The hardness of Al–Si eutectic alloys

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The Vickers hardness values of Al–Si eutectic alloys, solidified unidirectionally at rates ranging from 2.8×10^{-5} to $1\ \text{cm sec}^{-1}$, have been determined. These are compared with associated tensile and compressive properties. It is shown that there is no close correlation of hardness and strength over the entire range of growth rates although similar trends are seen between hardness and compressive yield strength. It is concluded that caution should be exercised when inferring strength from hardness data.

1. Introduction

Thompson *et al.* [1] demonstrated that in aligned eutectics, the lamellar spacing (λ) appears to play a role similar to that of grain size (d) in the interpretation of the mechanical properties of a polycrystalline specimen and so a Petch–Hall [2, 3] relationship of the form:

$$\sigma_y = \sigma_0 + K_y \lambda^{-1/2} \tag{1}$$

may be observed, where σ_y, σ_0 and K_y are the yield stress, friction stress and a constant, respectively. Further, since $\lambda \propto (\text{growth rate})^{-1/2}$ [4], then it is to be expected that, if R is the growth rate

$$\sigma_y \propto R^{1/4}. \tag{2}$$

Noting this, and assuming a linear relationship between the Vicker's Hardness Number (VHN) and σ_y, Justi and Bragg [5] have reported that the VHN for unidirectionally solidified 99.999% purity Al–Si eutectic alloys increased linearly with $R^{1/4}$ up to a value of $\text{VHN} \simeq 55\ \text{kg mm}^{-2}$ at $R \sim 1.4 \times 10^{-3}\ \text{cm sec}^{-1}$ and thereafter changed only little. They also found that the hardness of chill-cast and furnace-cooled specimens were similar, but did not exceed about $\text{VHN} \simeq 50\ \text{kg mm}^{-2}$. More recently [6], these authors have published data on the tensile yield strength of Al–Si eutectic alloys for a limited range of growth rates and claim that there is a close correlation of hardness and tensile yield strength.

Having earlier reported [7] the results of a detailed study of the variation of the microstructure and mechanical properties of eutectic Al–Si with growth rate and being somewhat sceptical about the generality of any empirical VHN versus σ_y relationship, we decided to do a more detailed investigation of the relationship between the hardness of unidirectionally solidified Al–Si eutectic alloys and the growth rate. This was further prompted by the fact that Justi and Bragg reported that chill-cast and furnace-cooled specimens had similar (low) hardness values whereas it is well known that chill-casting usually produces material markedly stronger ($220\ \text{N mm}^{-2}$) than that from a sand mould ($120\ \text{N mm}^{-2}$).

2. Experimental procedures

2.1. Growth rate versus hardness

In their experiments, Justi and Bragg covered growth rates ranging from 2.8×10^{-5} to $1.3 \times 10^{-2}\ \text{cm sec}^{-1}$, using a horizontal Bridgman technique, whereas Sahoo and Smith in their earlier work [7] used specimens grown at growth rates 7.5×10^{-5} to $0.13\ \text{cm sec}^{-1}$ which represented the lower and upper limits of their apparatus. These specimens were available for hardness testing. In addition, further specimens were produced at intermediate growth rates. In order to cover higher growth rates it was necessary to construct a "direct-chill" apparatus [8]. This permitted the growth rate range 4×10^{-2} to 1 cm sec^{-1}, this upper value corresponding to that present during effective chill-casting. The equipment consisted of a vertical cylindrical ceramic mould, 3.8 cm diameter and 20 cm long, preheated to an appropriate temperature (400° C) to ensure unidirectional heat flow. The mould was provided with a tight, thin, mild steel bottom-chill which could be removed at will to permit a stream of cold water to be played directly upon the base of the specimen. A series of thermocouples were spaced at regular intervals along the axis of mould and were connected to a multi-pen temperature recorder to monitor the movement of the solid–liquid interface once the freezing had been initiated at the bottom.

From these measurements it was possible to construct a plot of the position of the solid/liquid interface (distance S from the chilled end) as a function of time. The slope of the curve ($\mathrm{d}S/\mathrm{d}t$) represents the rate of growth at any instant. Since

$$R = kS^{-1/2} \tag{3}$$

then

$$\log R = \log k - \tfrac{1}{2} \log S \tag{4}$$

and so a plot of R versus $\log S$ should yield a straight line (Fig. 1). This method was used to calculate R at distances close to the chilled end.

