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# Young's modulus of ceramic particle reinforced aluminium: Measurement by the Impulse Excitation Technique and confrontation with analytical models

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Young's modulus of particulate metal matrix composites with volume fractions of reinforcement ranging from 40% to 60% is measured with the Impulse Excitation Technique. Results are compared with predictions of four common micromechanical mean-field models. Good agreement is obtained with the Torquato identical hard spheres (TIHS) and the generalized self-consistent (GSC) model.



## 1. Introduction

Numerous analytical mean-field models exist to describe the elastic behaviour of particle reinforced metal matrix composites (PRMMCs). Highly loaded PRMMCs represent a good test benchmark for such models, since the spread between predictions is much more important for volume fractions of reinforcement around 50% compared to more common 15–30% encountered in commercial PRMMCs (see Fig. 1 of Ref. [1]).

A common difficulty in testing model predictions is finding accurate data for Young's modulus of metal matrix composites. The conventional measurement of Young's modulus, i.e. via tensile testing [2], is difficult with these materials: the proportional regime in such materials can be very short or inexistent (e.g. [3]) such that measuring Young's modulus with the tangent to the initial slope of the stress-train curve is often difficult and easily inaccurate [4,5]. Nieh and Chellman [6] thus reported large discrepancies in the values of Young's modulus measured by different research groups for an aluminium alloy reinforced with 20 vol.% of SiC whiskers. In order to extend the proportional regime, they suggest that the measurements be conducted after a small plastic prestraining. Other authors use unload–reload cycles. Johnsen and Selnaes [7] used several unload–reload cycles after prestraining, but observed a pronounced hysteresis and cyclic creep. Warner and Stobbs [8] suggested that the modulus of short-fibre reinforced MMCs be measured on reloading after prestraining using low stress amplitude cycling about zero stress in order to stabilize the dislocation structure in the matrix. Prangnell et al. [9] compared this method with measurements made upon reloading after prestrain and obtained good agreement between the two methods. Kouzeli et al. [10] used unload–reload cycles between 30% and 70% of the preload to minimize cyclic creep and microplasticity effects. Drawbacks exist with the above methods, however. Firstly, using a prestrain will very often generate internal damage in the composite material and thus lower its apparent Young's modulus (e.g. [10,11]). Secondly, these measurements are strongly sensitive to specimen alignment, and possible backlash upon crosshead motion inversion.

Dynamic measurement of the elastic modulus is an alternative to quasistatic tensile tests. The strain interval used for the dynamic measurement of Young's modulus is small, which means in turn that stresses are small such that dislocation activity is negligible, as is the build-up of internal damage. The sample then behaves more truly as a linear elastic solid. Another advantage of this low amplitude method is that particles are kept in compression (due to thermal internal stress upon cooling) and therefore possible cracks in the particles remain closed. For these reasons, the measurement is expected to yield a higher and more accurate value compared to quasistatic measurements from mechanical tests. Among the dynamic testing methods, the Impulse Excitation Technique (IET) consists in subjecting a specimen to an external mechanical impulse and recording its resonant frequencies. Elastic properties can then be computed from these harmonic frequencies, knowing the geometry of the specimen and its density [12,13]. Strictly speaking, these are "dynamic" elastic moduli; in the following, we will omit the word "dynamic". Practical application of the method has been reported for various composite materials

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such as short fibre metal matrix composites [14], particle reinforced MMCs [15], whisker reinforced composites [16], interpenetrating phase composites [17], and multi-scale composites (double cemented carbides) [18].

The purpose of the present study is to report precise values of Young's modulus of metal matrix composites having a high volume fraction of reinforcement. To this aim, the dynamic Young's modulus is measured by the Impulse Excitation Technique on defect-free composites of pure aluminium or Al–Cu alloys reinforced with high volume fraction of $Al_2O_3$ particles. These composites are produced in our laboratory and exhibit two-phase (uniform matrix and reinforcement) microstructures. We then use these values to test several mean-field models that are commonly used in the literature to describe the elastic behaviour of this class of material.

## 2. Experimental procedures

### 2.1. Material

Matrices employed are either pure 99.99% Al (Hydro Aluminium GmbH, Grevenbroich, Germany), Al2%Cu or Al4.5%Cu (Alusuisse SA, Neuhausen, Switzerland). The alloyed matrix composites are heat treated to the T4 condition. Two types of reinforcement of different sizes are used: (i) polygonal-shaped $Al_2O_3$ powder with an average size of 6, 15 or 25 μm, or (ii) angular-shaped $Al_2O_3$ of average size 4, 10, 33 or 59 μm. The polygonal particles are produced by hydrolysis of aluminium alkoxide (by Sumitomo Chemicals Co., Tokyo, Japan), and are equiaxed, with rounded near-spherical shapes presenting a few facets. The angular Alodur® WSK particles (Treibacher Schleifmittel, Laufenburg, Germany) are produced by the Bayer process and then crushed and sieved. These have irregular shapes and their mean aspect ratio was measured in earlier work from metallography as the short over long main axis of equivalent 3D oblate spheroids, leading to a value of 0.3 on average for the different particle sizes [19]. Typical microstructures of these composites are presented in Fig. 1.

