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Mechanical Response of the Sn–Bi Binary Eutectic Composite under Controlled Solidification

Rajesh Kant

Associate Professor, Higher Education Department, Government of J&K

Abstract

The mechanical response of the Sn–Bi binary eutectic composite (58 wt% Sn – 42 wt% Bi) was systematically investigated as a function of solidification mode and growth velocity. Differential scanning calorimetry (DSC) confirmed a eutectic melting temperature of 408.2 K. Anisotropic directional growth specimens were prepared under controlled cooling, alongside rapidly solidified specimens prepared by ice-bath quenching near 273 K. Macrohardness was evaluated through modulus of rupture, tensile strength, and compressive strength, while local microhardness was characterized using the Vickers indentation technique. Mechanical properties exhibited a non-monotonic dependence on growth velocity: strength and hardness increased from the slow-growth region to an optimal moderate-growth velocity near 3.1×10^{-7} m s^{-1}, followed by a decrease in the fast-growth region. At the optimal growth velocity of 3.1×10^{-7} m s^{-1}, the modulus of rupture, tensile strength, and compressive strength reached peak values of 60.2×10^{5} N m^{-2}, 72.6×10^{4} N m^{-2}, and 73.19×10^{4} N m^{-2}, respectively. Vickers microhardness at 20 g load increased from 16.2 kg mm^{-2} at 0.50×10^{-7} m s^{-1} to a peak of 39.8 kg mm^{-2} at 3.1×10^{-7} m s^{-1}. These results indicate that controlled directional growth yields an aligned eutectic morphology and mechanically reinforcing architecture that significantly enhances overall mechanical performance.

Keywords: Sn–Bi eutectic; directional solidification; growth velocity; macrohardness; Vickers microhardness; lamellar composite.

1. Introduction

Eutectic composites represent an important class of heterogeneous materials consisting of two or more solid phases co-crystallized from a liquid phase of eutectic composition. The overall mechanical performance of eutectic alloys is strongly governed by the spatial distribution, physical scale, phase morphology, and interfacial orientation of their constituent phases [4, 5]. Controlled directional solidification enables precise tailoring of microstructural scale through regulation of kinetic growth velocity.

Among binary metallic eutectic systems, the Sn–Bi system provides a critical framework for testing the relationship between growth kinetics, solidification morphology, and mechanical strength [1, 2]. In the Sn–Bi eutectic, complex regular morphology develops wherein the Sn phase grows without facets while the Bi phase exhibits partially irregular orientation behavior. This investigation systematically isolates the

Sn–Bi binary eutectic system (58 wt% Sn – 42 wt% Bi) under controlled solidification, providing detailed macrohardness and microhardness characterization across distinct kinetic growth regions.

2. Materials and Methods

2.1 Material Preparation and Thermal Characterization

High-purity tin (99.5% purity, LOBA, melting point ~504.5 K) and bismuth (99.5% purity, LOBA, melting point ~543 K) were used to prepare the binary eutectic alloy at a targeted composition of 58 wt% Sn and 42 wt% Bi. Chemical homogeneity was achieved using the heat-and-chill blending procedure. The eutectic melting temperature was determined to be 408.2 K via differential scanning calorimetry (DSC).

2.2 Solidification Procedures

Anisotropic directional growth specimens were prepared within thin glass tubes subjected to controlled external cooling, establishing steady-state directional solidification across growth velocities ranging from 0.50×10^{-7} m s^{-1} to 8.0×10^{-7} m s^{-1}. Instantaneous, non-directional specimens were produced by rapid quenching of molten alloy charges in an ice-water bath maintained near 273 K.