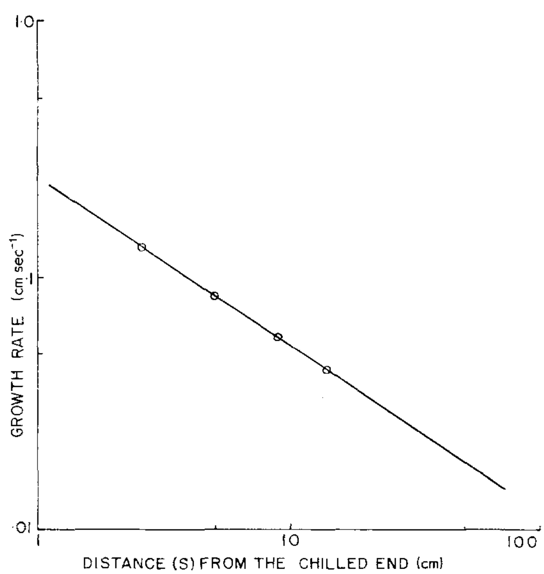

Figure 1 Linear relation between growth rate (R) and the distance from the chilled end (S) in the direct-chill method.

The general procedures adopted in the preparation of alloys have been described earlier [7, 9]. For hardness testing, cylindrical specimens about 6 mm long and 6.3 mm diameter were prepared. They were carefully polished to produce parallel faces on which the diagonals of the Vickers indentations were clearly visible and easily measured. A 2.5 kg load, rather than the 1 kg load used by Justi and Bragg [5], was selected in order to produce an indentation which covered a larger area relative to "interparticle" spacing. On average, twelve readings were taken for each sample. For longitudinal hardness measurements the specimens were sectioned parallel to their growth direction, mounted in cold-setting resin, polished and tested. A check on mounted and unmounted specimens revealed no detectable difference in hardness value.

3. Results

3.1. Microstructure versus growth rate

This has been discussed in detail earlier [7]. It was shown that the silicon morphology changed progressively with growth rate in the following manner: branched dendrites $R \lesssim 2 \times 10^{-4}$ cm sec^{-1}; complex regular $3 \lesssim R \lesssim 11 \times 10^{-4}$ cm sec^{-1}; irregular flaky form, $11 \lesssim R < 80 \times 10^{-4}$ cm sec^{-1}; (modified) fibrous form $R > 80 \times 10^{-4}$ cm sec^{-1} (Fig. 2.).

3.2. Mechanical properties

The hardness values of unidirectionally solidified alloys are given in Table I. These, together with the mechanical strength data from our earlier study [7] and that from material produced in the "direct chill apparatus" are plotted in Fig. 3. For comparison purposes, the hardness results of Justi and Bragg [5] are also included.

It is seen that no close correlation of hardness with strength exists over the range of growth rates examined. However, it is apparent that both hardness and compressive yield strength rise for low and high growth rates.

3.3. Chill-casting and hardness

As referred to earlier, we were surprised to see that Justi and Bragg [5] had observed that the hardness of a so-called "chill-cast" specimen was similar to that of a slowly cooled one. In order to examine this further, the following experiments were performed.

Eutectic material was chill-cast by pouring the molten alloy at a temperature of about 640° C into a cold split-steel mould to produce rods of

