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Effect of Solidification Kinetics and Vickers Indentation Conditions on Mechanical Properties of Sn-Bi-Cd Alloy

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Abstract

The present work examines the relationship between anisotropic growth velocity and the mechanical behaviour of the Sn–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 25.9 wt%, Bi 53.9 wt%, Cd 20.2 wt%, with a measured eutectic melting point of 376.2 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 52.10×10^{5} N m^{-2}, tensile strength is 63.90×10^{4} N m^{-2} and compressive strength is 66.30×10^{4} N m^{-2}. Microhardness rises from 16.40 kg mm^{-2} at 0.50×10^{-7} m s^{-1} to 35.30 kg mm^{-2} at 3.10×10^{-7} m s^{-1} and decreases to 17.10 kg mm^{-2} at 7.50×10^{-7} m s^{-1}. At 20 g, Hv remains approximately 34.50–34.80 kg mm^{-2} over 20–150 s. Hv decreases from 36.50 kg mm^{-2} at 10 g to 16.70 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 manuscript's 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.

1. Introduction

Eutectic alloys provide a useful route for producing in-situ composite structures because their constituent phases can crystallize together from a common melt. The 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–Bi–Cd system, the study further examines whether the same growth–property relationship is reproduced in microhardness measurements.

2. Materials and Methods

2.1 Alloy Preparation and Thermal Characterization

The investigated eutectic alloy had the composition Sn 25.9 wt%, Bi 53.9 wt%, Cd 20.2 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 376.2 K, which is close to the corresponding literature value.

2.2 Solidification Procedures and Experimental Setup

Specimens were solidified anisotropically and instantaneously using the growth devices. 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.

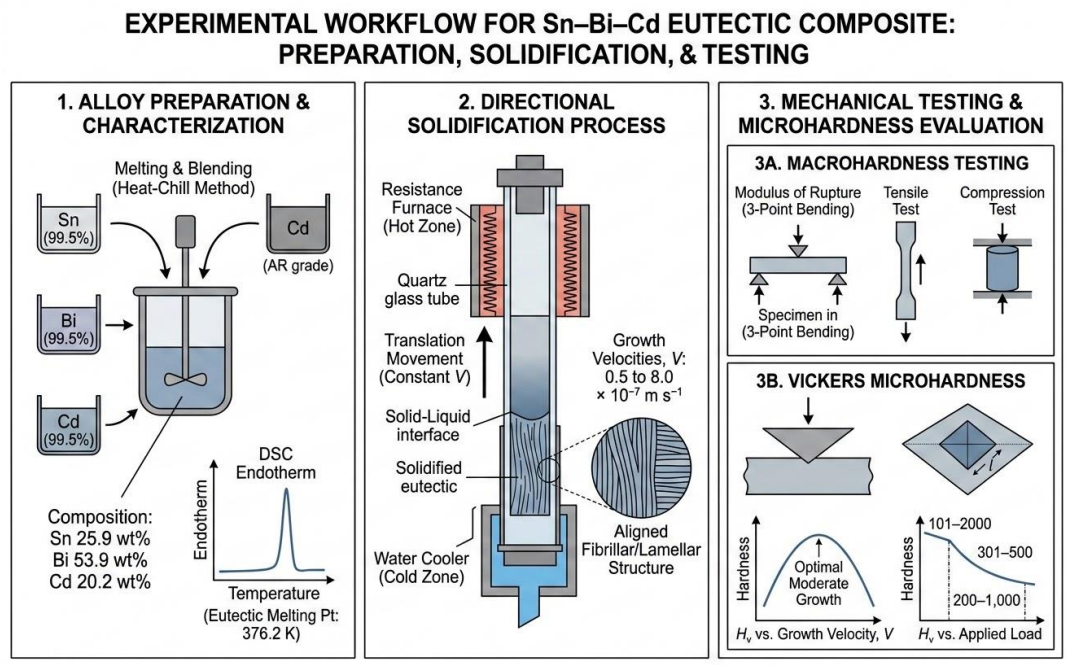


Figure 1. Schematic representation of the experimental directional solidification apparatus and directional growth workflow for the Sn–Bi–Cd eutectic alloy.

2.3 Mechanical Testing and Microhardness Characterization

The specimens were prepared and tested for macro- and microhardness after directional/isotropic solidification under the stated growth conditions. Microhardness was evaluated by the Vickers method. For the variable-load experiment, the indentation time was held at 20 s. For the indentation-time experiment, the applied load was held at 20 g. The tabulated values are averages of the measured parameters.

