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# The structures of fully eutectic aluminium–silicon alloy castings

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Strontium-modified aluminium alloys containing 14 to 15 wt% silicon were cast with fully eutectic structures by using heated moulds and high-purity materials. In alloys containing the additional elements magnesium, copper or nickel, a distinct eutectic colony structure was evident, outlined by intermetallic compounds. At the edges of the castings the eutectic colony structures and the aluminium grains (revealed by anodizing) were of a similar scale. Further from the mould walls the eutectic colonies contained several aluminium grains. This is believed to result from the blocking of growth of the aluminium phase by the silicon phase.

## 1. Introduction

In the past the majority of papers on eutectic solidification has dealt solely with features on the scale of the constituent eutectic phases. Papers describing larger scale structures, such as the grain structure [1, 2], have generally been based on unidirectional solidification techniques which provide the level of control necessary to produce fully eutectic structures. In commercial casting processes, primary phases are almost always present and, even in small quantities, primary phases have been shown to influence the grain structure of the eutectic [3].

Unidirectional solidification studies of the aluminium–silicon system [2, 4] have shown that a range of hypereutectic alloys may form fully eutectic microstructures if solidified rapidly. It has also been shown [2, 5] that strontium additions, as well as modifying the eutectic silicon morphology, also strongly suppress the formation of primary silicon particles, presumably by neutralizing heterogeneous nucleating agents.

Commercial wear-resistant alloys are now available which rely upon the formation of a fully eutectic microstructure for optimal properties. These alloys are based on a modified aluminium–silicon eutectic structure with additional elements forming hard intermetallic compounds [6].

The aim of the present work was to investigate the large-scale structure of fully eutectic, modified aluminium–silicon castings, and to examine the distribution of intermetallic compounds produced by small additions of other elements.

## 2. Experimental programme

Alloys containing 14 to 15 wt % silicon were produced from high-purity aluminium and silicon using a vacuum induction furnace. Where required, additions of nickel or copper were made prior to melting and additions of magnesium were made directly to the melt prior to pouring. Strontium additions of 0.06 wt % were made using a 2.4 wt % master alloy. A summary of alloys produced is given in Table I.

In a previous paper [5] we have shown that large numbers of primary silicon particles are initiated, during the early stages of solidification, from the eutectic colonies formed in the transient chill zones adjacent to the mould walls. In order to produce fully eutectic microstructures, castings, of the type shown in Fig. 1, were made in permanent metal moulds pre-heated to 650° C in order to prevent any solidification during pouring. After pouring, the molten metal was allowed to stand for 10 to 15 sec and then water jets were directed at the outside of the mould. This technique eliminated chill zones while producing a cooling rate sufficiently fast to allow full modification and to prevent an excessively coarse microstructure from forming.

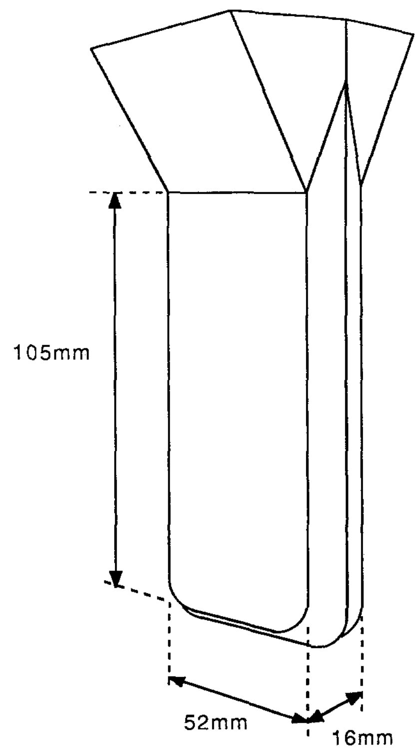



*Figure 1* Design of casting produced from water-cooled mould initially heated to 650° C.