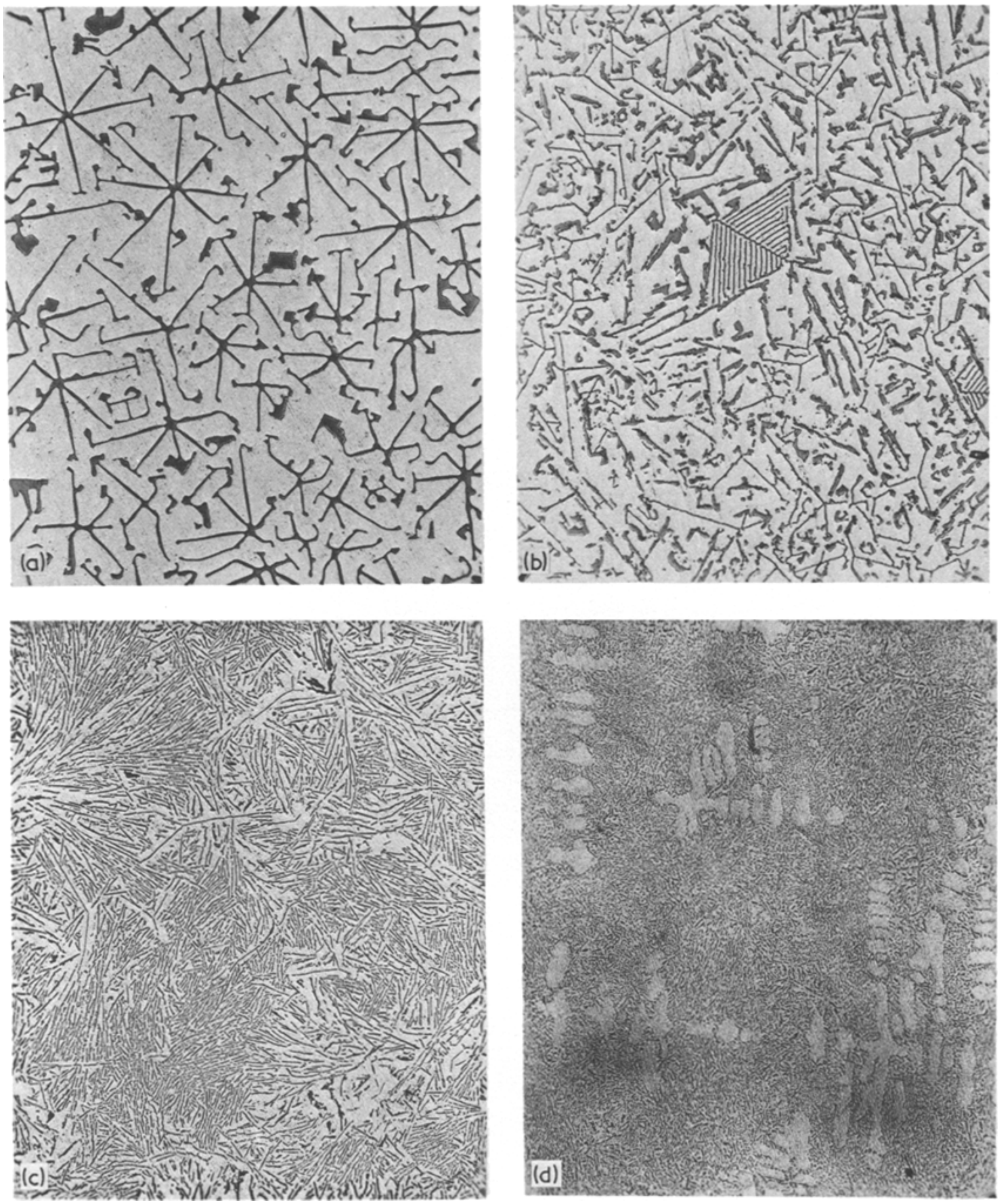

Figure 2 Optical micrograph of transverse sections through directionally solidified Al–Si eutectic alloys showing the silicon morphology at various growth rates. (a) Branched dendrites, 7.5×10^{-5} cm sec^{-1} ($\times$ 130). (b) Complex regular, 4.4×10^{-4} cm sec^{-1} ($\times$ 110). (c) Irregular flaky form, 4.4×10^{-3} cm sec^{-1} ($\times$ 110). (d) (Modified) fibrous form, 1.3×10^{-1} cm sec^{-1} ($\times$ 170). (Temperature gradiant ~ $40°$ C cm^{-1}).