The Vickers microhardness relation in the form $H_v = 1854.4\ L/d^2$, with the diagonal-length quantity defined according to the instrument calibration. L is the applied load and d is the measured indentation

diagonal in the corresponding calibrated units. The tabulated hardness values are therefore retained as reported rather than recalculated from rounded OCR-visible intermediate values.

The macrohardness-related properties and the microhardness data exhibit the same broad velocity dependence: strength rises from the slow-growth region, reaches a maximum around the moderate-growth region, and then declines during fast growth. The agreement between macroscopic strength measures and Vickers microhardness supports the interpretation that the mechanical response is closely related to the solidification-generated fibrous morphology. The moderate-growth region is associated with a comparatively complete, aligned and well-attached fibrillar structure, whereas excessive growth velocity is associated with increased kinetic undercooling and morphological disruption.

2.4 Integrated macro- and microhardness interpretation

The compressive strength increases with growth velocity up to the moderate-growth region and then decreases at higher velocities. For Sn–Bi–Cd, the maximum reported compressive strength is 66.30 at V = 3.10×10^{-7} m s^{-1}.

The tensile strength increases with growth velocity up to the moderate-growth region and then decreases at higher velocities. For Sn–Bi–Cd, the maximum reported tensile strength is 63.90 at V = 3.10×10^{-7} m s^{-1}.

The modulus of rupture increases with growth velocity up to the moderate-growth region and then decreases at higher velocities. For Sn–Bi–Cd, the maximum reported modulus of rupture is 52.10 at V = 3.10×10^{-7} m s^{-1}.

3. Results and Discussion

3.1 Macrohardness and Mechanical Strength

As shown in Figure 2 and Table 1, the mechanical strength of the Sn–Bi–Cd eutectic composite varies strongly with growth velocity. At 3.10×10^{-7} m s^{-1}, the modulus of rupture reaches 52.10×10^5 N m^{-2}, tensile strength reaches 63.90×10^4 N m^{-2}, and compressive strength reaches 66.30×10^4 N m^{-2}, compared to 17.30×10^5 N m^{-2}, 21.10×10^4 N m^{-2}, and 21.80×10^4 N m^{-2} for instantaneous solidification.

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

Growth velocity, V ($\times 10^{-7}$ m s^{-1})	Modulus of rupture ($\times 10^5$ Nm^{-2})	Tensile strength ($\times 10^4$ Nm^{-2})	Compressive strength ($\times 10^4$ Nm^{-2})
0.0	17.30	21.10	21.80
0.50	17.60	21.70	22.30
0.80	21.70	27.20	31.00
1.20	31.60	41.00	45.70
1.50	38.20	50.20	52.90
1.70	41.70	53.50	56.20
2.10	46.20	58.70	56.20
2.50	50.00	62.10	60.80

2.80	51.00	63.00	65.00
2.95	51.50	63.30	65.00
3.10	52.10	63.90	66.30
3.50	51.70	63.00	65.50
3.80	50.20	62.70	64.70
4.20	47.80	61.10	63.10
4.60	45.20	58.20	61.00
5.50	35.90	50.20	51.90
6.50	23.70	38.10	39.50
7.00	18.00	31.30	33.40
7.50	12.30	24.70	26.70

