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INTRODUCTION

Feathery crystals occur in DC-cast ingots of nearly all aluminium alloys. This unique solidification structure was first noticed after the introduction of the DC casting process and has since then been the subject of several investigations (1-7).

It has been shown that the feathery crystals are built up by numerous lamellar twin crystals with a thickness of 50-200 μm piled together almost parallel to each other to form large regions, the size of which may amount to some ten centimetres. Each lamella is divided by a central (111)-twin boundary, parallel to the plane of the lamella. The grain boundaries between the lamellae are of the normal, high-angle type. The growth direction of the lamellae is one of the $[112]$ -type directions in the twin plane (7). It has been shown (2) that the feathery crystals grow more rapidly than ordinary, single-crystal grains. For this reason, together with the fact that new twin planes can easily be formed nearly parallel to the original one, feathery crystals easily spread out over the cast structure and can under certain circumstances take up almost the entire volume of the ingots.

Depending on the number and size of the feathery crystal regions in them, the ingots exhibit a more or less pronounced solidification texture. Some traces of this texture may still remain after subsequent production processes of rolling and heat treatments. In this way the feathery crystals give rise to a texture banding on the surfaces of plates after anodizing. Another type of surface defect which can occur in the presence of feathery crystals is the difference in brightness of the anodized plate surfaces which is a consequence of the smaller mean distance between second-phase particles formed during solidification in feathery crystal regions, as compared with the same distance in normal structure.

Factors Governing the Formation of Feathery Crystals in DC-Cast Ingots

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From these facts is evident how feathery crystals can hinder the production of an even quality of anodized products. Effort has therefore been made to modify the casting conditions in order to avoid their formation. It has, for example, been clearly demonstrated how feathery crystal formation depends on the manner in which the melt is fed into the mould (1). To ensure the production of ingots free from feathery crystals grain refiners containing titanium diboride are normally added to the melts. In the production of bright anodizing quality this technique is not entirely satisfactory, however, due to the tendency of the boride particles to agglomerate into bigger clusters which may give rise to streaks on the plate surfaces.

A better understanding of the mechanisms involved in the nucleation and growth of the feathery crystals would be of great help in establishing better casting conditions. In some recent investigations the importance of composition of the solidifying melts for the twin nucleation has been demonstrated, but a closer connection between composition, casting conditions and feathery crystal formation is still lacking.

The earliest statements concerning the composition come from Nakao (cited by Morris et al (2)), who found that feathery crystals formed only if the melt contained more than 0.04 w/o Ti, 2 w/o Cu, 2 w/o Mg or 8 w/o Zn and the solidification rate was higher than 0.04 cm/s.

Morris et al could find no feathery crystals in dilute Al-Fe and Al-Ni alloys, nor in Al-Ti alloys with a Ti content lower than 0.1 w/o. The solidification rate in the mould used was 0.12 cm/s near the chill and 0.06 cm/s at 10 cm away from it. The temperature gradient in the melt ahead of the solidification front was found to vary from 24°C/cm near the chill to almost zero at a distance from the chill surface.

Under these conditions the same authors obtained relatively few feathery crystals, even in the Ti interval 0.10-0.23 w/o Ti. These results led to the conclusion that the nucleation of twins is of rare occurrence.

The twins were found to be nucleated as a rule near the chill as well as at some distance from it.

Nakatani et al (3,4) investigated the feathery crystal formation in several alloys. They found that feathery crystals were formed in Al-melts in which the following elements had been dissolved to at least the concentrations given: 0.7 w/o Fe, 3.94 w/o Sn, 10.47 w/o Cu, 5.06 w/o Mg, 1.02 w/o Ni, 0.08-0.13 w/o Ti. No twins could be found after addition of 1-10 w/o Si, 0.5-4 w/o Mn, 1.0-4 w/o Cr or 1.0-10 w/o Zn. The cooling rate at the chill was 0.10-0.20 cm/s.

These authors tried to explain the different tendencies to produce feathery crystals from the solidification characteristics of the different alloying elements, i.e. from segregation ratios and diffusion rates in the melt.

The relative tendencies for feathery crystal formation in different alloys have also been studied by Watanabe et al (5) and Miyazawa et al (6). The influence of composition was best demonstrated in Al-Mg alloys. Feathery crystals were observed in directionally solidified Al-Mg alloys containing at least 10 a/o Mg, but when the Mg-concentration was raised to 16 a/o and above, the grain refining which accompanied the Mg-additions was so intense that the feathery crystals did not appear.

In separate castings which were vibrated during solidifications, twins were produced in an Al-2.5 w/o Mg alloy and also in Al of 99.85 % purity or better.

To account for their observations these authors (6) proposed a theory for the twin nucleation which is based upon the grain refining which occurs at the chill. If the number of randomly orientated crystals formed at the chill increases, a greater number of crystals will have an orientation such that a $[112]$ -direction is nearly parallel with the heat flow. It is supposed that twin growth is most likely to start from these grains.

