

# Growth-Rate-Dependent Mechanical Properties and Microhardness of a Pb–Sn–Cd Ternary Eutectic Composite

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**Abstract-** The present work examines the relationship between anisotropic growth velocity and the mechanical behaviour of the Pb–Sn–Cd eutectic composite. The alloy was prepared from the constituent metals using the heat-chill method and its eutectic melting point was determined by differential scanning calorimetry. The composition investigated was Sn 51.2 wt%, Pb 30.6 wt%, Cd 18.2 wt%, with a measured eutectic melting point of 418.2 K. Macrohardness-related strength modes and Vickers microhardness were evaluated as functions of growth velocity, indentation time and applied load. At approximately  $3.1 \times 10^{-7} \text{ m s}^{-1}$ , the modulus of rupture is  $50.70 \times 10^5 \text{ N m}^{-2}$ , tensile strength is  $61.80 \times 10^4 \text{ N m}^{-2}$  and compressive strength is  $64.20 \times 10^4 \text{ N m}^{-2}$ . Microhardness rises from  $17.60 \text{ kg mm}^{-2}$  at  $0.50 \times 10^{-7} \text{ m s}^{-1}$  to a maximum of  $37.60 \text{ kg mm}^{-2}$  at  $3.10 \times 10^{-7} \text{ m s}^{-1}$  and then decreases to  $17.80 \text{ kg mm}^{-2}$  at  $7.50 \times 10^{-7} \text{ m s}^{-1}$ . At a 20 g load, microhardness remains nearly constant with indentation time, ranging approximately from 36.10 to 36.70  $\text{kg mm}^{-2}$  over 20–150 s. With indentation load, Hv decreases from 39.50  $\text{kg mm}^{-2}$  at 10 g to 18.10  $\text{kg mm}^{-2}$  at 100 g. The results demonstrate a characteristic optimum or moderate-growth region in which the fibrous eutectic microstructure and mechanical response are maximized. The observations support the interpretation that directional/fibrillar growth produces stronger, more coherent microstructures than instantaneous or very rapid growth.

**Keywords—** eutectic composite; anisotropic growth; growth velocity; macrohardness; microhardness; Vickers hardness; fibrillar microstructure.

## I. INTRODUCTION

Eutectic alloys provide a useful route for producing in-situ composite structures because their constituent phases can crystallize together from a common melt. This manuscript treats anisotropic solidification as a means of developing aligned eutectic fibres and relates the resulting growth morphology to mechanical properties. The central experimental observation is that the mechanical response is not monotonic with growth velocity: slow, moderate and fast growth regions can be distinguished, with the moderate region giving the most favourable strength. For the Pb–Sn–Cd system, the study further examines whether the same growth–property relationship is reproduced in microhardness measurements.

This work establishes the relevance of composite structure, crystal growth, eutectic morphology and strength relationships.

## II. MATERIALS AND METHODS

### 1. Alloy Preparation and Thermal Characterization

The investigated eutectic alloy had the composition Sn 51.2 wt%, Pb 30.6 wt%, Cd 18.2 wt%. Tin (99.5%, LOBA), lead of AR grade and cadmium (99.5%, LOBA) were used as supplied. The alloy was homogenized by the heat-chill method. The eutectic melting point was determined by differential scanning calorimetry using a Shimadzu DTG/DSC-60 instrument.

The measured eutectic melting point was 418.2 K, which is close to the corresponding literature value.

### 2. Solidification Procedures and Experimental Setup

For anisotropic directional growth, molten alloy charges were contained within thin glass tubes placed inside an air oven maintained approximately 30 K above the eutectic melting point (~543.2 K).

Controlled upward circulation of cooling water surrounding the tubes induced steady-state directional solidification. Rapid, non-directional solidification was achieved by instantaneous immersion of molten samples into an ice-water bath maintained at  $\sim 273$  K. Growth velocities ranging from  $0.50 \times 10^{-7} \text{ m s}^{-1}$  to  $8.0 \times 10^{-7} \text{ m s}^{-1}$  were systematically investigated.