In the following, a short-hand designation is used to distinguish the different composites, in the form "X-ADi". X designates the matrix alloy (A for 99.99% pure Al, A2C for Al2%Cu, and A4.5C for Al4.5%Cu); A stands for alumina reinforcement, D denotes the average particle size rounded to the nearest multiple of 5 and i the particle shape (a means angular, p polygonal).

These composites were produced by gas pressure infiltration [20]. This process consists in forcing a liquid metal into a loose ceramic particle preform, packed to its maximum tapped density, using pressurized argon gas; processing details can be found in Ref. [21]. The preform is produced by pouring powder in a crucible in several steps. After each step, the powder bed is densified by tapping the outside of the crucible and agitating it on a vibrating plate.

One can expect that with angular powder, because particles are not equiaxed, a slight texture will appear during preform preparation, particles tending to lie with their shortest axis along the vertical (and hence the crucible and specimen axis). In order to determine wether the angular particle composites are textured, ultrasonic measurements were made along several directions (rather than IET, because this was not possible along all directions given ingot dimensions). These were conducted on selected sections of beams ($8 \times 8 \times 6$ mm$^3$) of A-A60a, A-A35a and A-A5a composites. These specimens were cut by electro-discharge machining to obtain parallel faces. Measurements were conducted with a 10 MHz probe in pulse-echo mode between the first and third signal peak reflected by the bottom side of the sample. Ultrasonic speed was measured in two directions, one corresponding to the axis of the beam, the other perpendicular. Measurement of ultrasound speed in these two directions evidenced a slight texture: values were slightly higher in the direction perpendicular to the beam axis by 3%, 2.5% and 2% for A-A60a, A-A35a and A-A5a, respectively (average on three samples). The texture was thus slightly less important with small particles; this can be rationalized as a result of electrostatic forces, which are more important for small particles and prevent particles from arranging freely during preform preparation. This slight texture is hardly seen on metallographic cuts, see for example Fig. 1b, for which the beam axis lies vertically.

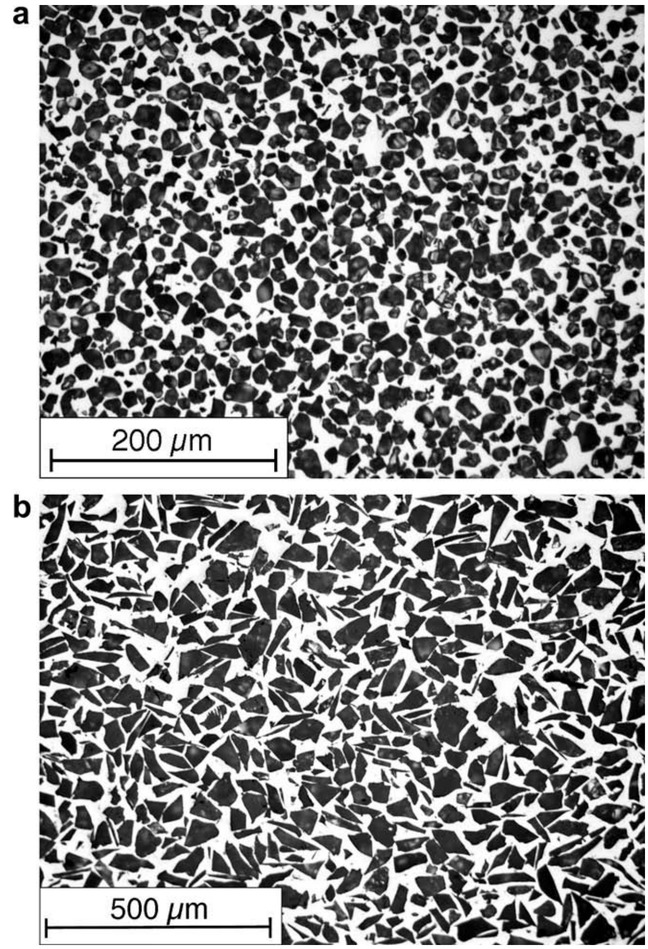


**Fig. 1.** Optical micrographs of PRMMCs with (a) 25 μm polygonal and (b) 59 μm angular $Al_2O_3$ reinforcements (dark phase).

The composites exhibit a high volume fraction of reinforcement, 40–60% depending on particle size and shape. Since gas pressure infiltration leads to a pore-free matrix, the volume fraction of reinforcement was calculated from the composites densities, which were determined by a hydrostatic weighting technique [22].

Two sets of specimen beams were machined by wire electro-discharge machining. Specimens from the first set have a width $b$ of 8 mm, a height $h$ of 6 mm and a varying length $l$ depending on the casting geometry. The second set is made of smaller specimens, of various sizes.

### 2.2. Measurement of Young's modulus

Young's modulus was measured by IET using a Grindosonic® apparatus (Lemmens Elektronics, Leuven, Belgium). Different vibration modes were excited for each specimen. For the small specimens (second set), only the first flexural harmonic was