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Ultrasonic velocity measurement of elastic constants of Al–CuAl$_2$ eutectic composite

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Ultrasonic velocity measurements were performed to determine the dynamic elastic stiffness constants of the Al–CuAl$_2$ unidirectionally solidified eutectic, which consists of unidirectional CuAl$_2$ platelets in an Al matrix. The phase velocity of ultrasonic waves in the eutectic was measured by the echo-overlap technique. The material was assumed to be transversely isotropic and its elastic constants, in units of 10^{10} dyn cm^{-2}, are found to be: $c_{33} = c_{11} = c_{22} = 122.8$, $c_{44} = c_{55} = 29.7$, $c_{12} = c_{13} = c_{23} = 59.5$, where the subscript 3 indicates the fibre direction. These results indicate that the Al–CuAl$_2$ eutectic is almost elastically isotropic or more precisely, has cubic symmetry. The elastic moduli are used to evaluate the engineering constants of this material. The value of Young's modulus is found to be in close agreement with that measured by others in quasi-static tests.

1. Introduction

The usefulness of unidirectionally solidified eutectics as fibre-reinforced composite materials has been demonstrated by various authors (e.g. [1-6]). It has been shown that production of a metallic fibre-reinforced material, by unidirectional eutectic solidification, presents many advantages over the usual procedure of physically mixing the high-strength whiskers in the form of plates or rods, with the matrix material. These advantages include: easy handling, very good bond between the fibres and the matrix and increase of the strength of the composite.

A complete knowledge of the mechanical properties of these eutectic composites is necessary, because they can exhibit a marked elastic anisotropy and they are of importance as structural materials. In the present paper, the mechanical properties of the Al–CuAl$_2$ unidirectionally solidified eutectic are determined experimentally by ultrasonic methods.

The Al–CuAl$_2$ eutectic has a microstructure consisting of alternating platelets of a ductile aluminium matrix and a high modulus reinforcing CuAl$_2$ intermetallic phase. The physical properties of this eutectic have been reported in [1-6].

Despite the number of papers devoted to this material, very little has been done concerning its mechanical behaviour in the elastic region; only the Young's modulus of the composite has been determined by classical static experimental methods and from this, the modulus of the CuAl$_2$ platelets through the law of mixtures [1-6]. A complete knowledge of the elastic stiffness matrix of the Al–CuAl$_2$ composite is very important, because this matrix governs the elastic behaviour of the material.

In this work, the complete set of the elastic stiffness constants of the Al–CuAl$_2$ is determined by measuring the velocities of ultrasonic waves propagating through the material. Use is made of the high-accuracy, echo-overlap-technique developed by Papadakis [7] and applied successfully for the measurement of the elastic constants of the Al–Al$_3$Ni eutectic by Grabel and Cost [8]. This technique is successful here because the specimen material has low mechanical damping, which is an essential requirement for multiple-echo techniques. In addition these measurements permit a critical examination of the elastic constants to establish the nature of the elastic anisotropy of Al–CuAl$_2$.

2. Experimental procedure

2.1. Specimen characteristics

In the eutectic solidification of the Al–33 wt % Cu eutectic, the matrix phase and the reinforcing phase are grown approximately simultaneously from a liquid of the same overall composition at the eutectic temperature. By a controlled solidification process, using a modified Bridgman technique, platelike whiskers are produced parallel to the growth direction. In this paper, direction 3 is parallel to the fibre direction. The specimen's rate of growth was 11 cm h^{-1} at a temperature of 366° C. Ingots of Al–$CuAl_2$ were produced in the form of cylindrical bars about 2.50 cm in diameter and 16.50 cm long.

The ultrasonic specimens were parallelepipeds with dimensions between 1.7 and 2.5 cm. They were spark-cut from the ingots so that the platelets were oriented at 0 and 45° to the longitudinal direction. The faces of the specimens were polished with 0.5 μm abrasive to a parallelness of at least 10 min of arc. The dimensions of the specimens were measured by a Van Keuren light-wave micrometer with an estimated accuracy of 0.001 %.

The density of the Al–$CuAl_2$ eutectic was determined to be 3.461 ± 0.006 g cm^{-3} from weight and dimensional measurements.