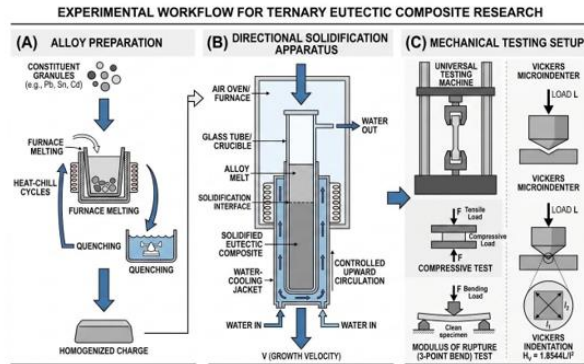


Figure 1. Schematic representation of the experimental directional solidification apparatus and directional growth workflow for the Pb–Sn–Cd eutectic alloy.

### 3. Mechanical Testing and Microhardness Characterization

Macrohardness parameters comprising modulus of rupture, ultimate tensile strength, and compressive strength were evaluated on rod-like specimens. Local microhardness was measured using a Vickers MHP-100 microhardness tester mounted on a Neophot-2 incident-light metallurgical microscope. Microhardness was examined as a function of growth velocity, indentation time at a 20g load. Hardness measurements were averaged across multiple indentations per specimen.

## III. RESULTS AND DISCUSSION

### 1. Macrohardness and Mechanical Strength

As shown in Figure 2 and Table 1, the macroscopic mechanical response of the Pb–Sn–Cd eutectic composite varies significantly with directional growth velocity. At an optimal moderate growth rate of approximately  $3.10 \times 10^{-7} \text{ m s}^{-1}$ , the modulus of rupture reaches  $50.70 \times 10^4 \text{ N m}^{-2}$ , tensile strength reaches  $61.80 \times 10^4 \text{ N m}^{-2}$ , and compressive strength reaches  $64.20 \times 10^4 \text{ N m}^{-2}$ . In contrast, under

instantaneous solidification conditions, the corresponding values drop sharply to  $16.30 \times 10^4 \text{ N m}^{-2}$ ,  $19.40 \times 10^4 \text{ N m}^{-2}$ , and  $20.90 \times 10^4 \text{ N m}^{-2}$ , respectively. Thus, anisotropic directional solidification at moderate growth velocities produces a substantially enhanced mechanical response compared to instantaneous solidification.

Table 1. Variation of macroscopic strength parameters of Pb–Sn–Cd eutectic composite with growth velocity.

| Growth velocity, $V$<br>( $\times 10^{-7} \text{ m s}^{-1}$ ) | Modulus of rupture | Tensile strength | Compressive strength |
|---------------------------------------------------------------|--------------------|------------------|----------------------|
| 0.50                                                          | 16.60              | 19.70            | 20.40                |
| 0.80                                                          | 22.70              | 24.30            | 8.20                 |
| 1.20                                                          | 31.20              | 36.70            | 42.70                |
| 1.50                                                          | 37.50              | 44.90            | 50.20                |
| 1.70                                                          | 40.30              | 50.70            | 54.30                |
| 2.10                                                          | 45.10              | 56.30            | 56.80                |
| 2.50                                                          | 49.20              | 60.20            | 62.70                |
| 2.80                                                          | 50.50              | 61.30            | 63.00                |
| 3.10                                                          | 50.70              | 61.80            | 64.20                |
| 3.50                                                          | 50.50              | 61.50            | 63.30                |
| 3.80                                                          | 50.10              | 59.80            | 62.50                |
| 4.20                                                          | 47.80              | 56.10            | 58.70                |
| 4.60                                                          | 45.20              | 52.50            | 54.70                |
| 5.50                                                          | 36.30              | 42.20            | 43.80                |
| 6.50                                                          | 23.80              | 27.80            | 29.60                |
| 7.00                                                          | 16.40              | 20.70            | 22.80                |
| 7.50                                                          | 8.70               | 9.80             | 12.20                |

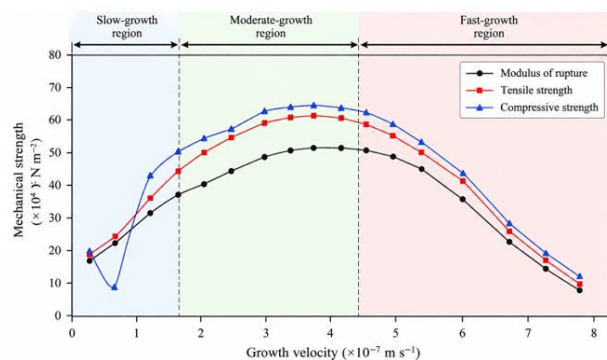


Figure 2. Variation of modulus of rupture, tensile strength, and compressive strength of the Pb–Sn–Cd eutectic composite with directional growth velocity.

