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Growth-Rate-Dependent Mechanical Properties of a Sn–Pb–Bi–Cd Quaternary Eutectic Composite

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Abstract — The present work examines the relationship between anisotropic growth velocity and the mechanical behaviour of the Sn–Pb–Bi–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 13.1 wt%, Pb 27.3 wt%, Bi 49.5 wt%, Cd 10.1 wt%, with a measured eutectic melting point of 342.2 K. Macrohardness-related strength modes and Vickers microhardness were evaluated as functions of growth velocity, indentation time and applied load. At 3.10×10^{-7} m s^{-1}, the modulus of rupture is 43.30×10^{6} N m^{-2}, tensile strength is 52.40×10^{6} N m^{-2} and compressive strength is 57.10×10^{6} N m^{-2}. Microhardness increases from 14.50 kg mm^{-2} at 0.50×10^{-7} m s^{-1} to 27.20 kg mm^{-2} at 3.10×10^{-7} m s^{-1}, then decreases to 13.30 kg mm^{-2} at 7.50×10^{-7} m s^{-1}. 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 Sn–Pb–Bi–Cd system, the study further examines whether the same growth–property relationship is reproduced in microhardness measurements.
This 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 13.1 wt%, Pb 27.3 wt%, Bi 49.5 wt%, Cd 10.1 wt%. Lead of AR grade, bismuth (99.5%, LOBA) and cadmium (99.5%, LOBA) were used as supplied; tin was used as the constituent specified for the relevant eutectic composition. 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 342.2 K, which is close to the corresponding literature value.

2. Solidification Procedures and Experimental Setup

Specimens were solidified anisotropically and instantaneously using the growth devices adopted in the preceding experimental chapter of the thesis. The principal anisotropic growth rate used for direct comparison of the eutectic composite and its constituent crystal samples was approximately 3.0×10^{-7} m s^{-1}. Additional experiments covered growth velocities from approximately 0.50 to 8.00 $\times$ 10^{-7} m s^{-1}, depending on the measurement.

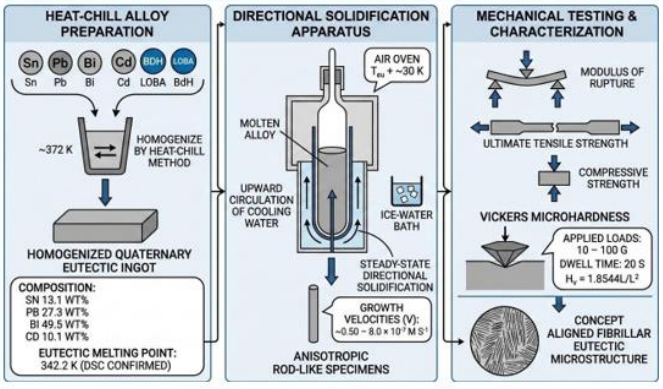

Figure 1. Schematic representation of the experimental directional solidification apparatus and directional growth workflow for the Sn–Pb–Bi–Cd eutectic alloy.

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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 mechanical strength of the Sn–Pb–Bi–Cd quaternary eutectic composite exhibits a strong dependence on growth velocity. At 3.10×10^{-7} m s^{-1}, the modulus of rupture is 43.30×10^{6} N m^{-2}, tensile strength is 52.40×10^{6} N m^{-2}, and compressive strength is 57.10×10^{6} N m^{-2}, significantly outperforming the values of 13.70×10^{6} N m^{-2}, 16.30×10^{6} N m^{-2}, and 18.30×10^{6} N m^{-2} observed for instantaneous growth.

Table 1. Variation of macroscopic strength parameters of Sn–Pb–Bi–Cd eutectic composite with growth velocity. Values are those reported in the thesis chapter.