2.2. Phase velocity measurements

The presence of long platelike fibres in the unidirectional Al–$CuAl_2$ composite leads one to assume that this is a transversely isotropic material with a plane of transverse isotropy perpendicular to the fibre direction. Thus, its elastic behaviour can be completely described by five elastic constants [9]. These five elastic constants can be determined by measuring five appropriate velocities of ultrasonic waves propagating in the material. These velocities are functions of the elastic constants and the density [10] and their measurement permits the dynamic stiffness elastic constants c_{ij} to be evaluated if the density is known. The echo-overlap method [7] of velocity measurement employed in this work is an adaptation of the ultrasonic pulse-echo technique and gives very accurate results by permitting cycle-for-cycle overlapping of echoes visually on the display oscilloscope. Papadakis has recently reported [11] that errors in the absolute values of the measured round-trip travel times can be less than 0.015 τ after diffraction phase and bond thickness corrections have been made. Here τ is the period of the fundamental vibrational mode of the transducer. All the velocity measurements were performed at a frequency of 10 MHz i.e. the frequency of an AC or X-cut quartz transducer generating transverse (shear) or longitudinal waves, respectively. The transducers were bonded onto the polished faces of the specimens with Salol.

Transverse and longitudinal waves were propagated through the specimen with wave propagation and particle displacement directions as indicated in Table I, where the velocities are given in terms of the stiffness elastic constants c_{ij} and the density ρ [10]. Quasi-longitudinal and quasi-transverse waves were also propagated at 45° to the fibre axis and the corresponding velocities measured.

In principle, in order to determine the five elastic constants, one needs wave-speed measurements of waves propagating along the fibre direction and perpendicular to it and measurement of the wave speed of a wave propagating along an axis 45° between the previous two directions [10]. However, as shown in Table II, additional measurements were made in the present study and this additional information served as a check of the overall accuracy of the measurements and of the assumed elastic anisotropy for Al–$CuAl_2$. Up to ten transit-time measurements comprised each wave-speed determination. Typically we observed about eight undistorted echoes for longitudinal and three for transverse waves. This permitted several echoes in the echo pattern to be used in the measurements. The measured wave-speeds never differed

TABLE I Elastic stiffness constant and velocity relations

Propagation direction*	Mode	Particle displacement	Equation
3	Longitudinal		$V_1 = (c_{33}/\rho)^{\frac{1}{2}}$
1	Longitudinal		$V_2 = (c_{11}/\rho)^{\frac{1}{2}}$
3	Transverse	1	$V_3 = (c_{44}/\rho)^{\frac{1}{2}}$
1	Transverse	3	$V_4 = (c_{44}/\rho)^{\frac{1}{2}}$
1	Transverse	2	$V_5 = ((c_{11} - c_{12})/2\rho)^{\frac{1}{2}}$
45° to fibres	Longitudinal		V_6 (+), see below
45° to fibres	Transverse	†	V_7 (−), see below

$$V_{6,7} = \{\{(c_{11} + c_{33} + 2c_{44})/2 \pm [((c_{11} - c_{33})/2)^2 + (c_{13} + c_{44})^2]^{\frac{1}{2}}\}/2\rho\}^{\frac{1}{2}}$$

*3 is the fibre direction.

†In the plane of fibre and propagation direction.

TABLE II Velocity measurements

Velocity	(10^5 cm sec^{-1})
V_1	5.96 ± 0.01
V_2	5.96 ± 0.01
V_3	2.98 ± 0.01
V_4	2.93 ± 0.01
V_5	3.02 ± 0.01
V_6	5.91 ± 0.03
V_7	2.97 ± 0.02

by more than 0.30%. The values of the various velocities with their uncertainties are listed in Table II.

3. Results and discussion

By using the measured wave-speeds in the equations of Table I, the values of the five elastic stiffness constants of the Al–CuAl$_2$ composite were calculated. They are tabulated in Table III.

TABLE III Elastic constants of Al–CuAl$_2$

Constant	Experimental value (10^{10} dyn cm^{-2})*	Velocity used to obtain c_{ij}
c_{33}	122.8 ± 0.8	V_1
$c_{11} = c_{22}$	122.8 ± 0.7	V_2
$c_{44} = c_{55}$	30.6 ± 0.1	V_3
	29.7 ± 0.1†	V_4
c_{12}	59.5 ± 0.9	V_5
$c_{13} = c_{23}$	59.5 ± 4.0‡	V_6
	62.2 ± 4.0	V_7

*Multiplying by a factor of 1.45×10^{-5} to obtain values in units of psi.
†This is chosen as the value of c_{44}.
‡More echoes are detected for longitudinal waves than transverse waves, and hence V_6 is selected to obtain the value of c_{13}.