From this short account it is clear that there is some uncertainty about which conditions will lead to the formation of feathery crystals. The presence of certain second elements has been shown to be necessary, but for the time being the available information contains some contradictions and it is not easy to predict the influence of a certain element in a given casting process.

The present investigation has been undertaken to improve the knowledge of the factors which govern feathery crystal formation. The experimental work has been carried out on a laboratory scale using a casting technique which is considered to represent an adequate model of the solidification situation which prevails during DC-casting. With this technique it has been possible to arrive at some further clarification of the significance of composition and cooling conditions for feathery crystal formation.

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EXPERIMENTAL TECHNIQUE

To produce feathery crystals samples were taken from melts by directional solidification using the equipment shown in Figure 1. The casting system has the form of a vertical, water-cooled lance which has a tip of copper screwed to its lower end. This tip is surrounded by a silica tube with a small hole (diameter 3 mm) at its bottom through which melt can enter the tube when the tip of the lance is dipped down into a melt. When melt comes into contact with the tip it begins to solidify and a macroscopically planar solidification front moves downwards inside the tube. Due to the shrinkage of the solidified metal the cast cylinder is firmly held to the tip, ensuring a good thermal contact during the growth of the full length of the samples. To prevent sticking the tip was coated with a thin layer of colloidal graphite.

The distance from the lowest, flat tip surface to the solidification front varied with the time from contact in accordance with the square-root law: $d = a\sqrt{t}$ where d is distance, t time and a is

a proportionality constant. By using tips of different geometrical form the constant in the equation could be changed. In the following discussion the different solidification rates obtained are characterised by assigning the corresponding solidification constants.

Solidification of the samples taken with the apparatus described proceeds towards the hotter melt. The thermal conditions thus are quite similar to those in a DC-casting at high or moderate superheat. The solidification rates obtained were in the region of practical interest, which was inferred from the dimensions of the segregation pattern in the microstructure of the samples: 20-75 μm . Slower solidification rates were obtained very near the cooling tip, however; see below.

Using the lance, samples were taken from melts of different composition. The melts were prepared in an induction furnace using a high-alumina ceramic crucible with a volume of about 1,5 l. Aluminium of technical purity (containing 0.2 w/o Fe and 0.1 w/o Si) was first melted, after which the alloying elements were added in elementary form or as master alloys of a purity comparable to that of the base metal. After each addition the melt was held for some minutes before any sample was taken in order to ensure complete dissolution. A sample was then taken by immersing the lance tip slowly into the melt with the aid of a hydraulic device. Solidification was as a rule allowed to proceed until the solidification front had almost reached the bottom of the silica tube, when the lance was raised and the melt excess ran out through the hole. Shorter samples were taken with the lance which gave the slowest solidification.

The sampling time for the three lance tips used was about 45, 70 and 160 s respectively.

In the test series the content of the alloying elements was successively raised to a final level which was supposed to lie well outside the region of practical interest or otherwise limited from the characteristics of the corresponding binary phase diagram.

A thermocouple (chromel-alumel) protected with an alumina tube continuously recorded the melt temperature, which was held $20-30^\circ\text{C}$

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RESULTS

above the liquidus temperature of each actual composition. The temperature control was attained by adjusting the power of the induction field which was switched on during the sampling. In separate experiments, it was shown that the induction field did not affect the solidification structure. It can be concluded that no stirring action could occur inside the silica tube.

After the lance had been drawn up from the melt the solidified cylindrical samples were removed from the tip and cut into halves. One of the section surfaces was ground with wet grinding paper with a finest grain size of 600 mesh. The ground surface was etched in a $\text{HNO}_3\text{-HCl-HF}$ -mixture to reveal the macro structure. Every sample surface, prepared in the way described, was carefully studied with a low-magnification binocular microscope and the presence of feathery crystals was recorded. In some instances further structure examination was carried out on conventionally prepared micro-sections.

All samples were analysed individually by wet-chemical or X-ray fluorescence methods. Analysis data from all series are collected in Table 1. Analyses made at several points along the whole length of some samples have shown that no significant macro-segregations occurred during solidification.

To get a better picture of the statistics involved in the nucleation of feathery crystals a series of Al-Fe alloys was run separately. Only three different compositions were studied in this series but 15 samples were taken from each melt. Data from this series are given in Table 2 and in Figure 1.

Some attempts were made to determine the cooling rate at different points along the samples. Thermocouples (chromel-alumel) with a rapid thermal response were inserted in the silica tubes at different positions along the tube axis. The rate of cooling of the solid immediately after solidification was evaluated directly from the time/temperature curves recorded.

3.1

Influence of composition

Using the apparatus described 13 binary alloy systems were investigated. Composition and structural data have been collected in Table 1. No feathery crystals at all have been observed in those alloys consisting of Al together with the elements Cr and Zr. In the systems Al-Mn, Al-Pb and Al-Bi one or two samples per series contained a feathery crystal. As there was no systematic increase in the number of twins with rising concentration of the second element in these systems the feathery crystals are considered to be a consequence of the impurity level of Fe, see below.

