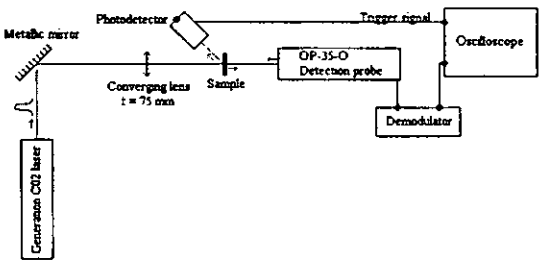


Fig.2 Laser-ultrasound set-up.

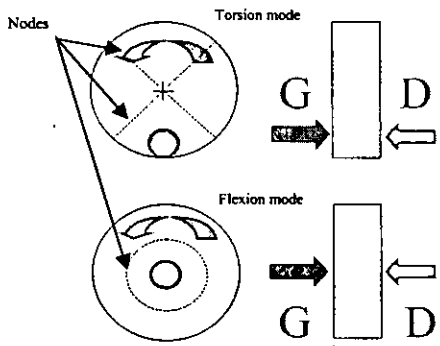
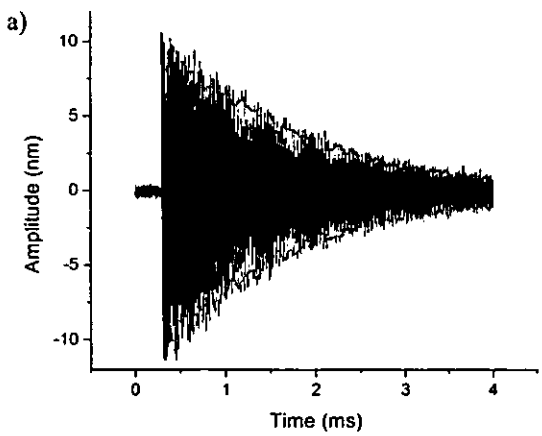


Fig.3 Schemes for generation and detection of the fundamental frequency of the torsion and flexion vibration modes (G: generation; D: detection).



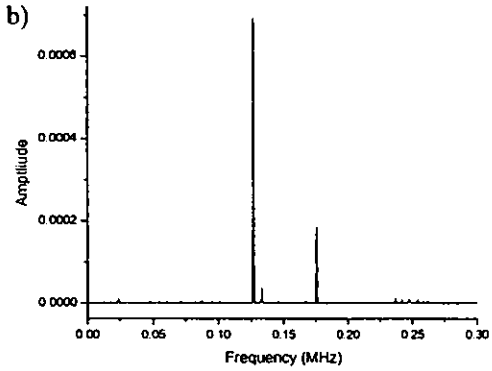


Fig. 4 Example of a) Surface displacement of a flexural vibration mode and its corresponding frequency spectrum b) obtained by FFT showing a clear resonance peak.

3. Results

3.1 Laser-ultrasonic results

Figure 5 presents the elastic moduli measured by laser-ultrasonics. A small difference in elastic modulus can be observed between the two families of specimens: 15.8 and 17.2 GPa for specimens A and B respectively. The standard deviations for the two sets of specimens are relatively small (0.87 GPa and 0.5 GPa for specimens A and B respectively). These standard variations are relatively small considering the sources of variations and errors on the density and frequency measurements. All specimens were not perfectly identical due to heterogeneity in the starting material. Indeed, all specimens did not have the same density and the elastic modulus is affected by the density [6]. Average densities of 2.11±0.05 g/cm^3 and 2.20±0.05 g/cm^3 were found for specimens A and B respectively. Errors in density mostly came from the thickness measurements that were done on specimens with unparallel faces, as observed during the mechanical tests (see next section). The plot of the elastic modulus vs the density of the specimens, shown on figure 6a, reveals a correlation between the two variables.

The Poisson's ratio is not highly affected by the density of the specimens within the density range characterized in the present study. Measured values are smaller than those generally reported in the literature for metallic foams. In fact, the Poisson's ratio has often been assumed to be close to 0.35 for metallic foams [1,7,8,9]. However, there is little experimental measurements of the Poisson's ratio reported in

the literature and work done on polymer foams confirm that the Poisson's ratio of foams can be different from those of the dense material [10].

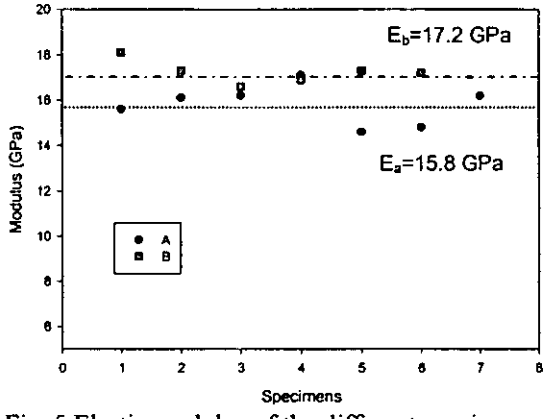


Fig. 5 Elastic modulus of the different specimens measured by ultrasonic resonance.