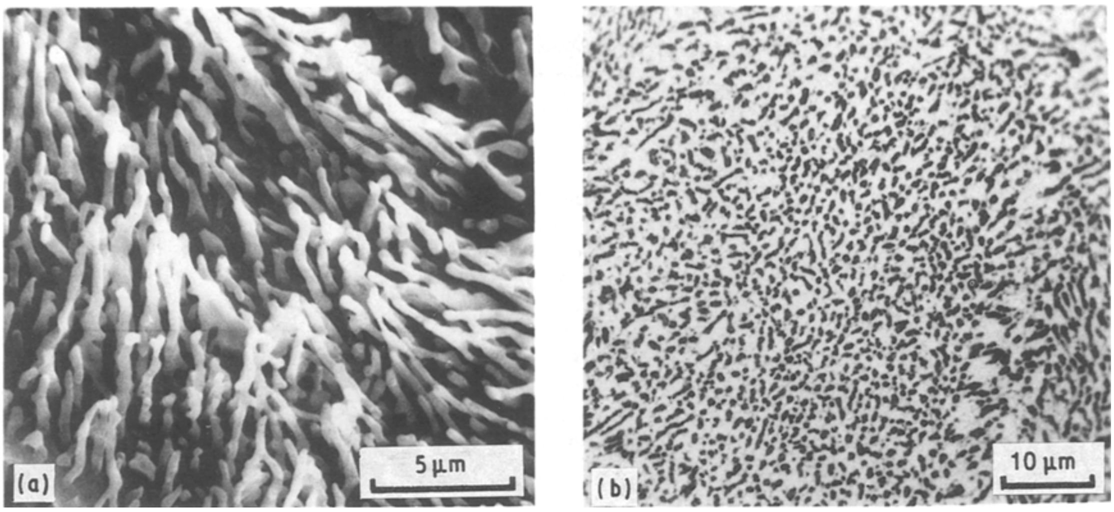



*Figure 2* Microstructure of the modified aluminium–silicon eutectic (alloy E): (a) scanning electron micrograph of deep-etched specimen, (b) optical micrograph.

Transverse sections of the castings were examined using optical microscopy. An anodizing technique was used to reveal the aluminium grain structure. The fine modified eutectic microstructures in as-cast alloys could not be studied using this technique due to silicon relief effects which interfere with the formation of an even anodic film. It was, therefore, necessary first to coarsen the silicon phase by holding for 50 h at 510° C. The as-cast grain boundaries were assumed to remain stable during heat treatment [7].

In addition to optical microscopy, a scanning electron microscope, supported by energy dispersive X-ray spectrometry, was used to analyse intermetallic phases and also to examine the eutectic structure revealed by deep etching of the aluminium matrix.

## 3. Results

A fibrous eutectic morphology, as shown in Fig. 2, formed throughout the castings. In some regions branched plate-like structures, referred to as skeletal silicon, could also be seen as shown in Fig. 3. Intermetallic particles were present within the copper-, nickel- and magnesium-containing alloys. Several examples, together with X-ray spectra obtained by energy dispersive spectrometry, are shown in Fig. 4. The compounds $CuAl_2$, $NiAl_3$ and $Mg_2Si$ phases were confirmed from their spectra and from standard metallographic tests.

The intermetallic particles in the copper- and magnesium-containing alloys were distributed throughout the castings outlining the large-scale eutectic colony structure. This is shown in Fig. 5, for the copper-containing alloy. The eutectic colony size varied greatly with position in the castings. In the centre a fine equiaxed structure formed, while closer to the edges the colonies were larger and often formed side branches giving a dendritic-like appearance. The nickel-containing alloy, shown in Fig. 6, formed three distinct regions: adjacent to the mould walls the microstructure was essentially binary eutectic aluminium–silicon. Further from the walls the eutectic colonies formed branched structures appearing as 'dendrites' of Al–Si eutectic surrounded by Al–Si–$NiAl_3$ eutectic. The central region consisted mainly of ternary Al–Si–$NiAl_3$ shown in greater detail in Fig. 7.

TABLE I Summary of Alloys

| Alloy* | Microstructure |
|---|---|
| E. Al–14.5 wt % Si | Al–Si binary eutectic |
| M. Al–14.5 wt % Si–0.65 wt % Mg | Al–Si binary eutectic and Al–Si–$Mg_2Si$ ternary eutectic |
| C. Al–14.5 wt % Si–2 wt % Cu | Al–Si binary eutectic + Al–Si–$CuAl_2$ ternary eutectic |
| N. Al–14.5 wt % Si–2 wt % Ni | Al–Si binary eutectic + Al–Si–$NiAl_3$ ternary eutectic |

*All alloys were strontium modified with 0.06 wt % Sr additions.