In the alloys of Al together with Ti, Fe, Ni, Mg, Sn, Cu, Si and Zn feathery crystals have been produced when the concentration of the alloying elements has exceeded a certain critical value. This concentration is very different for different elements, however. When the critical value has been exceeded feathery crystals occur in every sample taken and the number of nucleated twins increases slowly with increasing element content. An example of a sample series is shown in Figure 3.

When the solidification rate was changed it was found that the critical composition values varied a little. Structure data for all Al-Ni series are shown in Figure 4. The critical composition is displaced towards lower values for the higher values of the solidification constant. Similar observations were made by Wakatani et al (4). A possible explanation for this feature is discussed below.

Data for all systems in which feathery crystals were produced have been put together in Figure 5. It is seen that titanium is by far the most efficient element in promoting formation of the crystals and that for the other elements a considerably higher concentration is required. All series show the same displacement of the critical composition with solidification constant.

The significance of the critical composition values is demonstrated by the special series of Al-Fe alloys. The results are shown in Table 2 and have been plotted in Figure 2. The points in the figure represent the probability of obtaining feathery crystals from melts of different compositions if only one single sample is taken with a lance giving a solidification constant $a = 5.96 \text{ mm/s}^{1/2}$. If the two points of the lowest Fe-content are connected by a straight line and extrapolated to 100 % probability, this value is found to correspond to a composition of about 0.9 w/o Fe. The critical composition found for the same solidification constant in the other series when only one sample was taken with different compositions is about 0.8 w/o, in reasonably good agreement. Although no lower concentrations than 0.53 w/o Fe have been investigated statistically in the manner described, it is very likely that the probability of obtaining feathery crystals is reduced to zero if the Fe-concentration is made still lower. Samples taken from aluminium melts to which no alloying element had been added had a coarse structure with the columnar crystals radiating out from the tip.

In some of the systems investigated the successive additions of alloying elements produced a certain grain refining. The number of equiaxed grains which had been nucleated ahead of the solidification front was very small in most systems, but in the Al-Ti system the effect was considerable. When the Ti-content was raised to the vicinity of peritectic composition, i.e. 0.10-0.15 w/o Ti, the grain refinement had increased to such an extent that the growth of those feathery crystals which had been formed, stopped, and for even higher titanium content no feathery crystals at all are visible. Separate experiments have shown that the contribution from this grain refining mechanism could be reduced by increasing the superheat, but it was still considerable at or above peritectic composition. Hence it is probable that the intense nucleation in this system was a consequence of the peritectic reaction between melt and undissolved Al_3Ti -particles from the master alloy which had been added. It is well known that the rate of dissolution of the Al_3Ti -particles is very low. This grain refining may have stopped the growth of the feathery crystals but

it is not supposed to have affected the critical composition for their formation very much.

The basic mechanism for the grain refining observed in the other systems has not been fully clarified. In these systems the number of grains formed in the melt is so small that their influence on the feathery crystals has certainly been negligible.

3.2

Influence of cooling rate

A thorough inspection of the cast samples showed that the feathery crystals were nucleated at or near the cooling tip. This is not always evident from the longitudinal macrosections shown in Figure 3, but it has been confirmed by separate studies of microsections and also from series of successive macrosections along the samples, with the section surface perpendicular to the cylinder axis; see Figure 6. Since no nucleation has been found to take place far from the tip, it can be assumed that the cooling rate required for the nucleation of twins is very high. Attempts were made to estimate the cooling rate at the tip surface from the cooling rate data obtained from measurements by the inserted thermocouples. At a distance of 0.5 cm from the tip surface the cooling rate was found to be about 30°C/s ; 1.5 cm from the tip it was 8°C/s and was only slightly reduced farther away from the tip. Extrapolation from the cooling rate/distance data indicates that the cooling rate at the tip surface is about 100°C/s or higher.

Estimation of the cooling rate at the tip from the dimensions of the segregation pattern gives the same order of magnitude; at the tip the average distance between phase particles formed during solidification was 5-10 μm , which, according to data published by Matyja et al (9) corresponds to a cooling rate in the order of 10^2°C/s .

The solidification rate during sampling was varied by changing the copper tips. The cooling rate very near the different tips was found to be of the same order of magnitude, however, as was shown

by the dimensions of the segregation pattern. The cooling rate at a distance from the tips was of course very different in accordance with the different overall solidification rates. Evidently the initial cooling in contact with the tip is very rapid due to the fact that during this period of cooling the heat abstraction depends upon the heating-up of the copper tip. When the tip has been heated, further solidification and cooling rates depend on the access of cooling water to the back of the copper tip and on the area of contact between the tip and the solidified sample. As has been mentioned above nucleation of the twins was restricted to the first, non-stationary period of heat extraction through the copper tip.

The growth rates in the different samples varied from 0.1-0.5 cm/s near the tip to about $7 \cdot 10^{-3}$ cm/s at 4 cm from the tip giving the lowest solidification constant. Feathery crystals were found to grow under all these conditions, which shows that they, like ordinary dendrites, can grow under widely varying conditions.

