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The effect of growth velocity and temperature gradient on growth characteristics of matrix eutectic in a hypereutectic aluminium–silicon alloy

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The growth undercooling ΔT and eutectic interlamellar spacing λ have been measured as functions of growth velocity V and temperature gradient G for matrix Al–Si eutectic in the presence of primary silicon in Bridgman-grown hypereutectic Al–18.3 wt% Si alloy. $\Delta T/V^{1/2}$ shows a step decrease at $V > 270\ \mu m\,s^{-1}$ corresponding to a change in eutectic growth morphology from flake-like to fibrous, but there was no corresponding change in $\lambda V^{1/2}$. Analysis of published data on the effect of G on $\lambda V^{1/2}$ for the Al–Si eutectic shows good agreement with the single relationship $\lambda V^{1/2} = A\,G^{-n}$ with $A = 56 \pm 8\ \mu m^{3/2}\,s^{-1/2}(K\,mm^{-1})^n$ and $n = 0.24 \pm 0.03$ for the range $0.1 < V < 6 \times 10^4\ \mu m\,s^{-1}$ and $0.7 < G < 2000\ K\,mm^{-1}$.

1. Introduction

Hypereutectic Al–Si alloys are becoming increasingly important as the basis both of wear resistant, low thermal expansion casting alloys for engine blocks and related applications [1, 2] and of high performance powder metallurgy or spray-formed components for automobile compressors and other machinery [3–9]. Earlier work at Sheffield established functional relationships between primary silicon spacing and solidification variables [10, 11], and defined the conditions for formation and segregation of primary silicon [12, 13], mainly for the representative Al–18.3 wt % Si composition. The present paper reports results on the effect of solidification front variables on growth morphology, growth undercooling and interphase spacing of the matrix eutectic in this same alloy, solidified directionally by the Bridgman technique.

2. Experimental Procedure

The preparation of the Al–18.3 wt % Si alloy from 99.999% pure Al and 99.9% pure Si, the experimental detail of the Bridgman equipment used and its operation were as described previously [10,14], with the single difference that a resistance tube furnace was used as the heat source for Bridgman growth rather than induction heating. The alloy was Bridgman solidified at growth velocities between 0.05 and 1.03 $mm\,s^{-1}$, the specimen being quenched into a water bath when the solidification front of the Al–Si eutectic matrix passed the position of the inserted thermocouple bead. Temperature gradients between liquidus and eutectic temperatures of 10, 25 and 37 $K\,mm^{-1}$, determined from the logged temperature-time curves, were achieved at melt superheats of 150, 230 and 300 K respectively.

Optical and scanning electron microscopy were carried out on ground and polished longitudinal sections of resulting specimens both with and without immersion in 3% HCl for 3 to 4 days to remove the αAl of the eutectic. Measurements of growth temperature of eutectic silicon were restricted to areas away from primary silicon crystals where the quenched eutectic interface was relatively flat.

3. Results

The results for growth temperature T_G, corresponding growth undercooling $\Delta T = T_{EU} - T_G$ and interphase spacing λ for different combinations of growth velocity V and temperature gradient G are given in Table I, together with derived values of $\Delta T/V^{1/2}$ and $\lambda V^{1/2}$. The values of ΔT increase with increasing V as expected with a step increase in T_G between V of 270 and 400 $\mu m\,s^{-1}$, which is reflected in a substantial decrease in ΔT and $\Delta T/V^{1/2}$. $\Delta T/V^{1/2}$ shows an increase from 1.21 to 1.95 $K\,s^{1/2}\,\mu m^{-1/2}$ from V of 60 to 270 $\mu m\,s^{-1}$ and from 0.34 $K\,s^{1/2}\,\mu m^{-1/2}$ at 400 $\mu m\,s^{-1}$ to 0.48 $K\,s^{1/2}\,\mu m^{-1/2}$ at 1030 $\mu m\,s^{-1}$, the mean values being 1.71 ± 0.31 and 0.42 ± 0.06 respectively for the two ranges of V. The values of λ decrease with increasing V, again as expected, but without the step change between 270 and 400 $\mu m\,s^{-1}$ found for ΔT. $\lambda V^{1/2}$ shows an increase from 30.2 to 44.9 $\mu m^{3/2}\,s^{-1/2}$ with increase of V from 60 to 1030 $\mu m\,s^{-1}$ for G of