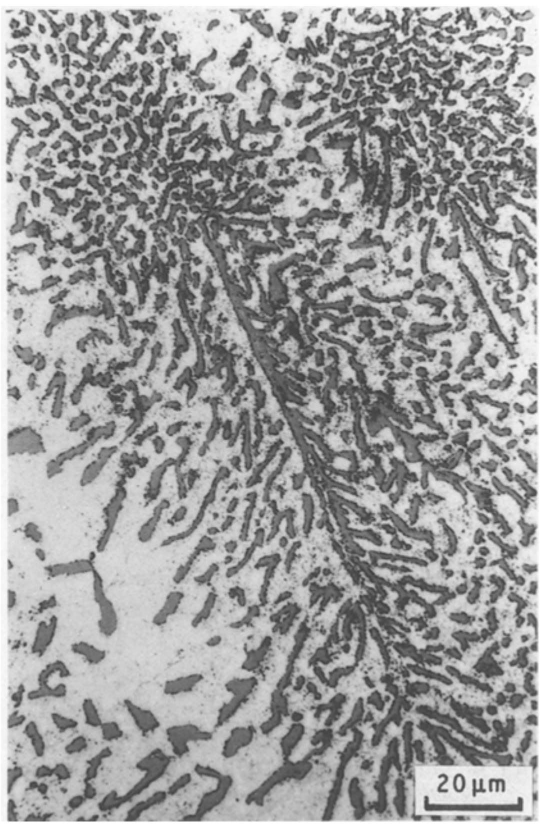



*Figure 3* Skeletal silicon formed in copper-containing alloy (C).