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DISCUSSION

4.1

Conditions for the formation of feathery crystals

From all the experimental data available it is evident that two necessary conditions must be fulfilled for the nucleation of twin crystals: the presence of certain alloying elements and a sufficiently high cooling rate during solidification. These facts were realised already by Nakao, but a comparison of the results from all the earlier investigations showed that widely different statements have been made concerning which elements it is that produce feathery crystals, what concentrations of these are needed and what solidification rates must be exceeded.

For example, Nakao obtained feathery crystals in Al-Zn alloys, and yet this could not be done by Nakatani et al. These authors produced feathery crystals in Al-Fe and Al-Ni alloys at a relatively low concentration, but Morris et al found no twins in dilute alloys from these same systems. In the Al-Cu system, Nakao found a critical content to be about 2 w/o, while Nakatani et al had to add more than 10 w/o and Watanabe et al more than about 2 a/o (circa 4 w/o).

The possibilities of determining the elements that produce feathery crystals and also of establishing their critical contents are very dependent upon the experimental techniques used to produce and also to detect the feathery crystals. To realise this, the concept of a critical concentration must first be clarified.

In the present investigation it has been demonstrated that there is no sharp concentration limit above which the feathery crystals suddenly appear. From the study of the twin nucleation frequency in the Al-Fe system it is obvious that there is a slight probability of twin nucleation even at a low concentration and that this probability increases with rising concentration of the element added to the Al-melt. Due to this fact there will always be a fundamental uncertainty in any determination of a concentration dependence, unless the determination is made from a great number of samples taken over a limited composition range.

The concentration dependence of nucleation can possibly explain the irregular occurrence of the feathery crystals in the Al-Mn, Al-Pb and Al-Bi alloys. There is apparently a low probability of nucleating twins in these alloys, either due to a low twin-forming tendency of the elements successively added or to the effect of the impurities in the base metal. As there was no systematic increase in the number of twins when the concentration of the alloying elements was increased, the most probable explanation for these twins is that they have been nucleated under influence of Fe, which is present as an impurity in all alloys studied. The Fe content in the Al metal is about 0.2 w/o and from the investigation of the nucleation statistics it is probable that Fe, also in such a low concentration, may have some influence on the twin formation.

The tendency of different elements to produce twins can be defined by finding the lowest concentration above which every sample solidified under standardized conditions shows at least one feathery crystal. Such a definition has been used in the previous works as well as in this investigation but with different results. Evidently the detection of the first appearance of feathery crystals is influenced by experimental factors. Some factors will be discussed here which are considered to affect formation, growth or detection of the feathery crystals and therefore must be controlled during any determination of the concentration dependence. The relative influence of these factors is different under different casting conditions.

If a melt with a given concentration of a twin-producing element is chill cast, the number of nucleated twins is greater the larger the area of contact between melt and chill. For this reason the critical composition, as defined above, will be inversely proportional to the area of the chill and the latter must be specified if any statement about a critical composition is to have any meaning.

Different chill areas have been used in different investigations and this variation may to some extent have affected the results. In the present investigation the solidification rates were changed by changing the geometrical form of the lance tips. This change was accompanied by a change in the area of the mantle surface, which was found to be the most effective chill surface. This variation of tip areas is the probable explanation for the slight variation in the critical composition values as shown in Figure 5. A similar variation was observed by Nakatani et al, who also varied the chill area in order to change the solidification rate.

The probability of twin nucleation could, in principle, be evaluated per unit area of chill wall. To do this the total number of twins has to be counted over a known area. Such an evaluation has not been included in the present work, mainly due to the difficulties of determining the total number of twins formed round the tips of such a complex form.

All evidence from the present work indicates that the nucleation has taken place near the tip. From this it has been concluded that the

initial chill is the most important factor in feathery crystal nucleation. This is also in agreement with what has generally been found in the samples in the earlier investigations. It has, however, also been stated that feathery crystals have been nucleated a considerable distance (several centimetres) from the chill (2). The reasons for this behaviour are not clear.

The intensity of the initial chill depends on the casting conditions, the dimensions of the chill mould, its thermal properties and the effectiveness of the water-cooling. The last factor will only influence the initial cooling if the mould wall has a low thermal capacity and high thermal conductivity. It is possible that the very high superheat (150-200°C) of the melt in some of the previous works has reduced the intensity of the initial chill effect and in this way reduced the frequency of twin nucleation. In the present investigation the superheat has only been 20-30°C, so the conditions for nucleation have been most favourable.

In any experimental technique which is based on the casting of a melt into a chill mould a very high superheat is necessary, however, to avoid an extensive chill nucleation. At low superheat a great number of grains can be formed and if they are too numerous the growth of the feathery crystals can be hindered or made more difficult to detect. This fact may possibly explain the difficulties experienced (2) in obtaining feathery crystals when casting was carried out at a moderate superheat (20-100°C).

Grain refining by any other mechanism also hinders the growth of the feathery crystals. Grain refining by Al₃Ti-particles has been described in the present work and similar effects have been described by others, e.g. in Al-Mg alloys with a high Mg-content (6).