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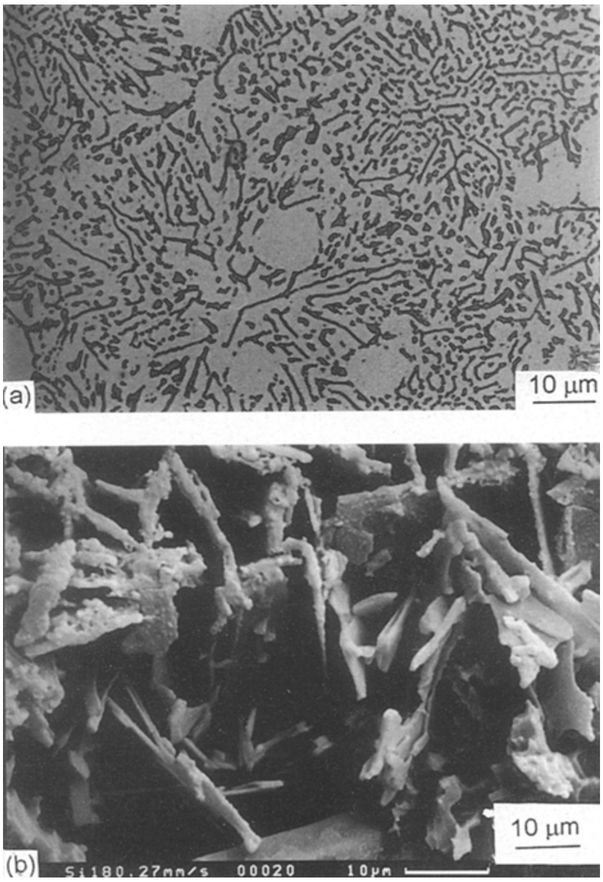

Figure 1 Basically flake-like morphology of eutectic silicon in Al–18.3 wt % Si Bridgman grown at 270 $\mu m s^{-1}$ and 10 $K mm^{-1}$. (a) Optical micrograph; (b) SEM micrograph of deeply etched surface.

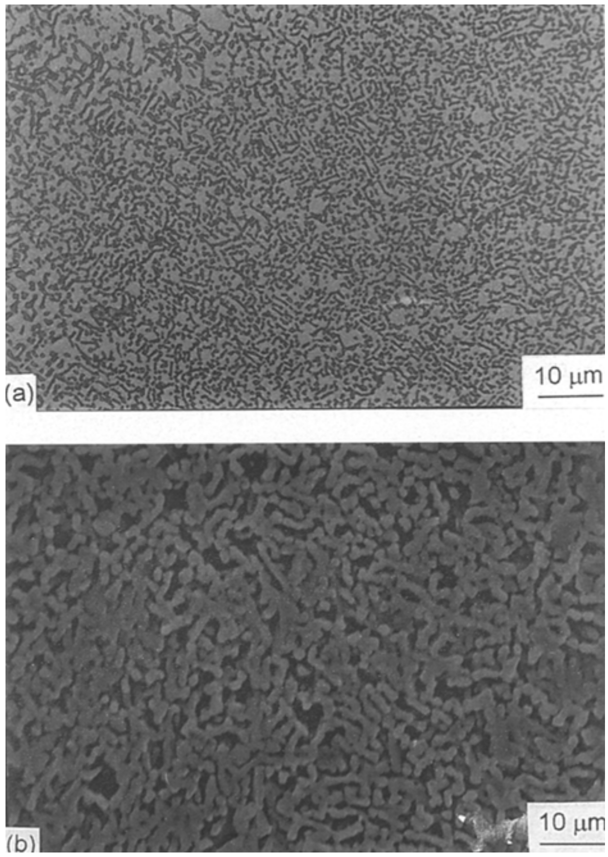

Figure 2 Fibrous morphology of eutectic silicon in Al–18.3 wt % Si Bridgman grown at 400 $\mu m s^{-1}$ and 10 $K mm^{-1}$. (a) Optical micrograph; (b) SEM micrographs of deeply etched surface.

10 $K mm^{-1}$ and there is a corresponding increase for G of 25 $K mm^{-1}$. The mean values of $\lambda V^{1/2}$ are 38.3 ± 5.5 and 32.6 ± 5.0 $\mu m^{3/2} s^{-1/2}$ for G of 10 and 25 $K mm^{-1}$ respectively, with a mean for the whole data set of 36.6 ± 6.1 $\mu m^{3/2} s^{-1/2}$. The sudden drop in $\Delta T/V^{1/2}$ between 270 and 400 $\mu m s^{-1}$ was associated with an observed change in eutectic growth morphology from basically flake-like at $V \leqslant 270$ $\mu m s^{-1}$ to fibrous at $V \geqslant 400$ $\mu m s^{-1}$ (compare Fig. 1(a, b) with Fig. 2(a, b).