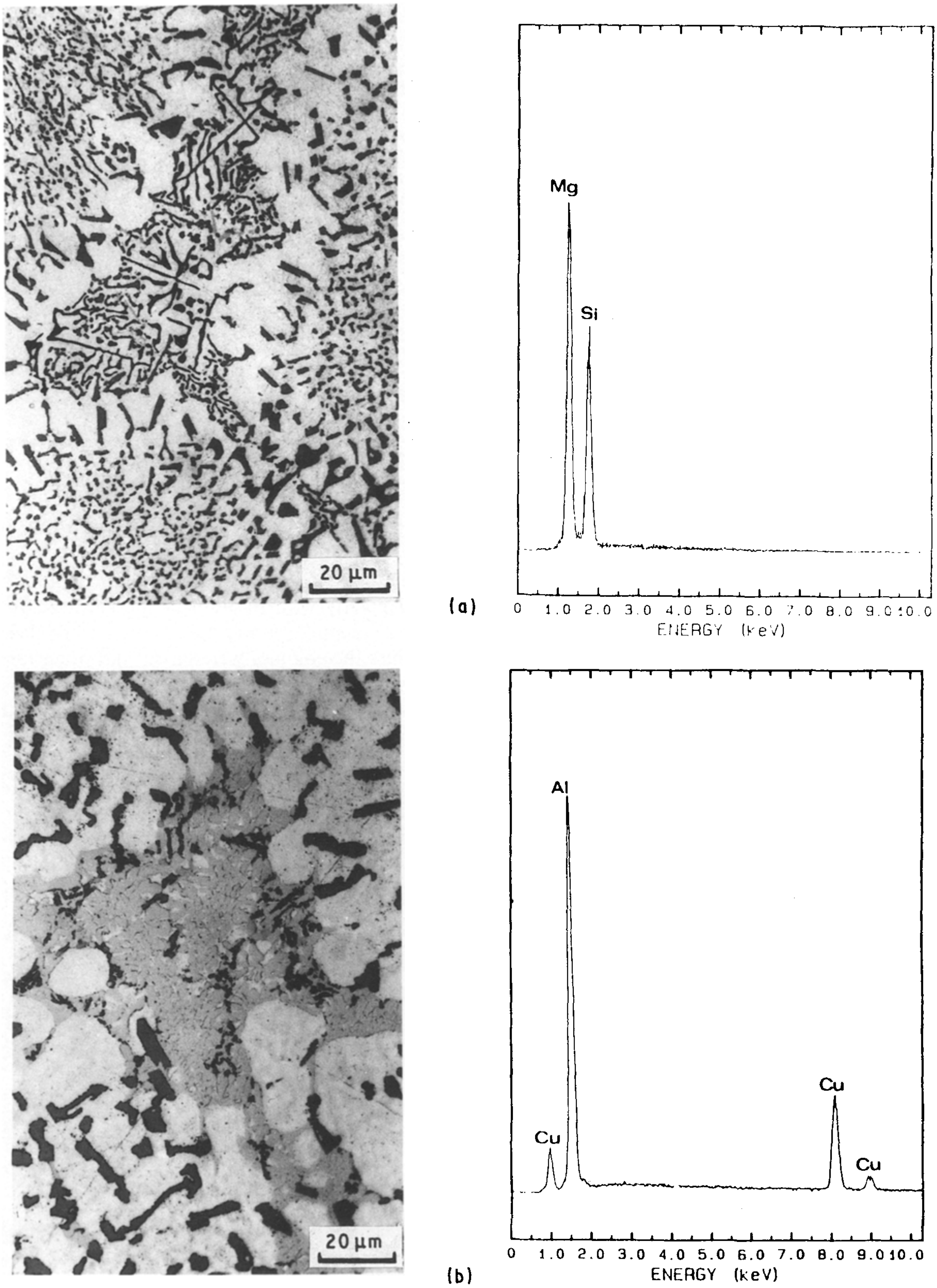
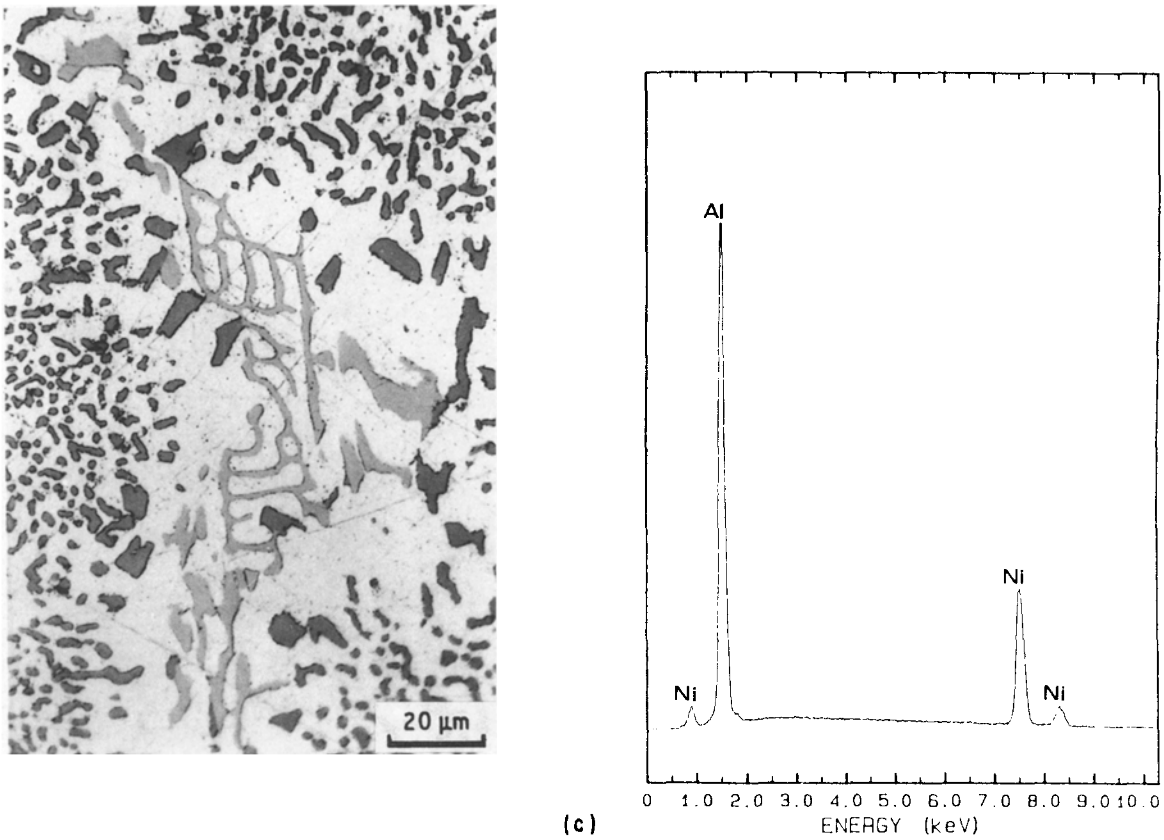



*Figure 4* Ternary phases formed at eutectic colony boundaries: (a) $Mg_2Si$ in alloy M, (b) $CuAl_2$ in alloy C, (c) $NiAl_3$ in alloy N.