Growth velocity, V ($\times 10^{-7}$ m s^{-1})	Modulus of rupture	Tensile strength	Compressive strength
0.50	13.40	16.40	18.10
0.80	17.60	19.50	22.40
1.20	22.50	23.60	28.80
1.50	27.60	28.80	35.40
1.70	32.40	35.10	40.90
2.10	34.70	39.90	46.90
2.50	40.20	45.80	50.90
2.80	42.10	50.60	55.20
3.10	43.30	52.40	57.10
3.50	42.70	50.80	55.90
3.80	39.50	48.60	53.10
4.20	34.80	43.70	49.20
4.60	29.70	37.10	42.30
5.50	24.60	30.80	36.60
6.50	20.10	24.10	30.70
7.00	16.30	20.30	23.20
7.50	13.40	16.60	18.80
8.00	13.30	16.10	18.40

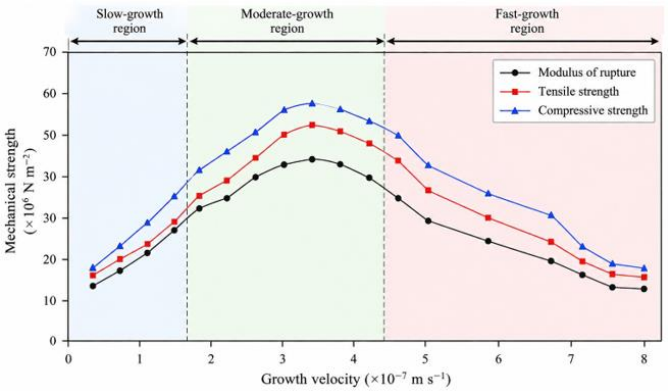

Figure 2. Variation of modulus of rupture, tensile strength, and compressive strength of the Sn–Pb–Bi–Cd eutectic composite with directional growth velocity.

2. Vickers Microhardness Analysis
As shown in Figure 3 and Table 2, Vickers microhardness increases from 14.50 kg mm^{-2} at 0.50×10^{-7} m s^{-1} to 27.20 kg mm^{-2} at 3.10×10^{-7} m s^{-1}, before decreasing to 13.30 kg mm^{-2} at 7.50×10^{-7} m s^{-1}. This parabolic trend matches the macrohardness strength behavior, confirming an optimal moderate growth rate.

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

V ($\times 10^{-7}$ m s^{-1})	H_v (kg mm^{-2})
0.50	14.50
0.80	15.70
1.20	17.90
1.50	19.30
1.70	21.50
2.10	23.40
2.50	25.30
2.80	26.60
3.10	27.20
3.50	26.20
3.80	24.70
4.20	22.80
4.60	20.60
5.50	17.60
6.50	14.50
7.00	13.70
7.50	13.30

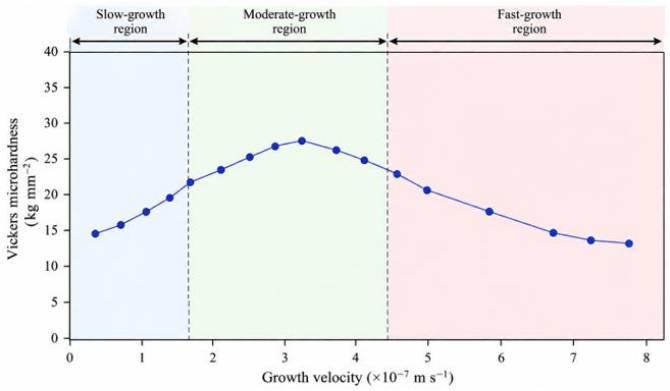

Figure 3. Vickers microhardness of the Sn–Pb–Bi–Cd eutectic composite as a function of growth velocity at an applied load of 20 g.

3. Microstructural Mechanisms and Solidification Kinetics

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 manuscript further notes that the strength hierarchy is compressive strength greater than tensile strength greater than modulus of rupture. For Sn–Pb–Bi–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 Sn–Pb–Bi–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 3×10^{-7} m s^{-1}.
- 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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