4. Discussion

The results for T_G and ΔT in Table I appear to be the first to be published for Al–Si eutectic in the presence of primary silicon in a hypereutectic Al–Si alloy, although there have been previous measurements of eutectic λ for such a situation. The sharp reduction in $\Delta T/V^{1/2}$ associated with the flake to fibre transition of the eutectic silicon is in accord with the results of Khan [15] and Najafabadi [16] for eutectic Al–Si in the absence or presence of Sr modifier. This flake to fibre transition at high V has been associated [15–20] with increasing difficulty in sustaining the twin re-entrant growth mechanism of eutectic silicon at high V resulting in a change from faceted growth of flake to non-faceted growth of fibre with an associated reduction in growth undercooling.

The magnitudes of $\Delta T/V^{1/2}$ [15, 16, 21–30] and $\lambda V^{1/2}$ [15, 16, 23–30, 32–39] reported in the literature for Al–Si eutectic in the absence of modifying additions are given in Tables II and III respectively, along with predicted values [22, 25–27, 29, 30, 32] mainly for the extremum [31], for comparison with the present results. Table II indicates that the values of $\Delta T/V^{1/2}$ from the present work for both flake and fibrous Al–Si eutectic are higher than previous measurements. This effect does not seem to be associated with temperature gradient or range of V investigated and our measured $\Delta T/V^{1/2}$ exceeds extremum predictions by a factor of more than two even for the fibrous eutectic. One possibility is that the presence of primary silicon in our microstructures has, by some mechanism yet to be defined, depressed the growth temperature of the eutectic that follows its formation. If, for example, certain impurities that are present act to promote the growth of silicon, it is possible that these are so depleted from the melt by the growth of primary silicon that eutectic silicon requires a higher undercooling to sustain its growth.

The measurements of $\lambda V^{1/2}$ in Table I, in contrast to $\Delta T/V^{1/2}$, do not show a detectable step change between V of 270 and 400 $\mu m s^{-1}$ corresponding to the change of morphology from flake to fibrous. Atasoy [35] reported a step decrease in λ corresponding to the flake to fibre transition with increasing V, while Khan [15] reported a steeper decrease in λ with increase in V for fibre than flake. Najafabadi [16]

TABLE I Growth temperature T_G, interphase spacing λ and their derivatives, as a function of growth velocity V and temperature gradient G for Al–Si eutectic in Bridgman-grown Al–18.3 wt % Si containing primary silicon. Equilibrium eutectic temperature T_{EU} was taken as 577.2 °C [26]

V (μm s^{-1})	G (K mm^{-1})	T_G (°C)	$\Delta T = T_{EU} - T_G$ (K)	$\Delta T/V^{1/2}$ (Ks$^{1/2}$ μm$^{-1/2}$)	λ (μm)	$\lambda V^{1/2}$ μm$^{3/2}$ s$^{-1/2}$
60	10	567.7	9.5	1.23	3.9 ± 0.5	30.2
60	25	–	–	–	3.5 ± 0.4	27.1
81	10	563.3	13.9	1.54	3.4 ± 0.4	30.6
81	25	–	–	–	3.1 ± 0.3	27.9
103	10	559.8	17.4	1.71	3.3 ± 0.3	33.5
103	25	–	–	–	3.2 ± 0.4	32.5
120	25	554.3	22.9	2.09	3.2 ± 0.4	35.1
201	10	552.3	24.9	1.75	2.7 ± 0.2	38.3
201	25	–	–	–	2.3 ± 0.2	32.6
270	10	545.1	32.1	1.95	2.6 ± 0.3	42.7
400	10	570.3	6.9	0.35	2.0 ± 0.2	40.0
510	10	–	–	–	1.9 ± 0.1	42.9
510	25	–	–	–	1.8 ± 0.2	40.6
600	10	566.4	10.8	0.44	1.7 ± 0.2	41.6
710	37	565.7	11.5	0.43	1.7 ± 0.1	45.3
1030	10	561.7	15.5	0.48	1.4 ± 0.2	44.9

TABLE II Comparison of previously reported measurements of $\Delta T/V^{1/2}$ for Al–Si eutectic in the absence of modifying additions with values from the present work for flake and fibrous morphologies