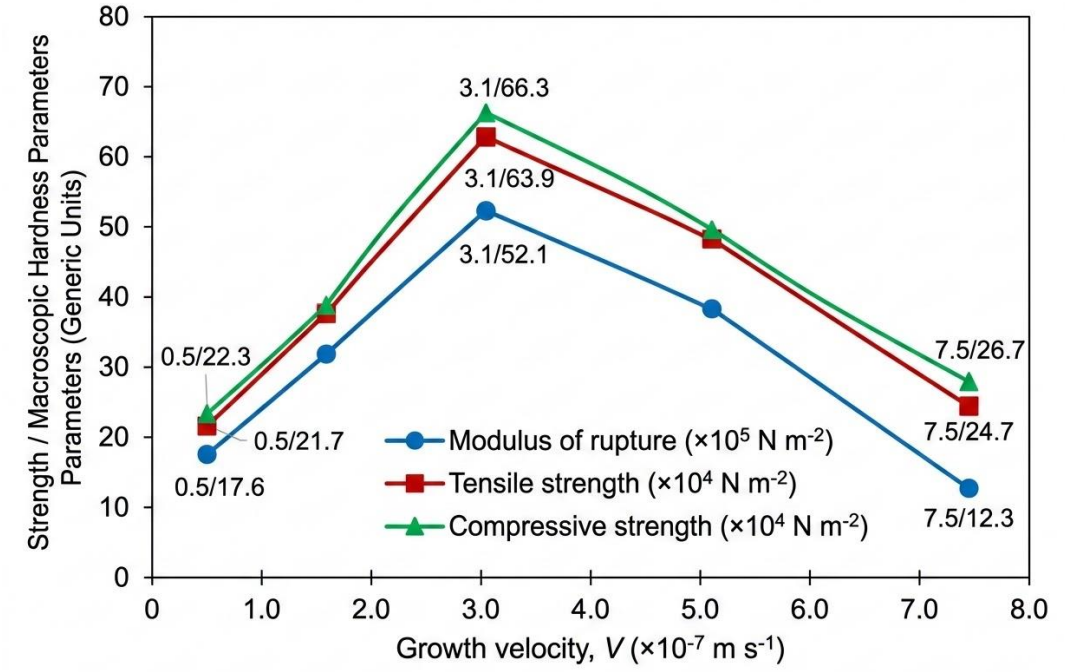


Figure 2. Variation of modulus of rupture, tensile strength, and compressive strength of the Sn–Bi–Cd eutectic composite with directional growth velocity.

3.2 Vickers Microhardness Analysis

As presented in Figure 3 and Table 2, microhardness rises from 16.40 kg mm^{-2} at 0.50 × 10^{-7} m s^{-1} to 35.30 kg mm^{-2} at 3.10 × 10^{-7} m s^{-1}, before declining to 17.10 kg mm^{-2} at 7.50 × 10^{-7} m s^{-1}. The trend exhibits a clear parabolic character with an optimum in the moderate growth region. Thus, the velocity dependence is distinctly non-monotonic and has the broad maximum expected for the moderate growth region. The manuscript associates this region with reduced kinetic undercooling, long non-aggressive fibres and a parallel, attaching fibrillar microstructure. Such a structure provides a plausible microstructural basis for the enhanced hardness observed near the optimum growth region.

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

V (×10⁻⁷ m s⁻¹)	H_v (kg mm⁻²)
0.50	16.40
0.80	18.20
1.20	23.50
1.50	27.00
1.70	29.20
2.10	30.70
2.50	31.20
2.80	34.80
3.10	35.30
3.50	34.60
3.80	32.80
4.20	31.70
4.60	29.50
5.50	26.90
6.50	24.20
7.00	22.30
7.50	17.10