## 2. Vickers Microhardness Analysis

As illustrated in Figure 3 and Table 2, Vickers microhardness exhibits a parabolic relationship with growth velocity. Microhardness increases from 17.60 kg mm<sup>-2</sup> at a slow growth velocity of  $0.50 \times 10^{-7}$  m s<sup>-1</sup> to a peak value of 37.60 kg mm<sup>-2</sup> at  $3.10 \times 10^{-7}$  m s<sup>-1</sup>, before decreasing to 17.80 kg mm<sup>-2</sup> at  $7.50 \times 10^{-7}$  m s<sup>-1</sup>. This non-monotonic microhardness trend strongly parallels the macrohardness strength behavior, identifying slow, moderate, and fast growth regimes.

Table 2. Vickers microhardness of Pb–Sn–Cd as a function of anisotropic growth velocity.

| V ( $\times 10^{-7}$ m s <sup>-1</sup> ) | H <sub>v</sub> (kg mm <sup>-2</sup> ) |
|------------------------------------------|---------------------------------------|
| 0.50                                     | 17.60                                 |
| 0.80                                     | 22.20                                 |
| 1.20                                     | 25.90                                 |
| 1.50                                     | 27.70                                 |
| 1.70                                     | 28.90                                 |
| 2.10                                     | 32.10                                 |
| 2.50                                     | 34.90                                 |
| 2.80                                     | 36.10                                 |
| 3.10                                     | 37.60                                 |
| 3.50                                     | 35.90                                 |
| 3.80                                     | 34.30                                 |
| 4.20                                     | 33.10                                 |
| 4.60                                     | 32.90                                 |
| 5.50                                     | 28.60                                 |
| 6.50                                     | 25.20                                 |
| 7.00                                     | 21.90                                 |
| 7.50                                     | 17.80                                 |

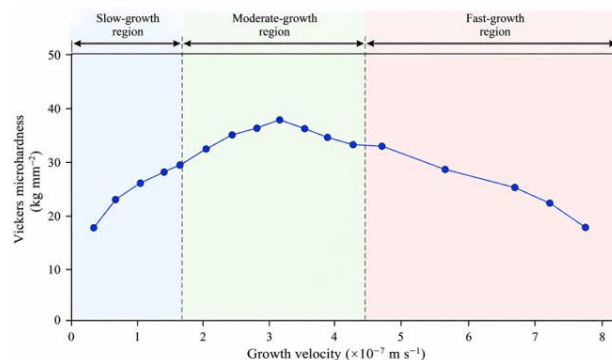


Figure 3. Vickers microhardness of the Pb–Sn–Cd eutectic composite as a function of growth velocity at an applied load of 20 g.

## 3. Microstructural Mechanisms and Solidification Kinetics

At a 20 g load, microhardness remains nearly constant with indentation time, ranging approximately from 36.10 to 36.70 kg mm<sup>-2</sup>.

The mechanical-property maximum is therefore associated with microstructural alignment rather than with growth velocity alone. The fibres act as reinforcing elements within the eutectic matrix, while the coherent, attaching morphology provides more effective load transfer. The observation is that the strength hierarchy is compressive strength greater than tensile strength greater than modulus of rupture. For Pb–Sn–Cd, the experimentally observed maxima conform to this general ordering.

The microhardness results independently reproduce the macrohardness trend. Hardness increases from the slow-growth regime into the moderate-growth regime and then declines at higher velocities. This agreement between macroscopic and microscopic measurements provides supporting evidence for the proposed connection between fibrillar eutectic growth and enhanced mechanical performance.

## IV. CONCLUSIONS

- The Pb–Sn–Cd eutectic composite exhibits a pronounced dependence of mechanical strength and microhardness on anisotropic growth velocity.
- The optimum response occurs in the moderate-growth region, close to  $3 \times 10^{-7}$  m s<sup>-1</sup>.
- Moderate anisotropic growth produces substantially higher strength than instantaneous solidification.
- Microhardness follows the same non-linear growth-velocity dependence as the macroscopic strength parameters.

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