The chances of detecting the feathery crystals also depend on the method used to investigate the structure of the samples. Usually it is easy to detect feathery crystals on a macro-etched surface if they have grown to a size of some millimetres or larger. Small twins can be difficult to observe: at least, in some alloy systems where the development of the structure details by the etchant is inferior. In these cases the investigation of the samples must be

carried out on polished micro-sections.

If the cast samples are cut lengthwise and the section surface is etched, some feathery crystals may escape observation if they are not cut through by the section surface. This fact will also contribute to the uncertainty of the determination of a critical composition. A more reliable method to detect any feathery crystals formed is to cut the unidirectionally solidified samples perpendicular to the growth direction at some distance from the chill.

To explain the influence of the alloying elements on the twin growth two different theories have been proposed. The present experimental data have been used to test the validity of these hypotheses. Masutani et al suggested that the stability of the feathery crystals depends on the segregation phenomena occurring during solidification. This hypothesis was tested by correlating the tendencies to produce twins expressed by the critical compositions, found in this work, with distribution coefficients and other characteristics of the corresponding phase diagrams. These attempts have not been very successful and there cannot, at any rate, be a simple relationship between the ability of an element to produce twins and the segregation behaviour of the same element in Al.

If the mechanism suggested by Miyazawa et al should be responsible for the feathery crystal formation, it could be expected that the grain size in the nucleation areas ought to vary in accordance with the varying tendencies to produce twin crystals. To check this, measurements of grain size at the chill in several alloy systems have been carried out on samples from the present work.

A slight reduction in grain size with increasing element content has been determined in all series studied for this effect, but no systematic grain size trend, such as that elements which were more effective in producing twins also gave a smaller grain size, could be found.

The present experimental material thus cannot give support to either of the two theories for feathery crystal formation.

Formation of feathery crystals in the DC-casting process

Against the background of the experimental results, most known facts about the appearance of the feathery crystals in DC-cast ingots and how they are influenced by the casting variables can be explained.

Aluminium of technical purity always contains some Fe and Si as impurities. The most commonly cast aluminium is of 99.5% purity and contains about 0.2 w/o Fe and 0.1 w/o Si. In this alloy it can be assumed that, in accordance with the experimental results, Fe has the strongest influence on the twin nucleation. As a consequence of the statistics involved, there is a slight probability of nucleating twins even at this low Fe-content. If the cooling rate is high and there is a large chill area, some twins may be nucleated at a still lower impurity content. Thus twins have been reported formed in DC-cast Al of 99.9% purity (5).

As it has been found that most of the common alloying elements by themselves favour twin nucleation, further alloying of the base metal will increase the tendency of the melt to produce feathery crystals on solidification.

The composition requirement which was found necessary for twin formation is thus fulfilled for most aluminium alloys, which is born out by the fact that feathery crystals have also been observed in most DC-cast alloys.

The second requirement for the nucleation of twins was that the melt had to be cooled at a sufficiently high rate. In order to estimate the cooling rates during solidification of DC-cast ingots, measurements of dendritic arm spacings have been carried out from the surface and inwards to the central parts of an ingot. The dendritic arm spacings were found to be about 10 μm at the outer surface, increasing over the first millimetres inwards and then suddenly falling to a second minimum value of 10-15 μm about 10 mm from the surface, after which there is a slight increase towards the centre. The minimum values of about 10 μm show that solidification has taken place there at a cooling rate of about 100°C/s. A

cooling rate of this order of magnitude was found to be necessary to nucleate twins so this condition is fulfilled in these two surface layers.

The feathery crystals probably originate from the second rapidly cooled layer, 10 mm under the ingot surface. This conclusion can be made from the fact that feathery crystals are never observed at the very surface of the ingots. If a DC-cast ingot is cut perpendicular to the casting direction and the section surface is macro-etched, a surface zone with a thickness of about 10 mm is seen all around the circumference of the ingot section. If such an ingot contains regions with feathery crystals these are always enclosed within this surface shell.

This 10 mm surface layer is formed during the casting period when the ingot is cooled by the mould wall; see Figure 7. The very first metal that solidifies is rapidly cooled by direct contact with the mould wall but, due to the shrinkage of the solidified crust, the direct contact is lost and further solidification proceeds at a lower rate. The total number of nuclei formed in the outermost, rapidly chilled surface layer (thickness less than 1 mm), is so great that any twins which may be formed there cannot grow to any appreciable size. Possibly the stirring action of the melt oscillations at the mould wall may contribute to hindering the growth of the twin crystals.

The sudden rise in cooling rate 10 mm from the ingot surface is due to the onset of the direct water-spray cooling under the mould. In this layer twins can be nucleated and start to grow inwards, but any outwards growth is hindered by the already solidified surface shell.

The inward-facing "surface" of this shell can be considered as an internal chill from which the feathery crystals are nucleated. The total area of this "chill" in an ingot of normal dimensions amounts to several square metres. This area is so large that even at a low content of a twin-producing element one or more twins are likely to be formed.