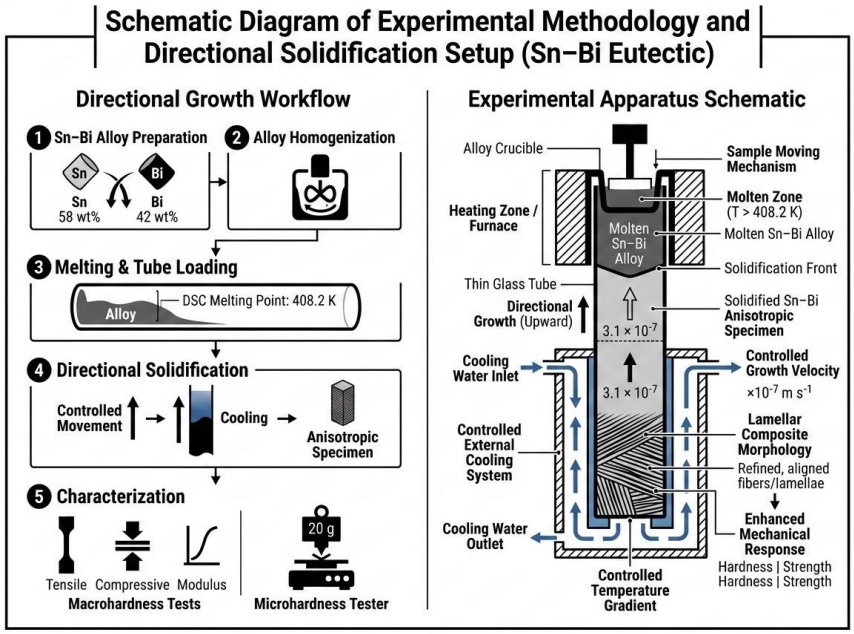

Figure 1. Schematic representation of the experimental methodology and directional solidification process.

2.3 Microstructure and growth morphology

The manuscript reports complex-regular morphology for Sn–Bi. The growth parameter is stated as less than two for Sn and greater than two for Bi, so Sn behaves as a non-faceted constituent while Bi develops faceted morphology. At moderate directional growth the phases form longer, attaching fibres/lamellae; at large kinetic undercooling, lamellae become shorter, disconnected and crossing. The chapter therefore links mechanical performance to the integrity and orientation of the eutectic microstructure.

2.4 Mechanical and microhardness measurements

Macrohardness-related measurements included modulus of rupture, tensile strength and compressive strength. Vickers microhardness was measured at approximately 300 K with an MHP-100 tester over 10–100 g. For the growth-velocity series, the indentation load was 20 g and dwell time 20 s. For the dwell-time series, the load was 20 g and time was varied from 20 to 150 s. For the load series, dwell time was 20 s and load was varied from 10 to 100 g.

3. Results and Discussion

3.1 Macrohardness-related response

Quantity	Anisotropic growth	Instantaneous growth	Sn phase, anisotropic	Sn phase, instantaneous	Bi phase, anisotropic	Bi phase, instantaneous
Span, ×10−2 m	8.5	8.5	8.5	8.5	8.5	8.5
Diameter, ×10−2 m	1.62	1.6	1.5	1.52	1.53	1.51
Load for rupture, kgf	20.1	4.6	2.2	1.7	2.8	1.8
Modulus of rupture, ×10^5 N m−2	60.2	14.4	8.4	6.1	9.9	6.7
Crystal radius, ×10−2 m	0.63	0.62	0.62	0.6	0.61	0.63
Tensile load, kgf	79.4	20.3	12.2	9.9	12.1	9.6
Tensile strength, ×10^4 N m−2	72.6	16.8	10.1	8.8	10.3	8.2
Crystal radius, ×10−2 m	0.61	0.6	0.61	0.6	0.6	0.62
Compression load, kgf	85.6	19.8	13.2	10.7	13.2	8.9
Compressive strength, ×10^4 N m−2	73.2	17.5	11.3	9.4	11.7	7.4

Table 1. Sn–Bi macrohardness-related data values are reported averages.

3.2 Macrohardness and Mechanical Strength

The measured macrohardness and mechanical strength parameters for the Sn–Bi eutectic composite across various directional growth velocities are summarized in Table 2.