A small number of aluminium dendrites was also present. The colony structure of the binary alloy could not be discerned due to the absence of intermetallic compounds.

The aluminium grain structures of the binary aluminium–silicon alloy and the magnesium- and copper-containing alloys were revealed successfully by anodizing. The grain structure of the copper-containing alloy is shown in Fig. 8. Adjacent to the mould walls several large grains were present. At a short distance from the mould walls these gave way to large numbers of very fine equiaxed grains which, in turn, gave way to large grains in the centre of the casting. The grains in the central region appeared to have a fine subgrain structure. At the mould walls the grain and colony boundaries appeared to correspond although some grains contained more than one colony. Further from the wall the grain size was much smaller than the colony size while in the central region the colonies appeared to correspond to the subgrains.




(c)

*Figure 4* Continued.

## 4. Discussion

The microstructures obtained may be interpreted using a generalized binary phase diagram, shown in Fig. 9. The structures of the binary alloys form on the line between the binary and ternary eutectics. Solidification begins with the growth of the binary aluminium–silicon eutectic while the liquid becomes enriched in the third element and eventually solidifies as the ternary eutectic. The compositions of the magnesium- and copper-containing alloys are relatively close to the binary eutectic, while the nickel-containing alloy is somewhat closer to the ternary eutectic composition (about 5% Ni) resulting in a much greater proportion of ternary eutectic in this alloy. The growth of a binary eutectic in ternary alloys is analogous to the growth of the primary phase in a binary alloy. From its appearance in Figs 5 and 6 the eutectic may also grow in a dendritic manner similar to that of a primary phase.

The grain and colony structures appear to be of considerable complexity. Earlier studies [1] have shown that for normal eutectics (eutectics forming regular lamellar or fibrous structures) several eutectic colonies form within each grain and result from the development of a cellular growth interface. Studies [2, 8] of unmodified aluminium–silicon alloys revealed a small aluminium grain size resulting from the blockage of the aluminium phase by the silicon phase during solidification. The modified eutectic, however, behaves as a normal fibrous eutectic having a large grain size [2].

The fine grain size in regions intermediate between the edges and centres of the castings appears contrary to the expected behaviour of the modified eutectic, however, it may be explained by the presence of skeletal silicon. Skeletal silicon has been reported in previous work [5, 9] and appears similar to the

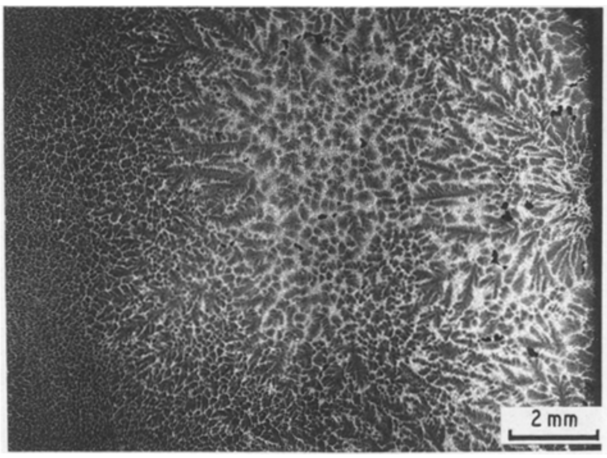



*Figure 5* Eutectic colony structure in alloy C.

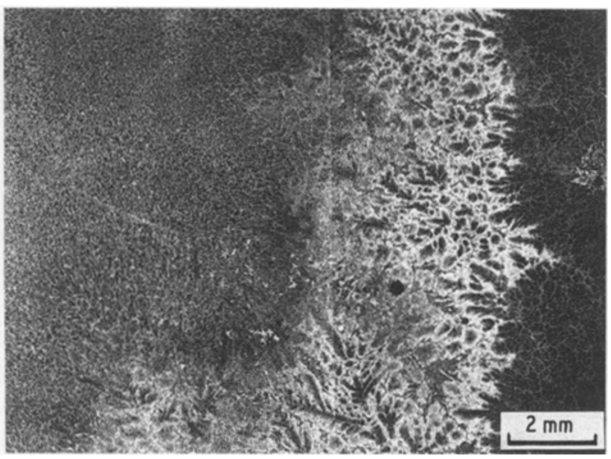



*Figure 6* Eutectic colony structure in alloy N.