Once they are formed the twin crystals will spread themselves out through the ingot structure if their growth is not effectively hindered. To stop the growth a very intense nucleation ahead of the growing lamellae is required. This is normally achieved by addition of commercial grain refiner, containing TiB_2 -particles. Nucleation of the Al-phase, stimulated in this way, is made more easy if an alloying element is added. This is a consequence of the depression of the growth temperature of the solid which follows the addition, and by which the effective supercooling is increased. For this reason the common opinion has arisen that alloys are less prone to feathery crystal formation than Al containing less of other elements. As has been shown, the contrary is actually the case but, if alloying elements are added to an aluminium melt all processes are simplified that can lead to the formation of new grains, which hinder the growth of any feathery crystals formed. From the practical observation that alloys can more easily be given a satisfactory grain-refining it can be concluded that the latter effect is predominant.

Studies of the influence of the casting conditions have shown that more feathery crystals are formed if casting is performed at a high temperature, if no grain refiner is added and if the melt is fed into the mould slowly and in a horizontal direction (1). Obviously, all these three factors will reduce the number of grains which may hinder the growth of the twins: a slow inlet of melt into the top layers of the melt pool will give rise to very few grains by dendrite fragmentation, and a high casting temperature will reduce the extension of the supercooled melt zone and also remelt detached dendrite fragments to a greater extent.

If, instead, a cool melt is led in a rapid flow in vertical streams down into the sump the number of grains formed by dendrite fragmentation processes will be high, and together with a TiB_2 -addition a fine-grained structure will be obtained in this way.

Another way of hindering the growth of the feathery crystals is to stir the melt, which can be done either by mechanical or by electrodynamic means. It has been shown (2) that stirring of the melt past the growing twins will stop the twin growth, possibly by making the distribution of solute at the solidification front less favourable.

Stirring is also known to increase the nucleation and the extra grains formed will contribute as purely geometrical obstacles to the twins.

By changing the casting temperature and the melt discharge as described, the growth, rather than the nucleation, of the feathery crystals can be influenced. Their nucleation is probably very little changed in this way. As most aluminium alloys will give twins if the cooling rate is high enough, the only way to avoid nucleation is to reduce the cooling rate. The secondary cooling can be reduced by reducing the amount of cooling water, supplied either by a constant spray or by the pulsation technique. The fact that in this case the rate of casting has to be reduced will probably make this method less attractive, however.

4.3

Formation of feathery crystals in other solidification processes

From the experimental results it is to be expected that feathery crystals ought to appear in all solidification processes where impure aluminium or aluminium alloys are rapidly solidified. Several observations show that this is also the case; for example, it is known that continuously cast thin bands (Hunter) and weld beads are sensitive to feathery crystal formation (10,11).

In the continuously cast bands the rate of cooling is 10^2 - 10^3 °C/s and the area of the rapidly cooled surface is large in comparison with the volume of the cast metal. It is quite understandable that many twins will be nucleated in aluminium alloys cast by this process, even with a low content of a twin-producing element.

During welding, the filler metal solidifies very rapidly under the direct cooling action of the adjacent metal parts which have been welded together. Study of the dendritic arm spacings in the bead indicates that cooling rates can be as high as about 10^3 °C/s. The filler metal may be strongly superheated and excessive nucleation in the molten pool is not very probable, so most grains in the weld

deposit are grown directly on to the grains of the base metal. If a twin crystal is formed it will have a good chance of spreading out. Feathery crystals have also been frequently found in weld beads, especially when welding has been carried out at a low travel rate (11). This is possibly caused by a higher superheat under these conditions, suppressing the nucleation in the liquid.

5 SUMMARY

- 1 Two conditions are necessary to nucleate feathery crystals in cast aluminium: Presence of certain alloying elements in the melt and a cooling rate of about 10^2 °C/s.
- 2 Provided the cooling rate is high enough, the number of nucleated twin crystals is proportional to the area of the chill and to the concentration of the twin-producing element.
- 3 Under identical solidification conditions the following elements were found to have the same tendency to form feathery crystals at the concentrations given (in weight per cent): Ti 0.015, Fe 0.85, Ni 1.10, Mg 1.30, Sn 2.90, Cu 3.50, Si 5.55, Zn 6.45.
- 4 The surface layers of a DC-ingot solidify at a cooling rate which is of the same magnitude as the critical. Hunter bands and welds are cooled still more rapidly.
- 5 Nucleation of twins in DC-ingots can be avoided only by reducing the intensity of the secondary cooling.
- 6 Growth of feathery crystals can be stopped by an efficient grain refining or by stirring of the melt. These factors can be optimised by appropriate choice of casting conditions.

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Table 1 Experimental data.