Growth velocity (×10^{-7} m s^{-1})	Modulus of rupture (×10^5 N m^{-2})	Tensile strength (×10^4 N m^{-2})	Compressive strength (×10^4 N m^{-2})
0.5	14.6	17.2	17.5
0.8	22.1	21.6	24.5
1.2	32.4	35.5	40.7

1.5	37.5	47.8	57.1
1.7	43.3	57.5	62.8
2.1	50.2	66.0	68.2
2.5	57.3	69.1	71.0
2.8	59.0	71.5	72.7
3.1	60.2	72.6	73.19
3.5	59.9	72.5	73.2
3.8	59.0	71.5	72.0
4.2	57.0	69.5	70.8
4.6	53.4	66.5	67.7
5.5	44.5	57.5	59.3
6.5	33.5	42.3	45.7
7.0	27.0	33.2	37.3
7.5	20.1	25.0	28.0
8.0	12.3	15.6	19.4

Table 2. Macrohardness and mechanical strength parameters of the Sn–Bi eutectic composite as a function of growth velocity.

As shown in Table 2 and Figure 2, the mechanical strength exhibits three distinct kinetic growth regions:

1. **Slow-growth region (< 1.5 × 10^{-7} m s^{-1}):** Mechanical strength increases progressively with growth velocity as interphase spacing decreases.
2. **Moderate-growth region (1.5 × 10^{-7} m s^{-1} to 3.5 × 10^{-7} m s^{-1}):** Peak mechanical properties are attained, reaching an optimum near 3.1 × 10^{-7} m s^{-1} with a modulus of rupture of 60.2 × 10^{5} N m^{-2}, tensile strength of 72.6 × 10^{4} N m^{-2}, and compressive strength of 73.19 × 10^{4} N m^{-2}.
3. **Fast-growth region (> 3.5 × 10^{-7} m s^{-1}):** Mechanical strength decreases sharply at higher growth velocities, declining to 12.3 × 10^{5} N m^{-2} (modulus of rupture), 15.6 × 10^{4} N m^{-2} (tensile strength), and 19.4 × 10^{4} N m^{-2} (compressive strength) at 8.0 × 10^{-7} m s^{-1}.