TABLE 1 Room-temperature mechanical properties of directionally solidified Al–Si eutectic alloys

Growth rate (cm sec)	VHN ($kg\,mm^{-2}$)		0.2% off-set yield strength, ($MN\,m^{-2}$) [7]		U.T.S. ($MN\,m^{-2}$) [7]
	Longitudinal	Transverse	Compressive	Tensile	
3.5×10^{-5}	45.8	53.1	–	–	–
7.5×10^{-5}	49.1	52.2	476.0	41.3	120.7
	–	–	442.0	–	–
	–	–	438.0	–	–
1.5×10^{-4}	44.5	50.2	340.0	53.1	111.5
	–	–	330.0	57.8	109.5
4.5×10^{-4}	44.0	47.8	132.2	44.2	118.5
	–	–	130.0	42.7	110.0
1.1×10^{-3}	44.1	45.6	130.0	54.4	123.4
	–	–	134.4	48.2	125.6
1.4×10^{-3}	45.8	45.1	–	–	–
4.5×10^{-3}	46.2	47.6	93.7	54.5	140.0
	–	–	95.8	53.1	144.0
			88.2	–	–
4.5×10^{-2}	49.2	49.6	–	60.6	155.0
1.3×10^{-1}	60.6	60.2	100.5	63.5	157.0
	–	–	108.0	–	–
Chill-cast	–	78.0	148.8	101.5	220.0
			152.4	102.0	220.0

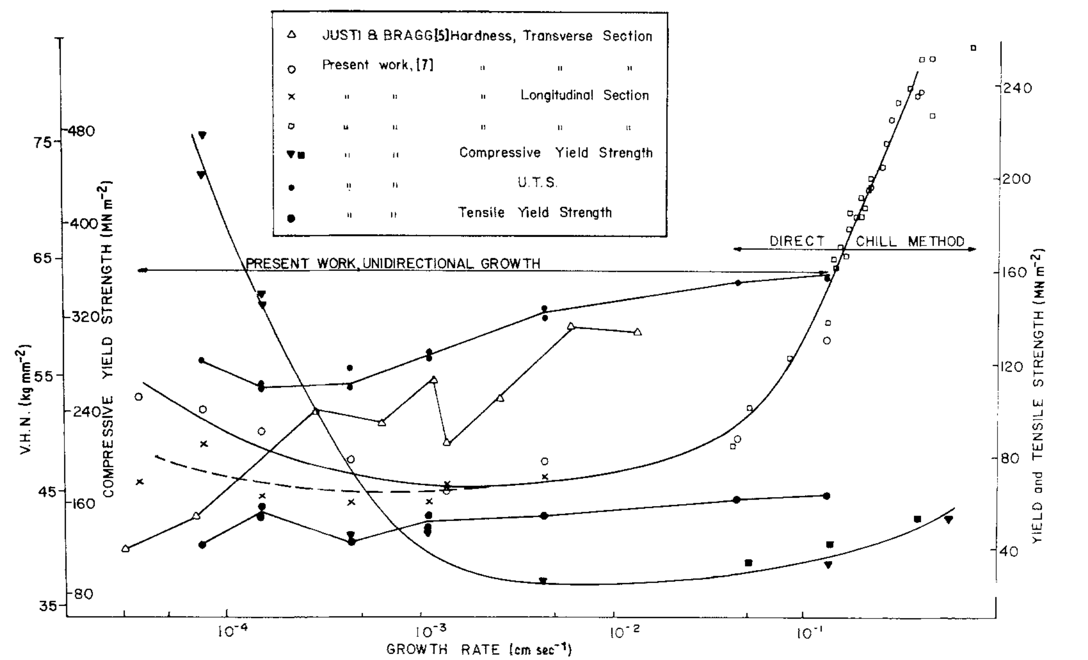

Figure 3 Effect of solidification rate on the hardness (VHN, 2.5 kg load), tensile and compressive yield strengths (0.2% off-set) and the U.T.S. of the Al–Si eutectic alloys.

0.80 cm diameter. The hardness (VHN) of such material was about 78 to 81 kg mm^{-2}. A similar result was obtained for the chilled-end of specimens produced in the "direct-chill" apparatus referred to earlier. The microstructures were similar. However, the VHN of furnace-cooled material was found to be only 49 kg mm^{-2}. By comparison, Justi and Bragg [5] report that the hardness values for chill-cast and furnace-cooled samples were similar ($\sim$ 50 kg mm^{-2}) and less than those of the samples grown unidirectionally in the higher growth rate range. Unfortunately they do not report the technique employed for chill-casting.

In order to examine the change in hardness with the manner of chill-casting, small amounts of the alloy were cast onto a thick copper block to produce a casting 1.0 cm thick. In this case the VHN of the surface in contact with the copper block was about 53.1 kg mm^{-2}. The hardness values were found to increase along the thickness of the casting such that the hardness of the top surface exposed to air was about 63.0 kg mm^{-2}. Such an increase might be expected when it is recalled that a considerable increase in compressive strength may arise from the columnar growth of silicon [7].