Alloy system	Sampling time (s)	Average solidification constant (mm/s ^{1/2})	Composition of samples (v/o)															
			Samples containing feathery crystals are underlined															
Al-Ti	180	1.86	0.015	0.025	0.040	0.056	0.065	0.083	0.095	0.110	0.114	0.170						
	60	5.81	0.005	<u>0.022</u>	<u>0.035</u>	<u>0.050</u>	<u>0.062</u>	<u>0.086</u>	<u>0.094</u>	<u>0.108</u>	<u>0.145</u>	0.163						
Al-Fe	180	2.16	0.75	0.84	0.89	1.04	<u>1.13</u>	<u>1.20</u>	<u>1.35</u>	<u>1.42</u>	1.53	1.68	2.19					
	70	5.38	0.02	0.05	0.11	0.27	0.55	0.80	0.83	<u>0.98</u>	<u>1.06</u>	1.68						
Al-Ni	180	3.35	1.09	1.25	1.30	1.48	1.64	1.74	1.95	2.10	2.25	2.25	2.24					
	70	5.73	0.028	0.050	0.075	0.13	0.30	0.57	1.02	1.27	1.52	2.01						
Al-Mg	180	1.94	0.90	1.27	1.50	1.92	2.01	4.74	1.09	1.14	1.32	1.39	4.23	4.40	6.40			
	70	5.97	0.010	0.031	0.050	0.12	0.33	0.66	1.30	1.40	1.90	2.76	3.32					
Al-Sn	180	1.86	2.84	2.93	3.21	3.62	4.02	4.56	1.26	2.42	2.86	3.02	3.40	5.10				
	70	5.36	0.03	0.06	0.10	0.17	0.44	0.72	3.62	4.03								
Al-Cu	180	1.86	3.19	3.29	3.60	3.78	3.82	4.02	4.48	3.15	3.51	4.12	5.30	6.19	7.40			
	70	5.50	0.027	0.053	0.101	0.32	0.61	1.19	2.39	4.50								
Al-Si	180	1.86	0.10	0.24	0.48	1.00	1.40	3.60	2.85	10.20	11.50							
	70	5.71	4.50	4.90	5.80	6.50	6.70	8.60	9.85	10.20	11.50							
Al-Zn	180	1.86	0.018	0.050	0.088	0.117	0.30	0.57	1.14	2.33	3.46	3.69	4.75	5.75	6.69			
	70	5.73	6.00	6.45	7.10	8.15	9.05	10.10	11.10	12.75								
Al-Mn	180	1.86	0.020	0.05	0.07	0.09	0.11	0.28	0.55	1.05	2.16							
	70	5.73	0.75	1.00	1.25	1.45	1.65	1.85	2.00									
Al-Pb	180	1.86	0.02	0.03	0.065	0.12	0.20	0.35	0.51	1.60								
	70	5.73	0.50	0.55	0.80	1.25	1.30	1.35	1.55									
Al-Cr	180	1.86	0.025	0.055	0.075	0.090	0.10	0.26	0.55	0.80								
	70	5.38	0.017	0.045	0.092	0.25	0.70	0.89	1.40	2.8								
Al-Bi	180	1.86	0.02	0.04	0.07	0.09	0.11	0.23	0.26									
	70	5.97																
Al-Zr	180	1.86	0.02	0.04	0.07	0.09	0.11	0.23	0.26									
	70	5.50																

Table 2

Twin nucleation statistics in the Al-Fe system.

Composition of the melt w/o Fe	Total number of samples	Number of samples containing feathery crystals	Per cent of total number
0.51	15	3	20
0.78	15	11	73
1.02	15	15	100

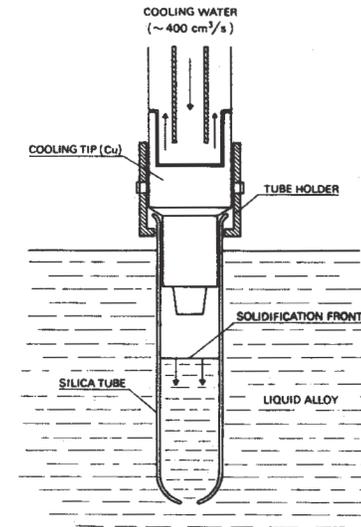


Fig.1 - Experimental equipment.

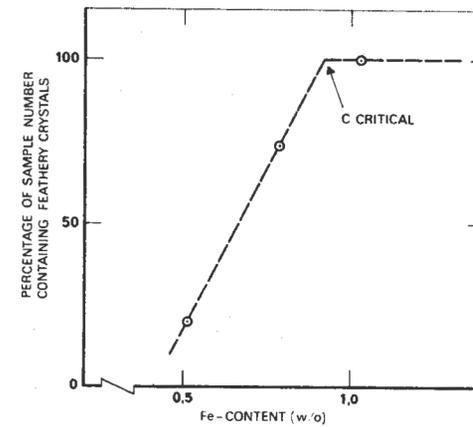


Fig.2 - Composition dependence of the twin nucleation frequency in the Al-Fe system.