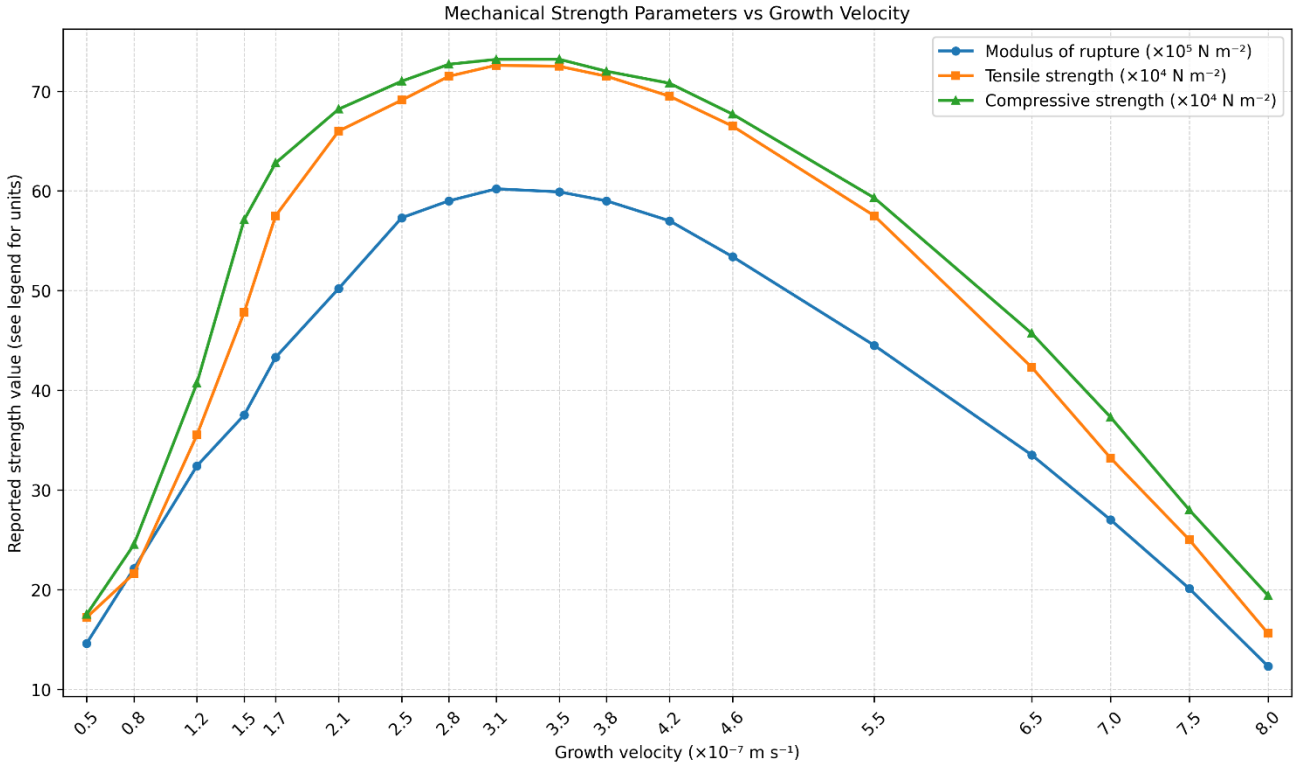

Figure 2. Variation of modulus of rupture, tensile strength, and compressive strength of the Sn–Bi eutectic composite with directional growth velocity.

3.3 Microhardness versus growth velocity

v (×10⁻⁷ m s⁻¹)	H_V (kg mm⁻²)
0.5	16.2
0.8	21.7
1.2	25.3
1.5	28.8
1.7	32.3
2.1	34.7
2.5	36.2
2.8	38.1
2.95	39.8
3.1	37.9
3.5	36.2
3.8	33.8
4.2	32.3
4.6	28.7
5.5	25.9
6.5	22.4
7.0	16.0

Table 3. Sn–Bi Vickers microhardness versus growth velocity at 20 g load and 20 s indentation time