The corresponding errors for the various c_{ij} constants are also shown in Table III, obtained by usual error analysis (e.g. in [12]). The difference between the two values for c_{13}, obtained from the velocities V_6 and V_7, is close to the experimental error (2%).

The two values of c_{44}, obtained from the velocities V_3 and V_4, are also different by roughly the experimental error (2%), a fact which agrees with the corresponding results for Al–Al$_3$Ni obtained by Grabel and Cost [8]. On the basis of theoretical predictions by Achenbach and Herrmann [13] and previous experimental evidence [14], it is assumed that the velocity V_4 is undispersed and provides the proper value for c_{44}.

The values found for the moduli c_{33} and c_{11} are essentially the same as is the case for c_{12} and c_{13}, indicating that the Al–CuAl$_2$ eutectic is elastically almost isotropic. This is in agreement with the experimental results of [3] concerning the Young's modulus of the Al–CuAl$_2$, which was found to be essentially isotropic along the three axes 1, 2 and 3. In a more precise description the material has cubic symmetry with three independent elastic constants c_{11}, c_{12}, c_{44} [10]. If the material is considered as isotropic, the isotropy condition $c_{12} + 2c_{44} = c_{11}$ [10] fails by about 7%. Thus, as in [15], we have used wave-speed measurements to check the assumed elastic anisotropy of the composite material.

Using the relations between the modili c_{ij} and the engineering constants for a transversely isotropic material provided by Tsai [9], the various modili of the composite were calculated and tabulated in Table IV.

As an additional check of our measurements we compare our results with the available data on this material which was obtained by other methods. In [1-6] static experimental values of Young's modulus along the fibre direction of the Al–CuAl$_2$ composite vary between 82.7×10^{10} and 101.3×10^{10} dyn cm^{-2}. These static values compare well with the dynamic value of 84.0×10^{10} dyn cm^{-2} obtained here. This indicates that the difference between the static and dynamic moduli is rather small for the Al–CuAl$_2$ eutectic, as it was also, for the Al–Al$_3$Ni eutectic [8]. It should be mentioned also that the dynamic resonance technique gives

TABLE IV Engineering constants of Al–CuAl$_2$ composite

Longitudinal Young's modulus	84.0×10^{10} dyn cm^{-2} (12.2×10^6 psi)
Transverse Young's modulus	84.0×10^{10} dyn cm^{-2} (12.2×10^6 psi)
Shear modulus in fibre direction	29.7×10^{10} dyn cm^{-2} (4.3×10^6 psi)
Bulk modulus*	80.6×10^{10} dyn cm^{-2} (11.7×10^6 psi)
Poisson's ratio along fibre direction	0.326
Transverse Poisson's ratio	0.326

*Computed according to the formula $K = (c_{11} + 2c_{12})/3$ given by [10], for a material of cubic symmetry.

a value of 86.90 × 10^{10} dyn cm^{-2} [16] for Young's modulus, which is close to the value obtained by the ultrasonic method.

The Young's modulus of the $CuAl_2$ platelets can be determined by using the results of the measurement on the composite and the law of mixtures [17]. Thus, for a volume fraction of fibres 0.475 [3] and Young's modulus of Al 71.7 × 10^{10} dyn cm^{-2}, a value of 97.5 × 10^{10} dyn cm^{-2} was obtained for $CuAl_2$, which compares well with static values of this modulus in [1, 3-6] ranging from 95.0 × 10^{10} to 134.0 × 10^{10} dyn cm^{-2}.

4. Conclusions

We have used measurements of the propagation of ultrasonic pulses in an Al–$CuAl_2$ eutectic composite material to determine its elastic constants and to check the correctness of the elastic anisotropy assumed for it.

We found that the elastic properties of this composite possess a cubic symmetry and are described by three independent elastic constants. As an approximation, the material is isotropic. The Young's modulus, evaluated from the elastic constants, differs little from the results measured by other investigators using static methods.

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