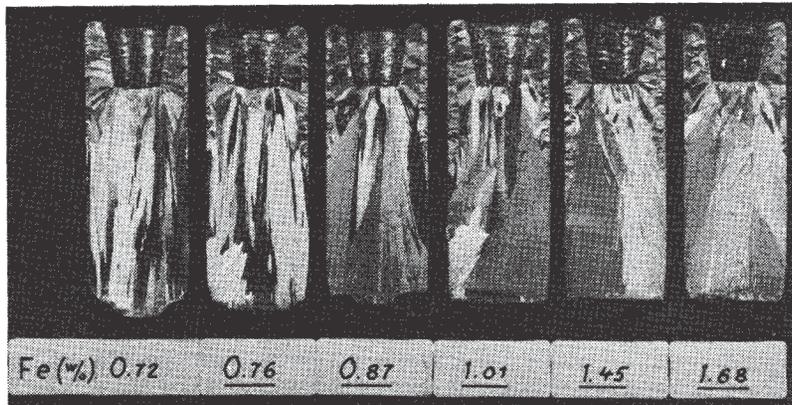


Fig.3 - Sample series from the Al-Fe system. Length of samples 60 mm.

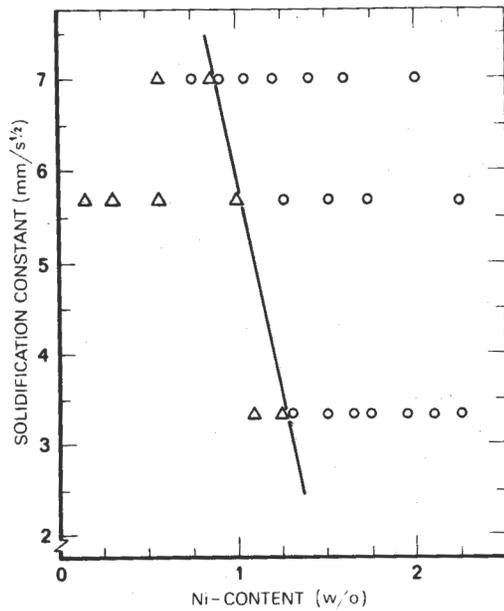


Fig.4 - Sample structures in the Al-Ni system as a function of composition at different solidification constants. Triangles = no feathery crystals, circles = feathery crystals.

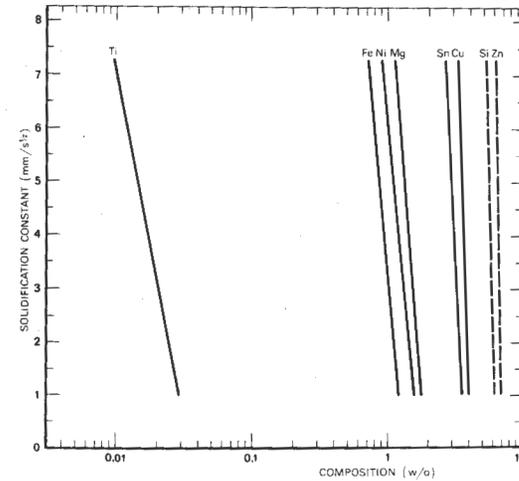


Fig.5 - Critical composition of all feathery crystal-producing elements at different solidification constants. All basic data from Table 1.

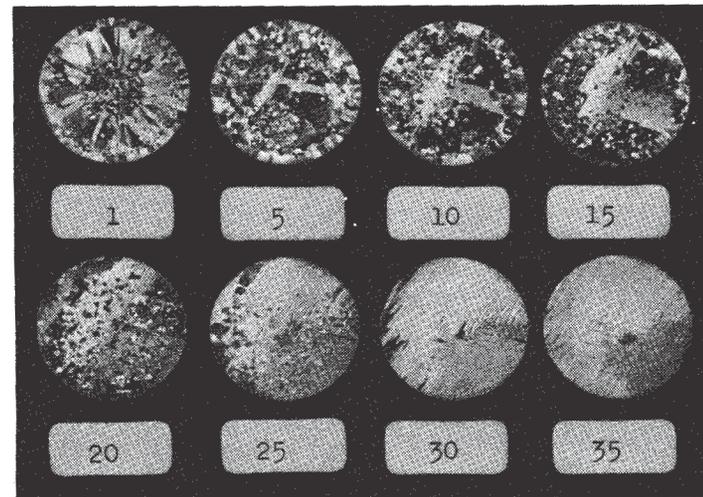


Fig.6 - Successive sections of a sample containing 1 w/o Fe. Figures indicate distance in mm from the lance tip. Sample diameter 20 mm.

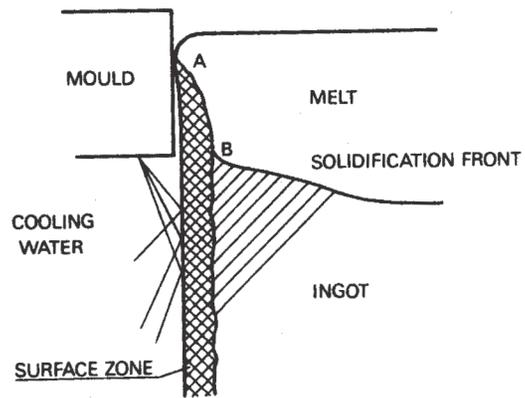


Fig.7 - Schematic illustration of the possible sites (A and B) where twins can be nucleated in DC-ingots.