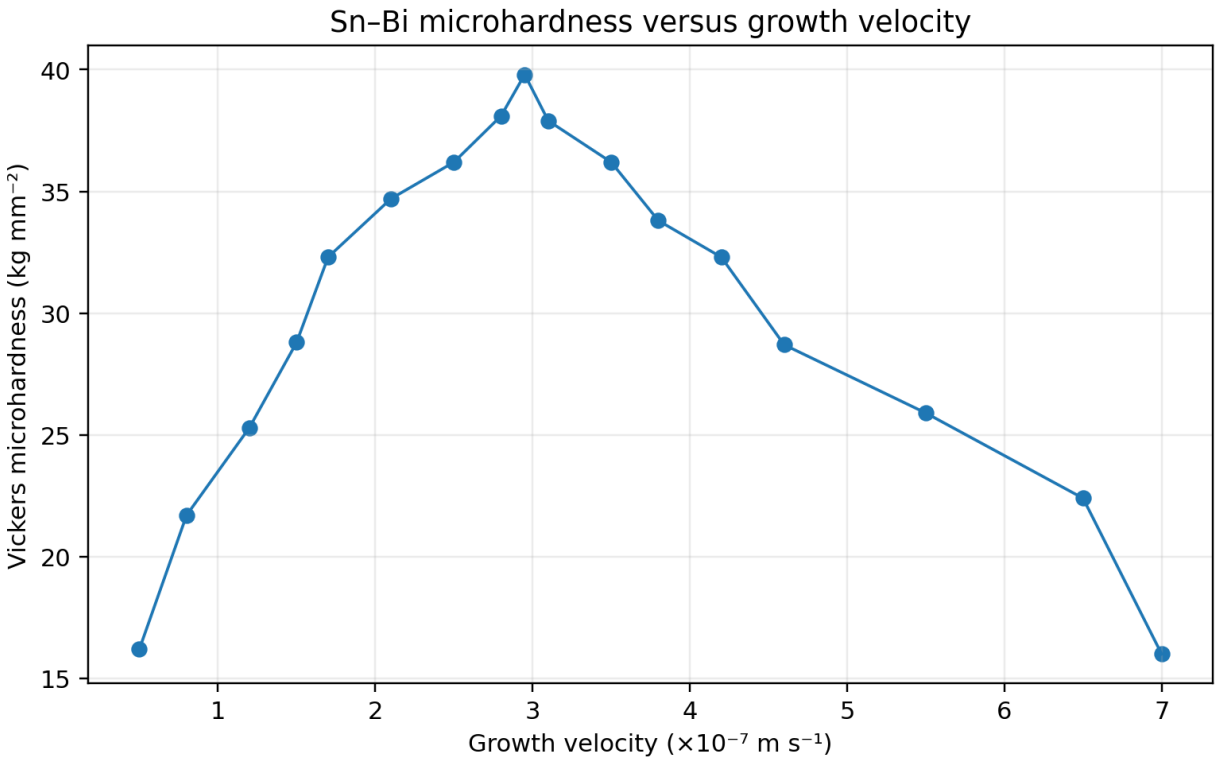

Figure 3. Sn–Bi microhardness as a function of anisotropic growth velocity.

Microhardness increases from 16.2 kg mm^{-2} at 0.50×10^{-7} m s^{-1} to 39.8 kg mm^{-2} at 3.10×10^{-7} m s^{-1}. It then decreases through 37.9, 36.2, 33.8, 32.3, 28.7, 25.9 and 22.4 kg mm^{-2} as the velocity reaches 7.00×10^{-7} m s^{-1}, before reaching 16.0 kg mm^{-2} at 7.50×10^{-7} m s^{-1}. The maximum therefore occurs in the same moderate-growth region.

3.4 Effect of indentation dwell time

Dwell time (s)	H_V (kg mm⁻²)
20	36.2
30	36.5
40	36.3
50	36.7
60	36.3
70	36.4
80	36.2
90	36.1
100	36.5
120	36.6
140	36.1
150	36.2

Table 4. Sn–Bi Vickers microhardness at 20 g load as a function of indentation time