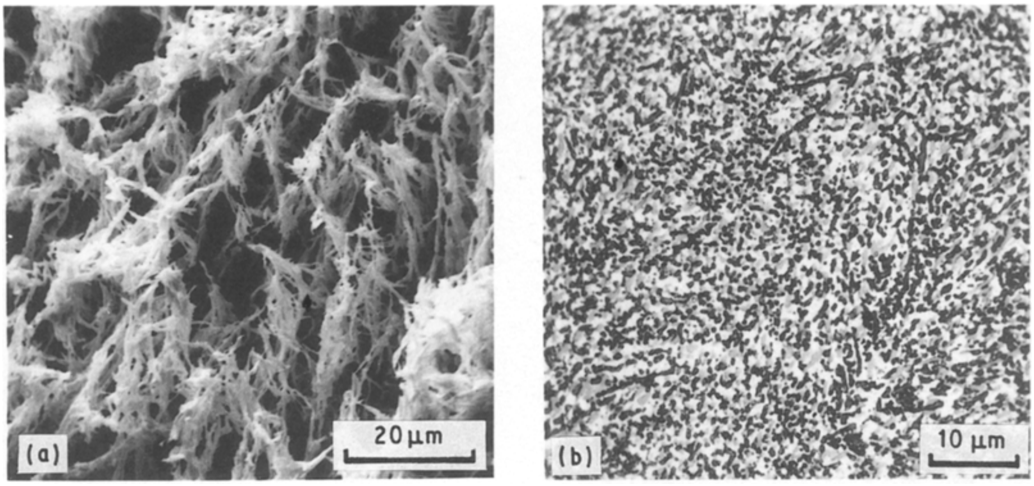



*Figure 7* Microstructure of the modified ternary eutectic Al–Si–$NiAl_3$ in alloy N. (a) Scanning electron micrograph of deep-etched specimen; (b) optical micrograph: dark phase is Si, light phase is $NiAl_3$.

complex-regular silicon morphology reported in unmodified hypereutectic alloys [10].

Fig. 10 shows the presumed sequence of events during solidification. Immediately after pouring, the mould and metal temperatures are both above the eutectic freezing temperature. Cooling proceeds fairly rapidly once the water jets are turned on, resulting in a layer of undercooled metal forming adjacent to the mould wall. At a critical undercooling, nucleation of the eutectic takes place at the mould wall, followed by rapid growth of the eutectic until the edge of the undercooled region is reached. During this stage it is assumed that the aluminium and silicon phases grow at a common interface. This early growth phase produces the region containing large aluminium grains adjacent to the mould wall. Once the solid–liquid interface reaches the solidus temperature, growth of the aluminium phase cannot proceed until further cooling takes place. However, as the alloy is of hypereutectic composition, the silicon phase may continue to grow leading to the formation of skeletal silicon. It is proposed that the arms of the skeletal silicon interfere with the subsequent advance of the eutectic aluminium phase. This results in the nucleation of new aluminium grains on the opposite sides of the arms leading to the formation of a polycrystalline aluminium phase. As cooling continues the temperature gradient at the solid–liquid interface falls until all of the remaining liquid is cooled to near the solidus temperature, or, if additional elements are present, to below the solidus temperature due to constitutional undercooling. The aluminium and silicon once again grow at a common interface resulting in large aluminium grains in the centres of the castings.

## 5. Conclusions

Under suitable conditions, strontium-modified aluminium alloys containing 14 to 15 wt % silicon may be cast with a fully eutectic microstructure. If additional elements are present the binary aluminium–silicon eutectic grows as a primary phase, often with a morphology that has a dendritic-like appearance, and the additional elements segregate to form a ternary eutectic from the last liquid to solidify.