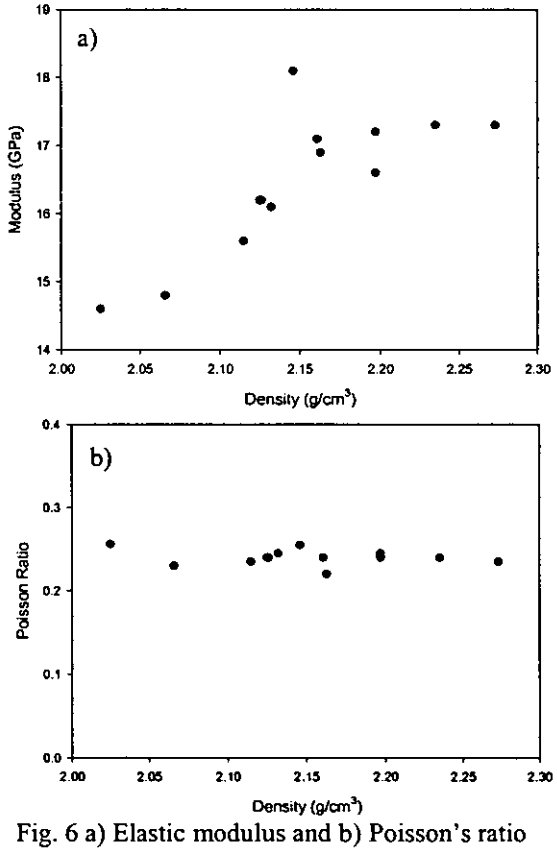


Fig. 6 a) Elastic modulus and b) Poisson's ratio measured by ultrasonic resonance as a function of density.

3.2 Compression tests

Figure 7 presents a typical compression curve showing the three deformation stages, the first linear regime preceded by the loading shoulder (1), the plastic deformation plateau (2) and the densification (3). The vertical lines on the curves represent the successive unloading done to monitor the evolution of the elastic modulus during the test.

During the compression test, a lateral expansion is observed (diameter expansion around 22% at 58% axial deformation). This causes the effective surface area of the compressed specimens to be 49% larger than that of the initial cylinders. Unfortunately, lateral expansion and volume changes were not recorded all along the deformation and this expansion has been assumed to be linear with axial deformation.

Some strain hardening occurs during the tests, as shown in Figure 7 (i.e. non-constant plastic deformation plateau). The stress increase with deformation is larger than 49% and cannot be only explained by the increase of the surface area of the specimens during deformation. However, elastic moduli are not affected by strain hardening and should not be modified by this effect.

Figure 8 presents an enlarged portion of the curve showing some measurement artifacts. In Figure 8a, the inflexion in the first regime is caused by the non-uniform deformation attributed to the non-perfect parallelism of the specimen faces. This effect can be more or less important depending on the quality of the specimen preparation and the thickness of the specimens. In the present study, the specimens were thin and were not faced to obtain optimum parallelism. This deformation at the beginning of the curves should be extracted for the calculation of the elastic moduli.

Once the faces of the specimens are parallel, a typical loading is observed. The slope during the loading stage (1) is lower than the elastic modulus of the foams. As mentioned in the introduction, both plastic and elastic deformations occur during loading causing the deformation to be more important and the slope to be significantly smaller.

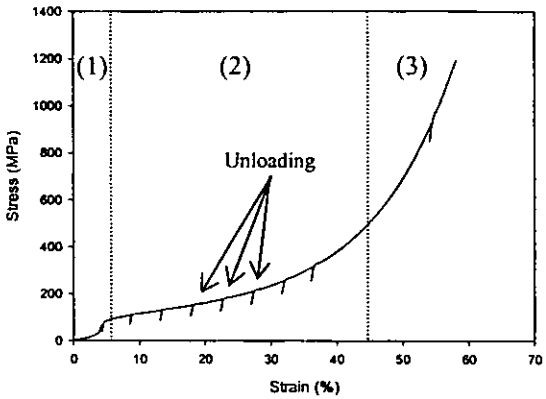


Fig.7 Typical compression curve obtained during the tests.

Figure 8b presenting an enlarged portion of the unloading shows some deviation from linearity in the unloading due to the precision of the LVDT transducers (Intertechnology, model 0243-0000). This deviation is particularly important due to the small thickness of the specimens and the small deformations measured during unloading (~10 μm). This effect varies in importance during the different unloading and may be a source of important errors in the evaluation of the elastic modulus with the unloading on thin specimens.