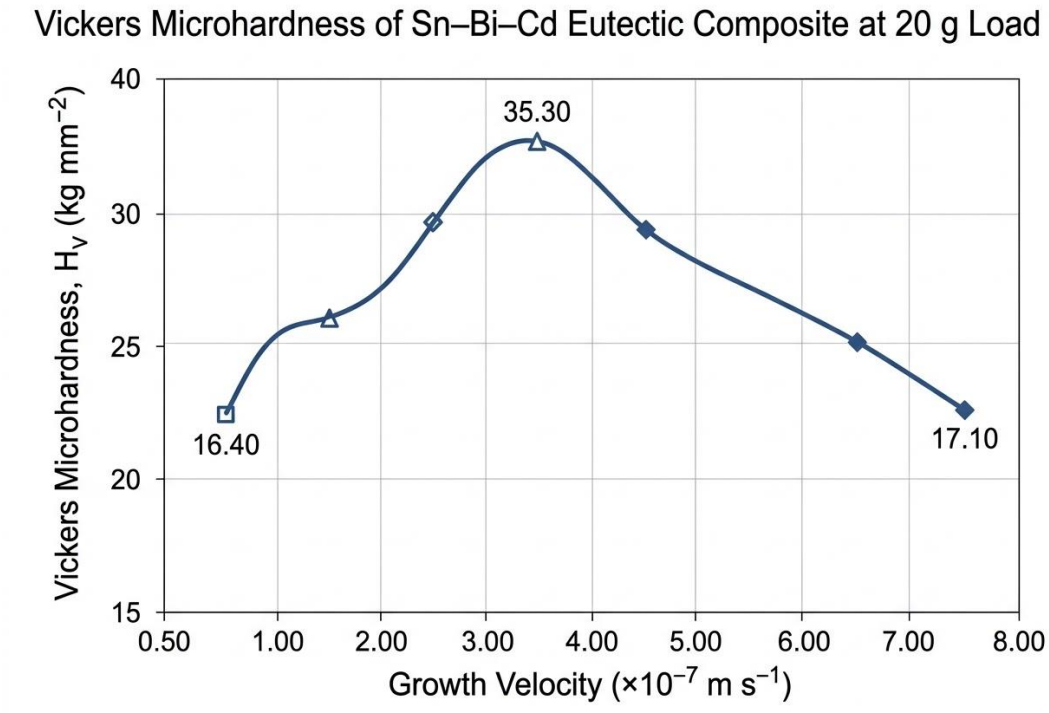


Figure 3. Vickers microhardness of the Sn–Bi–Cd eutectic composite as a function of growth velocity at an applied load of 20 g.

3.3 Indentation time Analysis

At a constant 20 g load, the measured hardness values vary only from 34.40 to 34.80 kg mm^{-2}. The mean is 34.61 kg mm^{-2} with a standard deviation of 0.12 kg mm^{-2}. This small variation supports the statement that, at normal temperature, the microhardness of the fibrous eutectic crystallites remains approximately constant over the investigated indentation-time range. The result indicates that the reported hardness is not strongly time-dependent under these test conditions.

Table 3. Variation of microhardness with indentation time at constant applied load L = 20 g for Sn–Bi–Cd.

Time (s)	Microhardness (Hv)
20.00	34.60
30.00	34.70
40.00	34.60
50.00	34.80
60.00	34.40
70.00	34.50
80.00	34.60
90.00	34.50
100.00	34.70
120.00	34.50
140.00	34.80
150.00	34.60

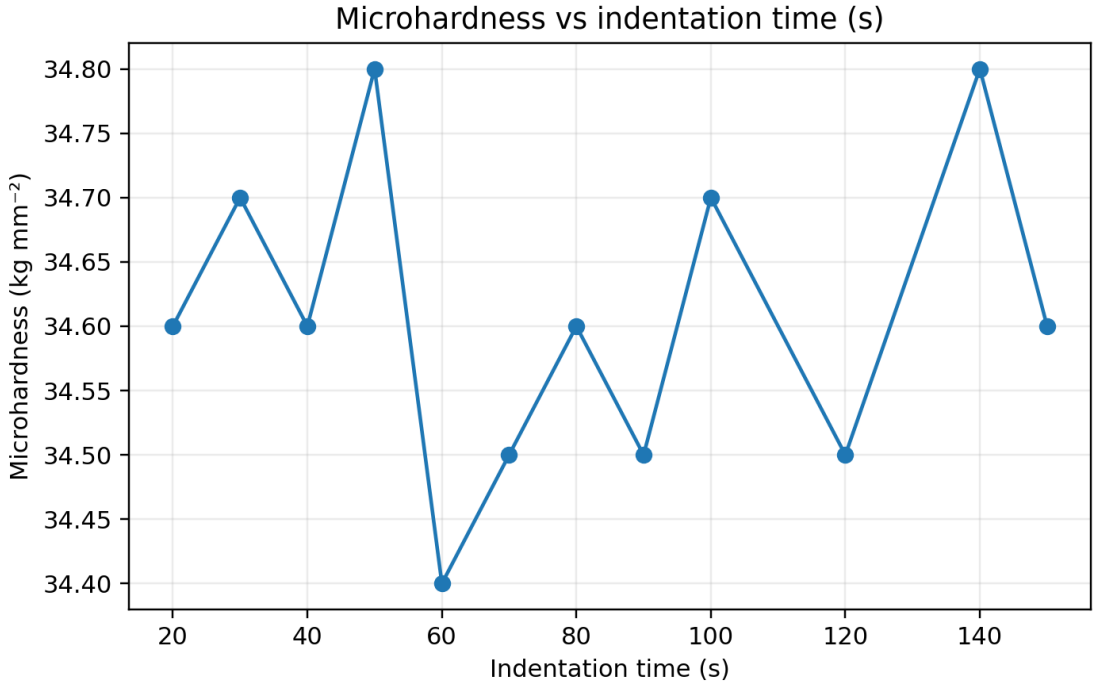


Figure 4. Microhardness as a function of indentation time at L = 20 g.

3.4 Applied load Analysis

At t = 20 s, hardness decreases from 36.50 kg mm^{-2} at 10 g to 16.70 kg mm^{-2} at 100 g. The decrease is steep at low-to-intermediate loads and becomes much smaller at higher loads. This is consistent with the indentation-size/depth explanation at small loads the indenter samples surface layers more strongly, while increasing penetration makes the response of deeper material increasingly important, producing an apparent approach to load-independent hardness. The manuscript describes the behaviour as tending toward saturation at about 70 g and above.