Alloy concentration (wt % Si)	Range of V (μm s^{-1})	Range of G (K mm^{-1})	Measured[a] $\Delta T/V^{-1/2}$ (K s$^{1/2}$ μm$^{-1/2}$)	Reference
Flake morphology				
13 to 17	10 to 200	11 to 23	1.36 ± 0.18	Steen and Hellawell [21]
			[0.128]	Fisher and Kurz [22]
12.9	15 to 400	0.5 to 15	0.96 ± 0.17	Toloui and Hellawell [23]
12.7	10 to 165	0.8	0.92 ± 0.18	Elliott and Glenister [24]
12.6 ± 0.2	10 to 200	11	0.46 ± 0.03	Hogan and Song [25]
			[0.148, 0.136]*	
6	6.7 to 15.5	5	0.30 ± 0.06	Grugel and Kurz [26]
6 to 12.6	1.3 to 31.6	15	0.34 ± 0.13	
			[0.235]	
12.62	0.6 to 206	6.3 to 14.9	0.52 ± 0.12	Liu *et al.* [27]
			[0.565 ± 0.148][b]	
12.7, 14.6	28 to 505	7.6	0.39 ± 0.13	Khan [15]
		12.2	0.32 ± 0.08	Khan and Elliott [28]
12.6	2 to 500	8	0.29 ± 0.04	Magnin *et al.* [29, 30]
			[0.176, 0.215][b]	
12.7	40 to 408	8.2, 12.2	0.47 ± 0.07	Najafabadi [16]
18.3	60 to 270	10.25	1.71 ± 0.30	Present work
Fibrous morphology				
14.6	642 to 875	7.6, 12.2	0.16 ± 0.05	Khan [15]
12.7	521 to 870	8.2	0.18 ± 0.03	Najafabadi [16]
18.3	400 to 1030	10, 25, 37	0.43 ± 0.05	Present work

[a] Values in square brackets are predicted $\Delta T V^{-1/2}$ for the extremum from the Jackson–Hunt model [31] for the eutectic alloy (12.6 w/o Si). Additional predicted extremum values of $\Delta T\ V^{-1/2}$ in K s$^{1/2}$ μm$^{-1/2}$ are 0.253 for 15.5 w/o Si and 0.316 for 26.6 w/o Si (Pierantoni *et al.* [32] for V of 1 mm s^{-1}). All predictions are for flake except for fibres.
[b] Incorporate modifications to Jackson–Hunt model.

however found no difference in $\lambda V^{1/2}$ between flake grown at $V \leqslant 400\ \mu$m s^{-1} and fibres grown at $V \geqslant 400\ \mu$m s^{-1} at G of 8.2 or 12.2 K mm^{-1}, in accord with our findings. The overall mean value of $\lambda V^{1/2}$ from the measurements in Table III is $32.4 \pm 12.0\ \mu$m$^{3/2}$ s$^{-1/2}$ which is in good accord with our result of $36.6 \pm 6.1\ \mu$m$^{3/2}$ s$^{-1/2}$. Several groups of investigators have shown [15, 23, 26–28, 33, 37, 38] that $\lambda V^{1/2}$ decreases with increasing G for the Al–Si eutectic. This is shown in Fig. 3 which plots $\log(\lambda V^{1/2})$ against $\log G$ for all of the results in Table III. Apart from the early results of Day and Hellawell [33] and that of Atasoy [35] and one of the results of Grugel and Kurz [26], all the data conform within $\pm$ 15% to

$$\lambda V^{1/2} = AG^{-n}$$

with $A = 56 \pm 8\ \mu$m$^{3/2}$ s$^{-1/2}$(K mm^{-1})^n and $n = 0.236 \pm 0.031$, with our results on the upper bound of

TABLE III Comparison of previously reported measurements of $\lambda V^{1/2}$ for Al–Si eutectic in the absence of modifying additions with values from the present work for the flake and fibrous morphologies

Alloy concentration (wt % Si)	Range of V ($\mu m\,s^{-1}$)	Range of G ($K\,mm^{-1}$)	Measured[a] $\lambda V^{1/2}$ ($\mu m^{3/2}\,s^{-1/2}$)	Reference
12 to 16	0.28 to 13.4	0.35 to 12.4	20.1 ± 0.6	Day and Hellawell [33]
			8.2 ± 12[b]	
14	0.33 to 3340	30	31.9 ± 6.6	Fredriksson *et al.* [34]
12.9	20 to 1200	0.7 to 15	40.8 ± 16.6	Toloui and Hellawell [23]
12.7	14.2 to 140	0.8	51.8 ± 7.4	Elliot and Glenister [24]
11.5 to 13.4	10 to 474	12	52.4 ± 16.4	Atasoy [35]
12.6 ± 0.2	10 to 200	11	27.7 ± 1.5	Hogan and Song [25]
			[7.71][d]	
6 to 12.6	1 to 300	5, 15	25.2 ± 3.2	Grugel and Kurz [26]
			[8.51][c]	
15.8, 17.0	10 to 1220	12.5	32.5 ± 4.3	Yilmaz and Elliott [36]
			14.5 ± 1.4[f]	
12.6, 14.6	11 to 830	3.2, 7.6, 12.2		Kahn [15], Kahn et al [3]
			41.3 ± 8.9	Kahn and Elliott [38]
12.6	0.6 to 206	4.3 to 14.9		
			[25.7 ± 1.7][e]	Liu et al [27, 38, 39]
			29.7 ± 4.4	
12.6	0.1 to 500	8, 16		
			32.5 ± 3.7	Magnin and Trivedi, Magnin *et al.*
			[10.6]	[29, 30]
17	8300 to 6×10^4	2000	13.4 ± 1.7[b]	Pierantoni *et al.* [32]
			[20.2 at $V = 1\,mm\,s^{-1}$]	
12.7	40 to 870	8, 12.2	34.0 ± 2.3	Najafabadi [16]
18.3	60 to 1030	10, 25	36.6 ± 6.1	Present work