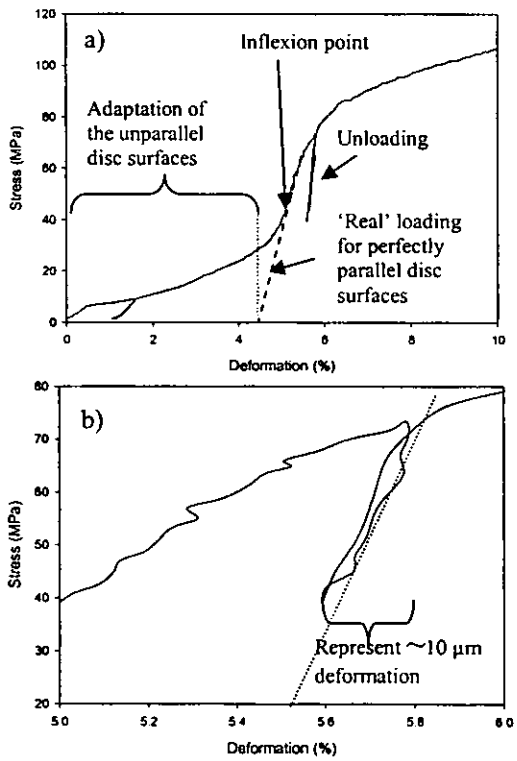


Fig. 8 Enlarge portion of a) beginning of the curve and b) second unloading.

Figure 9 presents the evolution of the elastic modulus with deformation. The elastic modulus decreases at low deformation indicating a modification of the material. The results are similar to those observed by [1,11] on closed-cell aluminum foams that showed a decrease of the elastic modulus as a function of the strain. The much smaller elastic modulus of the foam upon initial loading was believed to result from immediate yielding at cell nodes due to stress concentration [12]. The deformation in the foam is not homogeneous and continuous and plastic deformations may be localized in some areas, as demonstrated by different researchers [6,9]. Thus, after plastic deformation, the elastic modulus is measured on heterogeneous foams having a distribution of densities.

The elastic modulus evaluated along the compression should be corrected for the specimen shape modifications during the tests (face parallelism, thickness reduction, area increase). Correction for these effects is presented in Figure 9, considering a linear expansion of the radius with axial deformation. These effects are not negligible at high deformation (<15%). Between 30 and 50% deformation, the elastic modulus is more or less constant, even if the density of the material increases with deformation. An increase of the elastic modulus should nevertheless be expected at higher deformation, during the densification of the material, as reported in other work [1].

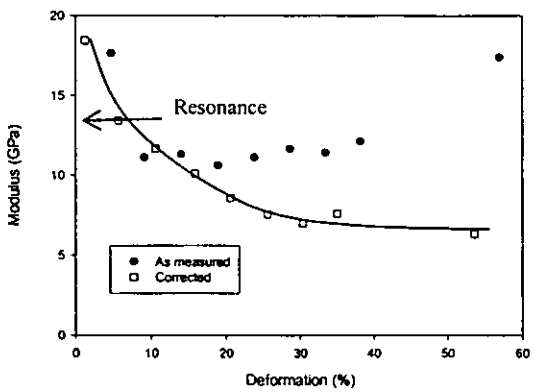


Fig. 9 Variation of the elastic modulus with deformation for Foam A; as measured and corrected for the specimens geometry modifications.

The values obtained in the present study are significantly higher than those reported in previous work [4]. This is mainly attributed to modifications in the starting powder formulation

and the processing conditions used in the present study that provided better consolidation of the particles during sintering and foams with lower porosity.

The correspondence between the elastic moduli measured by compression (i.e. extrapolated at zero deformation) and the elastic moduli measured using the resonance method compares relatively well. However, the average were taken on only 4 specimens for the compression curves (i.e. 3 curves showed too much variations to extrapolate the elastic modulus at zero deformation) while the average for the elastic moduli measured using the resonance method was calculated using all the results (7 measurements). Considering that some of the compression curves could not be used for the measurements of the elastic moduli, the values obtained by resonance can be considered as much more reliable, due to the thickness of the specimens characterized in the present study.

Table 1: Elastic moduli measured on specimens A using the compression curve and resonance methods.

Method	Elastic modulus (*GPa*)
Compression (4)	15.3±2.1
Resonance (7)	15.8±0.9

Conclusion

This paper presented an evaluation of the elastic properties of titanium foams using different methods. The results presented the difficulties and some measurement artifacts associated with the evaluation of the elastic moduli by standard compression tests on thin specimens.

The Ti foams show some level of consolidation during the compression tests (significant stress increase with strain during the second stage). The elastic modulus is reduced during compression despite the fact that the density of the material increases. This may be associated with damage and yielding due to stress concentration in the foams.

The elastic moduli measured by resonance are similar to those measured by compression. Standard variations of the elastic moduli measured by the resonance method are much smaller than those measured by compression. Resonance method can also be used to measure the Poisson's ratio. The measured Poisson's ratios were smaller than those usually reported in the literature. This is, however, coherent with other work done on polymer foams.

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