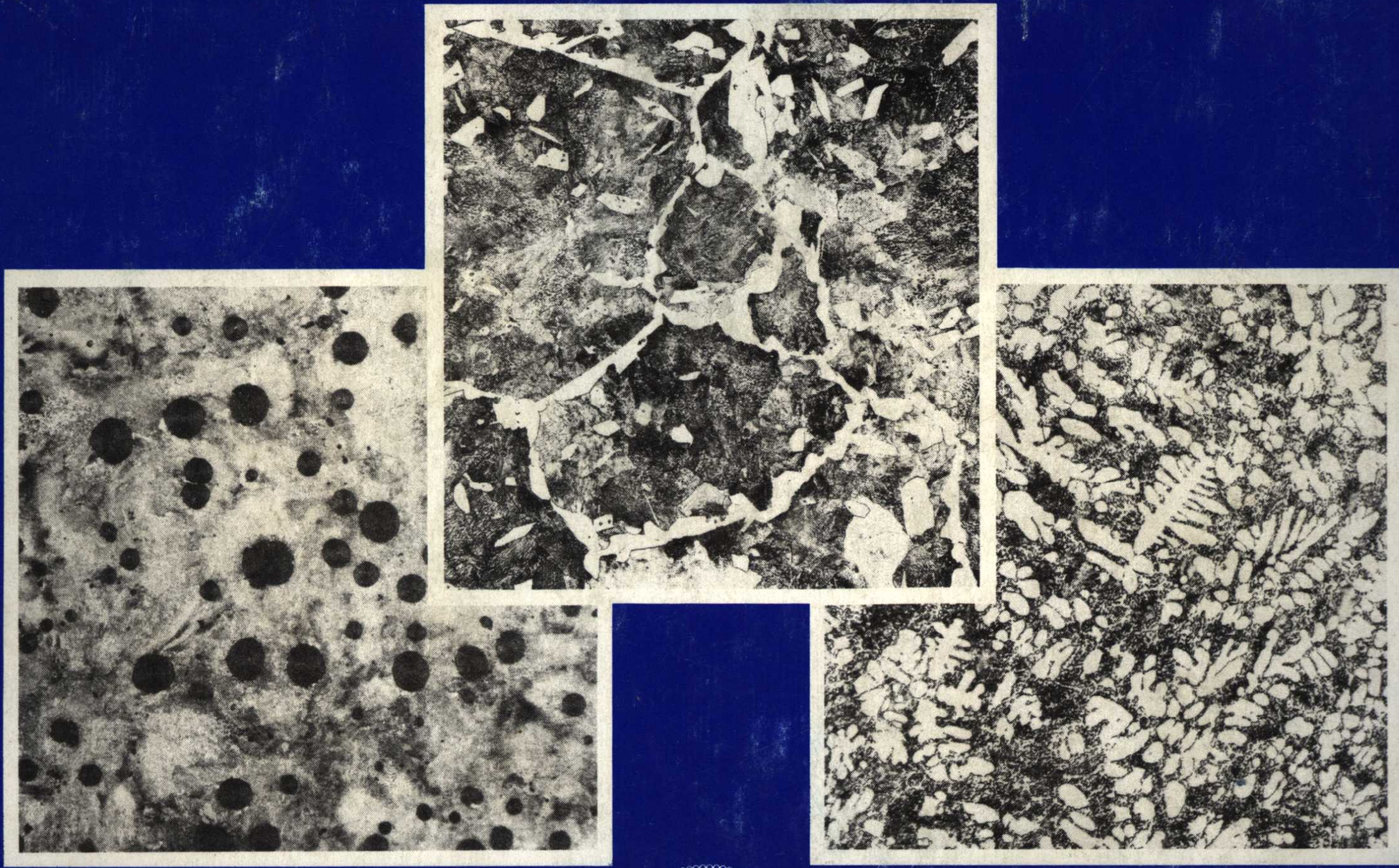
THE INSTITUTE OF BRITISH FOUNDRYMEN

Typical Microstructures of Cast Metals



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New Revised Edition

THE INSTITUTE OF BRITISH FOUNDRYMEN

TYPICAL MICROSTRUCTURES OF CAST METALS

Prepared by
Working Group P9
of the Technical Services Co-ordination Committee

New Revised Edition

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Preface

The Institute of British Foundrymen first published a book under this title in 1957, and it was reprinted in 1966. As stock diminished, a Working Party was convened to assess the case for revision and updating as opposed to a further reprinting. A policy of revision was agreed, and the Working Party has now completed its self-imposed task.