Table 4. Variation of microhardness with applied load at constant indentation time t = 20 s for Sn–Bi–Cd.

Load (g)	Microhardness (Hv)
10.00	36.50
20.00	34.70
30.00	30.30
40.00	25.80
50.00	24.20
60.00	19.80
70.00	17.40
80.00	17.20
90.00	16.80
100.00	16.70

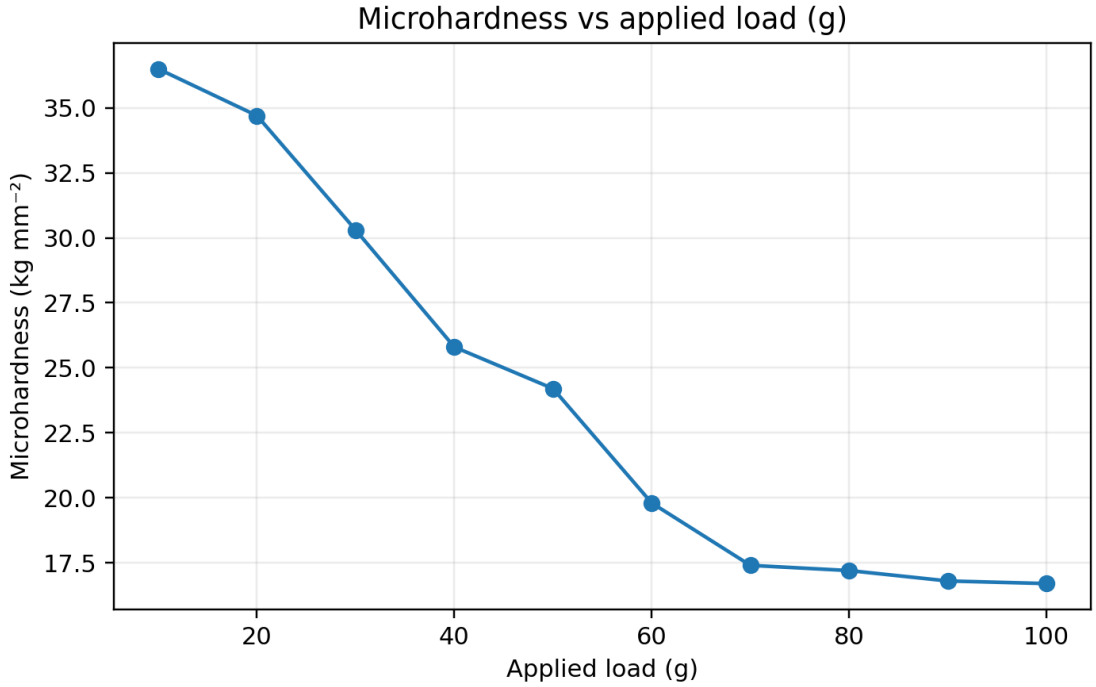


Figure 5. Microhardness as a function of applied load at t = 20 s.

3.5 Relationship to Eutectic Morphology

The growth-velocity dependence can be interpreted in terms of the morphology of the eutectic phases. The paper identifies a complex regular morphology for Sn–Bi–Cd. The observation is related to the growth characteristics of the constituent phases, particularly the faceted growth behaviour of bismuth. At large kinetic undercooling, short lamellae may become aggressive, disconnected and crossing, producing distorted microstructures. In contrast, moderate anisotropic growth reduces the kinetic undercooling and favours long, attaching, nearly parallel fibres, giving a more complete fibrillar structure.

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–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 region into the moderate-growth region 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.

4. Conclusions

1. The Sn–Bi–Cd eutectic composite exhibits a pronounced dependence of mechanical strength and microhardness on anisotropic growth velocity.
2. The optimum response occurs in the moderate-growth region, close to 3×10^{-7} m s^{-1}.
3. Moderate anisotropic growth produces substantially higher strength than instantaneous solidification.
4. Microhardness follows the same non-linear growth-velocity dependence as the macroscopic strength parameters.
5. At a constant 20 g load, microhardness is nearly independent of indentation time over the investigated interval, whereas increasing applied load lowers the measured Vickers hardness.
6. The results support the thesis interpretation that aligned fibrillar eutectic microstructures are responsible for the enhanced mechanical response.

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