

Growth-Dependent Macrohardness and Microhardness of the Pb–Cd Binary Eutectic Composite

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Abstract- The mechanical response of the Pb–Cd binary eutectic composite (36 wt% Pb – 64 wt% Cd) was systematically investigated as a function of solidification mode and growth velocity. Differential scanning calorimetry (DSC) confirmed a eutectic melting temperature of 513.2 K. Rod-like eutectic specimens were prepared via anisotropic directional growth, alongside rapidly solidified samples prepared by ice-bath quenching. 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 pronounced non-monotonic dependence on growth velocity: strength and hardness increased from the slow-growth region to an optimal moderate-growth velocity near $3.19 \times 10^{-7} \text{ m s}^{-1}$, followed by a marked decrease in the fast-growth region. At the optimal growth velocity, the modulus of rupture, tensile strength, and compressive strength reached maximum values of $60.5 \times 10^5 \text{ N m}^{-2}$, $66.22 \times 10^4 \text{ N m}^{-2}$, and $72.2 \times 10^4 \text{ N m}^{-2}$, respectively. Vickers microhardness at 20 g load increased from 18.2 kg mm^{-2} at $0.50 \times 10^{-7} \text{ m s}^{-1}$ to a peak of 38.6 kg mm^{-2} at $3.10 \times 10^{-7} \text{ m s}^{-1}$. These results demonstrate that the directional alignment and refined scale of the fibrillar/lamellar microstructures developed during moderate-velocity growth yield optimal mechanical performance.

Keywords— Pb–Cd eutectic; directional solidification; growth velocity; macrohardness; Vickers microhardness; fibrillar microstructure.

I. 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 [3, 5]. Controlled directional solidification enables precise tailoring of microstructural scale through regulation of kinetic growth velocity.

This study isolates the experimental findings for the binary Pb–Cd eutectic system to examine the fundamental relationships linking growth kinetics, microstructural organization, and resulting mechanical properties across macro- and micro-scale stress regions.

II. MATERIALS AND METHODS

1. Material Preparation and Thermal Characterization

High-purity lead (AR grade, BDH, melting point ~600 K) and cadmium (99.5% purity, LOBA, melting point ~593.5 K) were used to prepare the binary eutectic alloy at a targeted composition of 36 wt% Pb and 64 wt% Cd. Chemical homogeneity was achieved using the heat-and-chill blending method. The eutectic melting temperature was determined to be 513.2 K via differential scanning calorimetry (DSC, Shimadzu DTG/DSC-60).

2. Directional Solidification and Quenching Procedures

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 ~ 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.

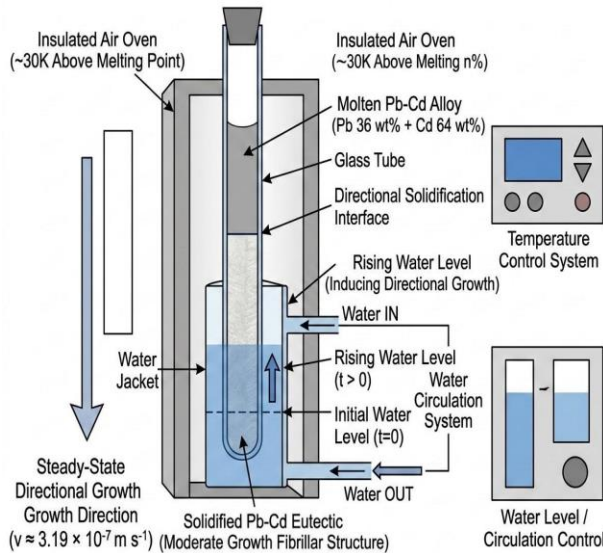


Figure 1. Schematic representation of the experimental directional solidification apparatus and directional growth workflow.

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

The measured macrohardness and mechanical strength parameters for the Pb–Cd eutectic composite across various growth velocities are summarized in Table 1.

Table 1. Macrohardness and mechanical strength parameters of the Pb–Cd eutectic composite as a function of growth velocity.

Growth velocity ($\times 10^{-7} \text{ m s}^{-1}$)	Modulus of rupture ($\times 10^5 \text{ N m}^{-2}$)	Tensile strength ($\times 10^4 \text{ N m}^{-2}$)	Compressive strength ($\times 10^4 \text{ N m}^{-2}$)
0.50	16.8	17.1	17.3
0.80	21.4	26.8	34.7
1.20	27.1	37.5	48.2
1.50	31.1	44.6	56.7
1.70	40.2	49.5	60.8
2.10	47.8	56.7	64.0
2.50	55.3	61.2	69.3
2.80	59.6	64.5	71.5
3.10	60.2	65.3	72.0
3.19	60.5	66.22	72.2
3.50	60.3	66.2	72.0
4.20	59.5	62.8	69.8
5.50	47.4	53.8	60.3
6.50	34.6	42.2	47.8
8.00	8.4	15.7	24.2

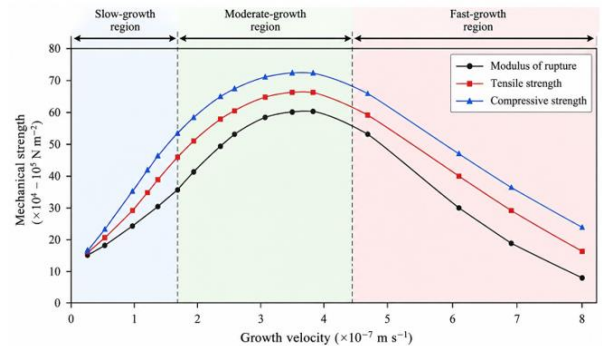


Figure 2. Variation of modulus of rupture, tensile strength, and compressive strength of the Pb–Cd eutectic composite with directional growth velocity.