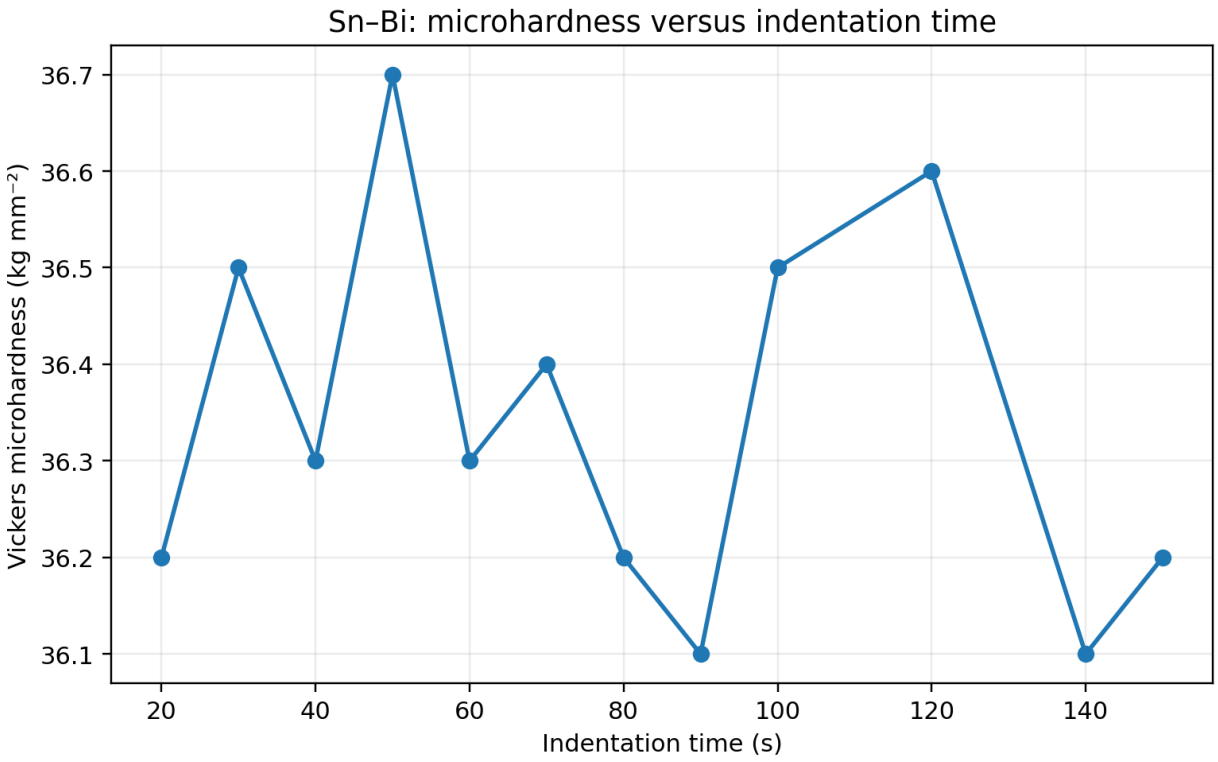

Figure 4. Sn–Bi microhardness versus dwell time at 20 g applied load.

The hardness remains within 36.1–36.7 kg mm^{-2} across 20–150 s. The absence of a systematic increase or decrease is consistent with the thesis statement that the Vickers microhardness remains approximately uniform with indentation time at constant load at room temperature.

3.5 Effect of applied indentation load

Applied load (g)	H_V (kg mm^{-2})
10	40.3
20	36.1
30	30.2
40	27.8
50	23.7
60	20.0
70	18.7
80	16.9
90	16.7
100	16.2

Table 5. Sn–Bi Vickers microhardness versus applied indentation load.