It is noted that, immediately following freezing, the as-cast material is subjected to an *in situ* anneal as it cools to room temperature. The extent of this will depend principally upon the earlier rate of freezing. In an attempt to determine the influence of this on the hardness of the as-cast specimens, it was decided to examine the manner in which the hardness of chill-cast samples changed with isochronal annealing in order to determine the temperature range within which the changes in mechanical properties are affected most significantly. To this end, eutectic alloys which had been chill-cast into the split-steel mould, to give a VHN = 78.3 kg mm^{-2}, were annealed for 1 h at (respectively) 200, 300, 350, 400 and 500° C and then furnace-cooled to room temperature. Afterwards they were tested for hardness and examined microscopically. Fig. 4 depicts the isochronal annealing behaviour of the chill-cast Al–Si eutectic alloy.

It can be seen that the anticipated decrease in hardness did take place. The most marked decrease occurred within the 300 to 400° C temperature range, a hardness value of 52 kg mm^{-2} resulting from an annealing temperature of about 370° C. It was noted that the silicon adopted a more sphe-

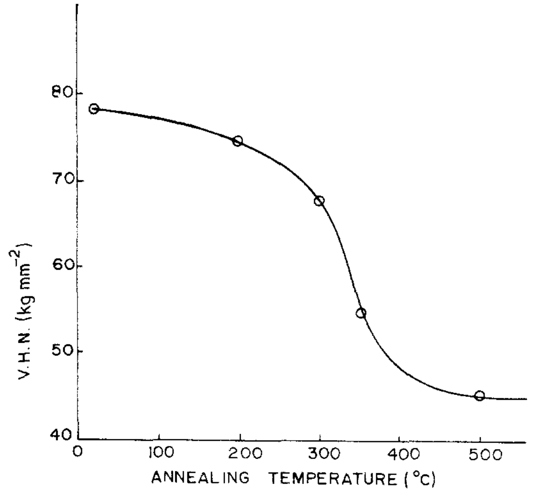

Figure 4 Effect of annealing temperature on the hardness (VHN, 2.5 kg load) of chill-cast Al–Si eutectic alloys.

roidized character (Fig. 5). In addition, microhardness measurements showed that the primary Al dendrites had also softened, presumably due to the removal of the expected Si super-saturation there.

It appears likely that the chill-cast material used by Justi and Bragg was obtained by pouring the molten eutectic onto a metallic plate, since its hardness is similar to that of the lower surface of the material we produced by casting upon a copper plate. Such a procedure is not very effective in producing a chill-casting since the resultant hardness is only slightly greater than that of the chill-cast alloy after being annealed at 500° C for 1 h. Since only a limited degree of structural coarsening was observed to have taken place in the latter but that the primary dendrites had softened considerably, it suggests that much of the hardness of a chill-cast specimen arises from internal residual stresses developed during casting. In addition, some solution strengthening will arise since Rosenbaum and Turnbull [10] observed that the yield stress of an Al–1% Si alloy increased by 60% when water-quenched, as compared with air-cooling.

4. Discussion

The relationships between hardness and other mechanical properties of materials are commonly empirical and tend to be limited to specific materials. For example, Schulson and Roy have recently reported [11] an excellent fit for the linear relationship of flow stress with hardness for annealed Zr_3Al alloys. There have been attempts

Figure 5 Optical micrographs of Al–Si eutectic alloys showing the effect of annealing on the silicon morphology of the chill-cast alloy (× 488). (a) Chill-cast. (b) Annealed, 350° C, 1 h. (c) Annealed, 500° C, 1 h.

TABLE II Interdependence of hardness and U.T.S.