The aluminium grain structure within castings of modified aluminium–silicon eutectic alloys may, under certain circumstances, be polycrystalline within a single eutectic colony, contrary to earlier reports [1, 2]. The polycrystalline region forms in castings at positions intermediate between the edges and the centre and appears to arise as a consequence of the growth of skeletal silicon which prevents the continuous growth of the eutectic aluminium phase leading to the nucleation of new grains. At the edges and

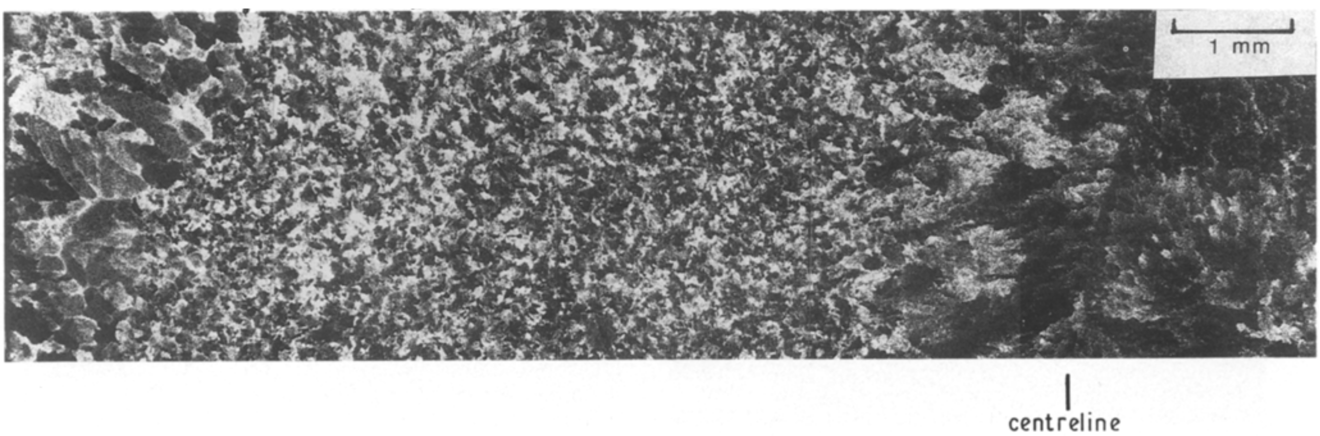



*Figure 8* Aluminium grain structure in a transverse section of alloy C (compare with colony structure in Fig. 5).

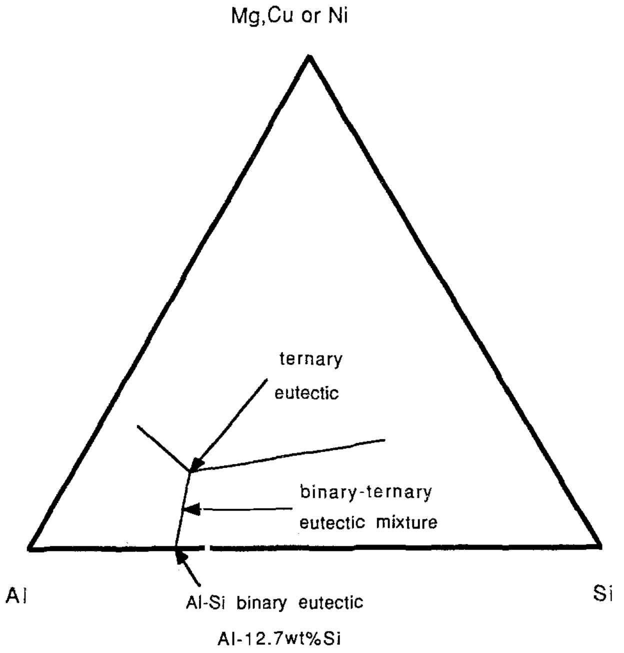



*Figure 9* General form of ternary phase diagram in alloys based on the Al–Si system, showing binary and ternary eutectic and the binary–ternary eutectic mixture.