The mechanical properties are illustrated in Figure 2 and Table 1 with three different kinetic regions:

- Slow-growth region ($< 1.5 \times 10^{-7} \text{ m s}^{-1}$): Mechanical strength grows steadily with growth velocity, as interphase spacing decreases.
- Moderate-growth region ($1.5 \times 10^{-7} \text{ m s}^{-1}$ to $4.5 \times 10^{-7} \text{ m s}^{-1}$): The maximum mechanical properties were obtained with an optimum at $3.19 \times 10^{-7} \text{ m s}^{-1}$ giving the modulus of rupture of $60.5 \times 10^5 \text{ N m}^{-2}$, tensile strength of $66.22 \times 10^4 \text{ N m}^{-2}$ and compressive strength of $72.2 \times 10^4 \text{ N m}^{-2}$.

- Fast-growth region ($> 4.5 \times 10^{-7} \text{ m s}^{-1}$): Mechanical strength decreases rapidly, to $8.4 \times 10^5 \text{ N m}^{-2}$ (modulus of rupture), $15.7 \times 10^4 \text{ N m}^{-2}$ (tensile strength) and $24.2 \times 10^4 \text{ N m}^{-2}$ (compressive strength) at $8.0 \times 10^{-7} \text{ m s}^{-1}$.

2. Vickers Microhardness Analysis

The variation in Vickers microhardness under a constant 20 g load and 20 s dwell time across different growth velocities is provided in Table 2.

Table 2. Vickers microhardness of the Pb–Cd eutectic composite at 20 g load and 20 s dwell time for various growth velocities.

Growth velocity ($\times 10^{-7} \text{ m s}^{-1}$)	Vickers microhardness at 20 g (kg mm^{-2})
0.50	18.2
0.80	20.0
1.20	25.5
1.50	28.0
1.70	31.1
2.40	33.7
2.50	37.0
2.80	37.2
3.10	38.6
3.50	38.0
3.80	38.5
4.20	36.6
4.60	34.7
5.50	29.5
6.50	22.1
7.00	19.8
7.50	17.6

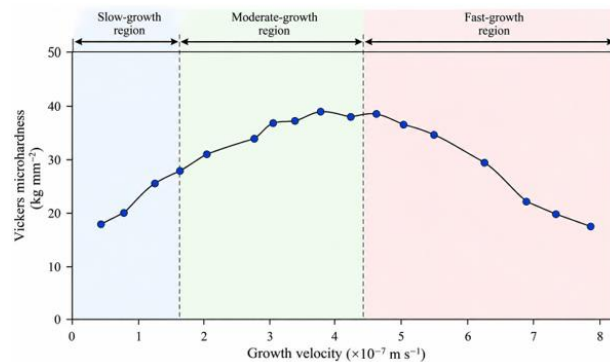


Figure 3. Vickers microhardness of the Pb–Cd binary eutectic composite as a function of growth velocity at an applied load of 20 g.

Microhardness follows a trend closely aligned with macrohardness (Figure 3), increasing from 18.2 kg mm^{-2} at $0.50 \times 10^{-7} \text{ m s}^{-1}$ to a maximum of 38.6 kg mm^{-2} at $3.10 \times 10^{-7} \text{ m s}^{-1}$, before decreasing at higher growth rates.

3. Microstructural Mechanisms and Solidification Kinetics

The enhanced strength and hardness observed in the moderate-growth region are associated with the formation of well-aligned, continuous fibrillar and lamellar structures exhibiting strong interfacial fiber–matrix bonding and low defect density [1, 4, 7, 8]. Under extreme kinetic undercooling at elevated growth velocities, lamellar continuity is disrupted, producing shortened, highly intersected, and fragmented structures that act as stress concentration sites and lead to microstructural degradation [6].

IV. CONCLUSIONS

- The binary Pb–Cd eutectic alloy (36 wt% Pb, 64 wt% Cd) exhibits a eutectic melting temperature of 513.2 K.
- Solidification mode and growth velocity strongly dictate macroscale strength and microscale hardness.
- Optimal mechanical performance occurs in a moderate growth velocity region centered near 3.1×10^{-7} to $3.19 \times 10^{-7} \text{ m s}^{-1}$.
- Maximum modulus of rupture ($60.5 \times 10^5 \text{ N m}^{-2}$), tensile strength ($66.22 \times 10^4 \text{ N m}^{-2}$), and compressive strength ($72.2 \times 10^4 \text{ N m}^{-2}$) coincide with peak Vickers microhardness (38.6 kg mm^{-2} at 20 g load).
- Microstructural transition from directional fibrillar/lamellar alignment to fragmented structures governs the mechanical property degradation in the fast-growth region.

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