Growth rate (cm sec^{-1})	U.T.S.		n^*
	H_V (longitudinal)	H_V (transverse)	
7.5×10^{-5}	0.256	0.232	–
1.5×10^{-4}	0.248	0.221	0.176
4.5×10^{-4}	0.260	0.239	–
1.1×10^{-3}	0.282	0.273	0.127
4.5×10^{-3}	0.307	0.298	0.175
4.5×10^{-2}	0.315	0.312	–
1.3×10^{-1}	0.259	0.261	0.152
Chill-cast	–	0.268	0.287

*Obtained from the slope of the log–log plot of $\sigma = k\epsilon^n$. where σ and ϵ are, respectively, true stress and true strain and k is a constant.

to generalize such a relationship. For instance, the original formula proposed by Tabor ([12] p. 107) was more recently modified by Cahoon [13] who suggested that

$$\frac{\text{U.T.S.}}{H_V} = 0.345\left(\frac{n}{0.217}\right)^n \tag{5}$$

where U.T.S. is the utlimate tensile strength, H_V is the hardness value and n is defined as the strain-hardening coefficient. It is evident from this equation that the ratio U.T.S./H_V should never fall below ~0.3 and for $n > 0.1$ it should increase with n. However, we find for the Al–Si eutectic alloy that this ratio is less than 0.3 for hardness measurements on both the longitudinal and transverse sections (Table II). In addition, the strain-

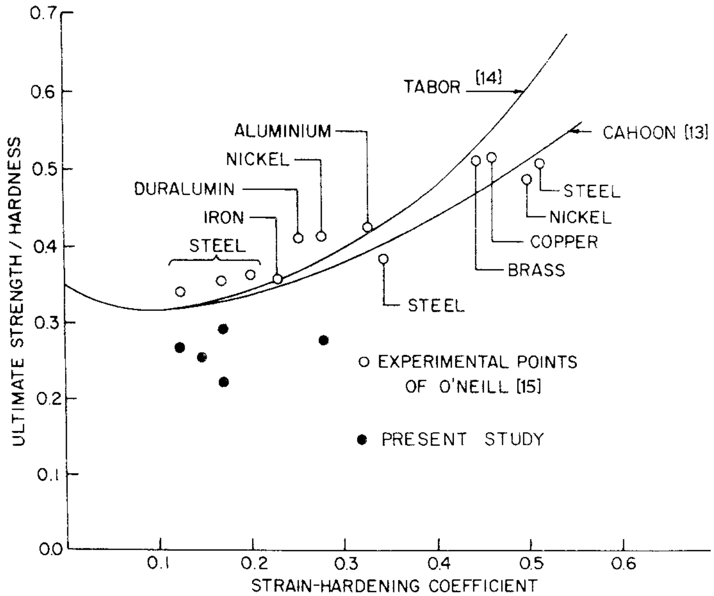

Figure 6 The variation of ultimate strength/hardness with strain-hardening coefficient for various metals from Cahoon [14], with data from the present investigation added. (The references in the figures are directed to the present paper.)

hardening coefficient, n, is seen to vary between 0.127 and 0.287 for the various growth conditions, the latter being close to the value of 0.24 reported for "Duralumin" by Tabor ([12] p. 108). These values have been superimposed on Cahoon's plot of U.T.S./H_v versus n (Fig. 6). It is noted that Cahoon's plot is unable to embrace these data.

Further to the relationship of hardness to strength, it is seen that the curve for compressive strength mirrors the V.H.N. versus R curve (Fig. 4) more closely than does that for tensile strength. The reasons for the higher compressive strength of the directionally solidified Al–Si eutectic, most marked at very low growth rates where large axial Si dendrites form, have been discussed earlier [7], and need not be repeated here. However, it is worth noting that the hardness of longitudinal sections of specimens grown slowly is also noticably lower than the equivalent measurements made on transverse sections. This suggests that the principal deformation around an indentation occurs perpendicular to the plane of the specimen surface and is compressive in nature. In general, fine-grained polycrystalline specimens exhibit little difference between tensile and compressive strengths since there is no marked structural anisotropy. This is also seen to be the case for Al–Si eutectic samples grown faster than 4×10^{-3} cm sec^{-1} when a less anisotropic distribution of silicon results, the axial dendrites being replaced by more irregular silicon forms.

5. Conclusions

(1) The Vickers hardness of Al–Si alloys solidified at rates ranging from $\sim 5 \times 10^{-5}$ to ~ 1 cm sec^{-1}, shows a strong dependence on the growth rate. However, this dependence is not closely reflected by changes in Y.S. or U.T.S.

(2) Hardness data should only be used as an indication of mechanical strength in those systems in which a close empirical fit has been previously obtained.

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