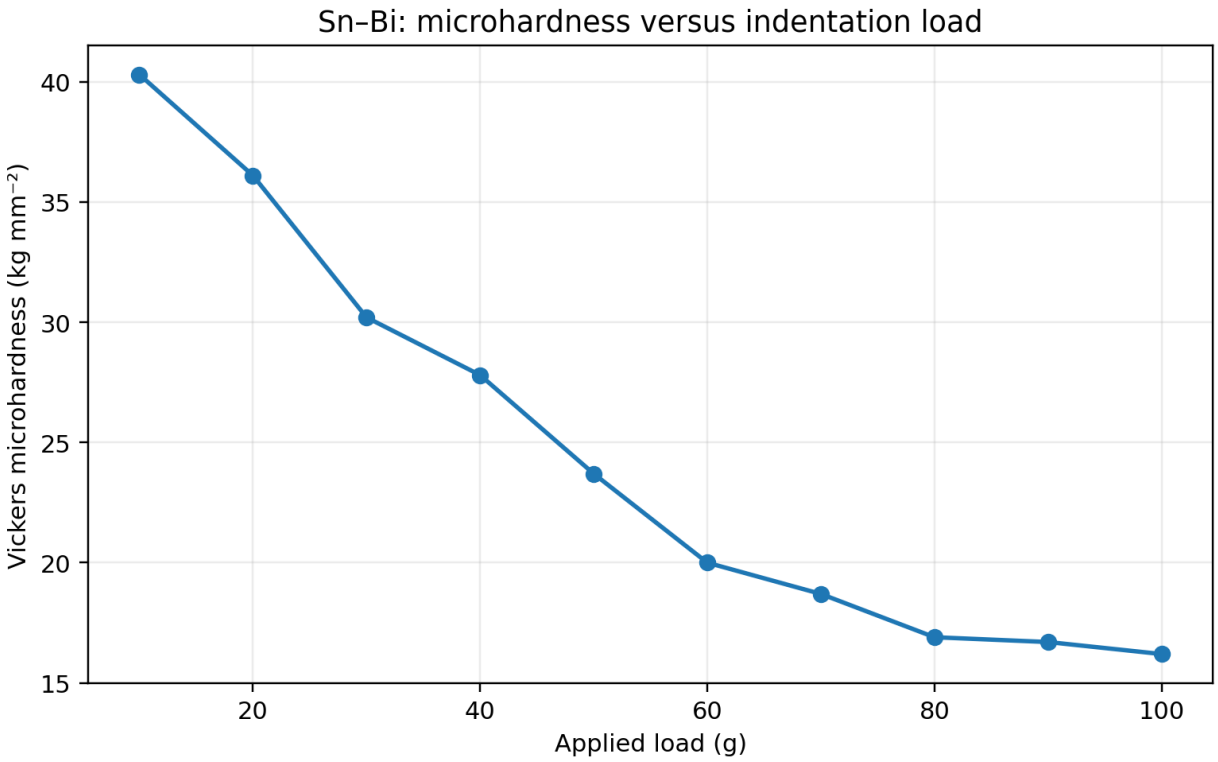

Figure 5. Sn–Bi microhardness versus applied Vickers load.

Hardness falls from 40.3 kg mm^{-2} at 10 g to 18.7 kg mm^{-2} at 70 g and subsequently decreases only gradually to 16.2 kg mm^{-2} at 100 g. The manuscript interprets the flattening at higher load as the consequence of deeper penetration and greater involvement of the underlying material.

4. Discussion

The most pronounced systematic effect is that of solidification velocity. The peak Sn–Bi microhardness of 39.8 kg mm^{-2} at 3.10×10^{-7} m s^{-1} occurs close to the maximum in the macrohardness-related curves. This agreement is important because the two measurement scales are mechanically different: the macro tests sample the bulk composite, whereas the Vickers test samples a localized region. Their shared maximum therefore supports the thesis interpretation that the microstructure generated in the moderate-growth regime is genuinely stronger rather than being only a measurement artefact.

The load effect is qualitatively different. Increasing load decreases the measured Vickers number because the indentation geometry and the sampled material volume change. At low loads the imprint is confined more strongly to near-surface material, while at larger loads the plastic zone penetrates deeper and interacts with more of the eutectic structure. The manuscript observations of indentations at 20, 50, 70 and 100 g are consistent with this interpretation.

The near-constant dwell-time response is also physically informative. Within the tested 20–150 s range, no monotonic creep-like drift is resolved by the conventional Vickers measurement at 20 g. This does not imply that Sn–Bi has no time-dependent deformation under all conditions; nanoindentation studies

of eutectic Sn–Bi demonstrate strain-rate-dependent creep behaviour. It means only that the thesis's conventional Vickers protocol did not produce a substantial systematic dwell-time dependence over this interval.

The manuscript describes the moderate-growth structure as a fibrous/lamellar composite in which the phases are comparatively long, attaching and aligned. Such morphology improves load transfer between phases. By contrast, rapid cooling creates short and distorted lamellae. Modern Sn–Bi literature likewise emphasizes the role of eutectic morphology and phase distribution in determining hardness and deformation behaviour, although the compositions and test conditions in those studies are not identical to the present manuscript experiment.

5. Conclusions

- The manuscript investigated a Sn–Bi eutectic reported as 58 wt% Sn–42 wt% Bi, with a DSC melting temperature of 408.2 K.
- Sn–Bi exhibits complex-regular morphology in the thesis interpretation, arising from non-faceted Sn and faceted Bi growth.
- At 20 g and 20 s, Vickers microhardness increases from 16.2 kg mm^{-2} at 0.50×10^{-7} m s^{-1} to 39.8 kg mm^{-2} at 3.10×10^{-7} m s^{-1}, then decreases at higher growth velocities.
- At 20 g load, changing dwell time from 20 to 150 s changes hardness only slightly, within 36.1–36.7 kg mm^{-2}.
- Increasing indentation load from 10 to 100 g decreases the Vickers number from 40.3 to 16.2 kg mm^{-2}, with the decrease becoming less steep at higher loads.
- The correspondence between the microhardness maximum and the moderate-growth region in the macrohardness-related properties supports a strong structure–property relationship controlled by directional solidification.

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