[a] Values in square brackets are predicted $\lambda V^{1/2}$ for flake eutectic growing at extremum from Jackson–Hunt model [31] for the alloy composition involved.
[b] Fibrous [32, 33] or local fine lamellae [33]
[c] A similar value (8.61 $\mu m^{3/2}\,s^{-1/2}$) was predicted earlier by Fisher and Kurz [22]
[d] For flake eutectic. Corresponding value of 3.09 $\mu m^{3/2}\,s^{-1/2}$ was predicted for fibrous eutectic.
[e] Incorporates modifications of the Jackson–Hunt model.
[f] Complex regular morphology.

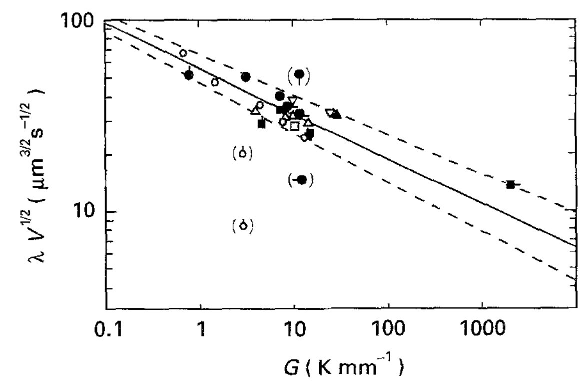

Figure 3 $\lambda V^{1/2}$ for Al-Si eutectic as a function of temperature gradient G from the experimental work summarized in Table III. ♁ Day and Hellawell [33]; ▲ Fredriksson *et al.* [34]; ○ Toloui and Hellawell [23]; ♁ Elliott and Glenister [24]; ♀ Atasoy [35]; □ Hogan and Song [25]; ♁ Grugel and Kurz [26]; –● Yilmaz and Elliott [36]; ● Kahn [15] Kahn *et al.* [37] Kahn and Elliott [28]; △ Liu *et al.* [27, 38, 39]; ■ Magnin *et al.* [29]; ■– Pierantoni *et al.* [32]; ●– Najafabadi [16]; ∇ Present work.

the scatter band shown in Fig. 3. This exponent n of 0.24 ± 0.03 compares with values of 0.5 [33], 0.33 [23], 0.25 [15, 28, 37] and 0.20 [27, 38] typical of results of individual studies over narrower ranges of G than in Fig. 3. The magnitudes of $\lambda V^{1/2}$ in Table III and Fig. 3 are typically a factor of three to eight times predicted values for the extremum and show no significant dependence on alloy concentration over the range 6 to 18 wt % Si.

5. Conclusions

1. Values of $\Delta T/V^{1/2}$ for the eutectic matrix of Bridgman solidified Al-18.3 wt % Si alloy containing primary silicon show a step decrease with increasing V above 270 $\mu m\,s^{-1}$ corresponding to a change in growth morphology from flake-like to fibrous.
2. No corresponding change in $\lambda V^{1/2}$ was found for the fibrous structure in agreement with most of the previous work on microstructures free of primary silicon and of modifying additions.
3. Analysis of published measurements of $\lambda V^{1/2}$ versus G for Al–Si eutectic free of modifying additions shows good agreement with the single relationship $\lambda V^{1/2} = AG^{-n}$ with $A = 56 \pm 8\,\mu m^{3/2}\,s^{-1/2}\,(K\,mm^{-1})^n$ and $n = 0.24 \pm 0.03$ for the range $0.1 < V < 6 \times 10^4\,\mu m\,s^{-1}$ and $0.7 < G < 2000\,K\,mm^{-1}$.

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