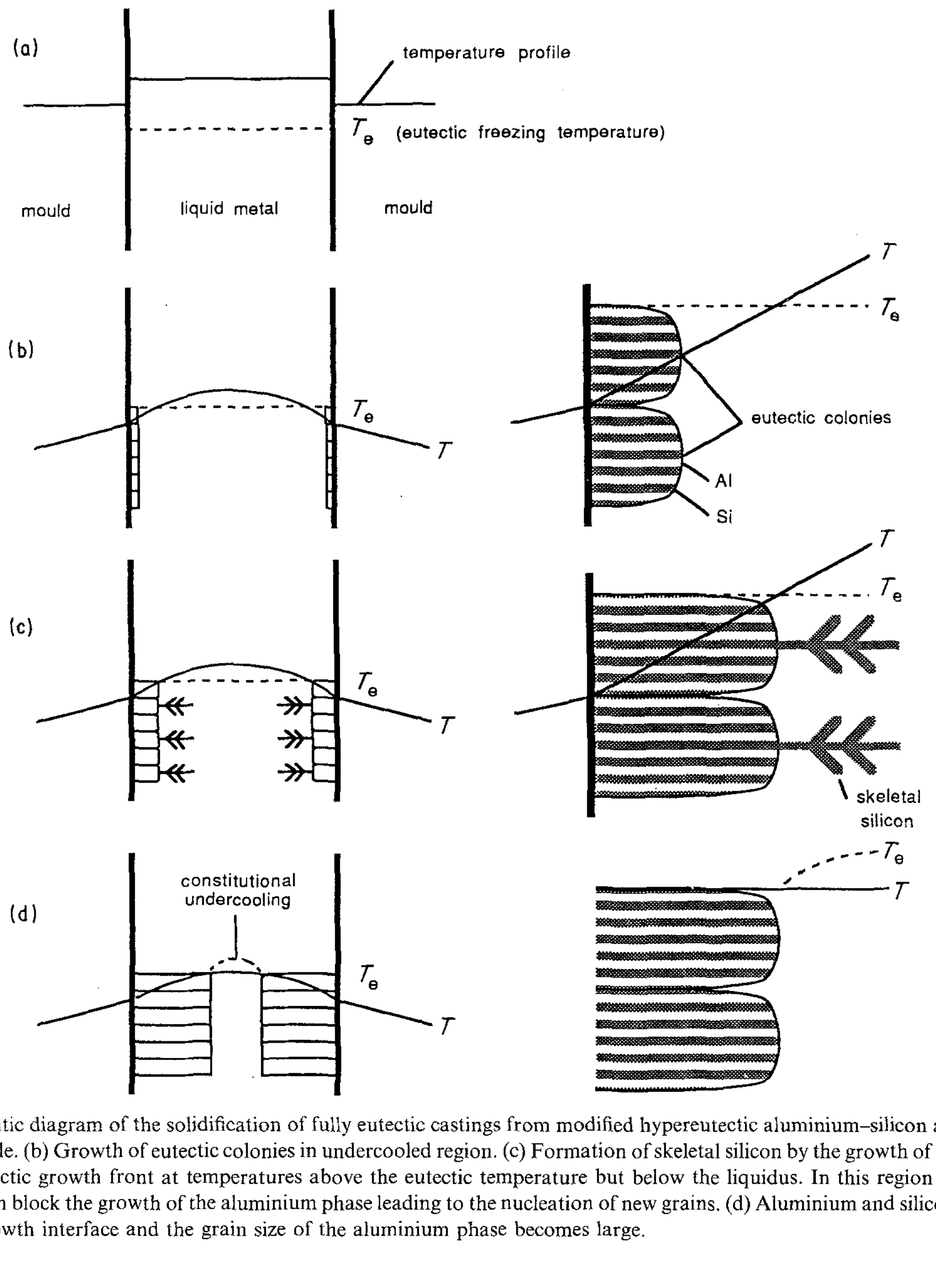



*Figure 10* Schematic diagram of the solidification of fully eutectic castings from modified hypereutectic aluminium–silicon alloys. (a) Initial temperature profile. (b) Growth of eutectic colonies in undercooled region. (c) Formation of skeletal silicon by the growth of the silicon phase ahead of the eutectic growth front at temperatures above the eutectic temperature but below the liquidus. In this region the arms of the skeletal silicon can block the growth of the aluminium phase leading to the nucleation of new grains. (d) Aluminium and silicon phases return to a common growth interface and the grain size of the aluminium phase becomes large.

centre of a casting the eutectic aluminium and silicon phases are predicted to grow at a common interface resulting in a large aluminium grain size.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