There were three primary reasons for recommending revision:-

First, and most important, it was felt desirable to increase the educational value of the book. Of course, there has been no intention to write a text-book on solidification, and the new volume assumes a reasonable level of basic knowledge. Nevertheless, based on that assumption, the aim has been to prepare a text which could be used by technologists and academics alike, and which would thereby contribute to a strengthening of the links between the research and production aspects of cast metals science and technology. This has meant some restructuring of the book and the incorporation of an introductory section on metallurgy and solidification. It is to be hoped that the resulting work will be of value to the teaching profession and that it will usefully supplement existing literature in the field.

Secondly, it was felt desirable to internationalise the book as far as possible since there is no strictly comparable publication and cast microstructures appear to be independent of geography. This has led to a greater emphasis being placed on alloy composition and reduced emphasis on national standards. Where these are referred to, there is some bias towards current British standards, but it is to be hoped that individual readers overseas can bring their own experience to bear on this matter. Essentially, this is an atlas of structures related primarily to composition and casting practice, and only secondarily to specifications.

Thirdly, and given the case for revision, it seemed appropriate to update the earlier work and to standardise as far as possible on matters of layout and presentation. In the interests of commercial use, opportunity has been taken to provide information in those areas where microstructure and end-use are closely linked, and, of course, to provide basic data on specimen preparation techniques. While the Working Party is well aware of the importance of the electron microscope, few examples of electron microscopy have been included, since it is clear that the cast metals industry will long continue to rely on the conventional optical microscope.

Inevitably, there will be much debate about the meaning of the word "typical". The question is ultimately insoluble and we can only say that we have done our best to honour consensus and expert views. It is also impossible to define *all* the elements of microstructure, particularly when it comes to what might be regarded as "defective" structures or even the well-known range of imperfections in castings, such as shrinkage, hot-tears or gas-induced porosity and inclusions. This is *not* an atlas of such defects: if it had been it would probably have been at least twice the size, with a corresponding increase in cost. Equally inevitably, there are some more or less significant omissions: we apologise for these, but there has to come a time when a halt is called, even if the material available is incomplete.

As Chairman of the Working Party, my own contribution has been very small compared with those who have borne the brunt of the work. We were helped initially by Mr. John Hall of the BNF Metals Technology Centre, and I would like to pay particular tribute to Dr. Peter Beeley of Leeds University for the introductory section; to Mr. Ian Hughes of BCIRA for the section on cast iron, to Dr. Jim Jackson and his colleagues at SCRATA for the section on steels, and to Dr. Voya Kondic of Birmingham University, with further assistance from Dr. Jackson, for the section on non-ferrous metals. All of these gentlemen have put long hours into the new publication, and together with members of the permanent staff of the IBF and Mr. John Wright and his colleagues in the SCRATA reprographics group, must take the credit for the end result. However, all of us would be ready to acknowledge our great indebtedness to many other helpers, and not least to those who undertook the substantial labour involved in pioneering the first edition.

J. A. REYNOLDS,
Chairman.
IBF Working Group P9.

Acknowledgements

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Dr. R. Durman	Bradley & Foster Ltd.
C. T. Moore	Court Works Ltd.

Those who supplied Material

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S. D. Apsley	BCIRA (formerly Birmid Qualcast Ltd.)

The Director and colleagues of BCIRA for assistance in providing advice, material and facilities.

SECTION III - CAST STEELS AND HEAT RESISTING ALLOYS

Most of the steel micrographs were prepared by E. J. Ridal, SCRATA

The Cast Steel Working Party consisted of:

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The nickel-base alloy micrographs were provided by Rolls Royce Ltd., Derby, and the cobalt-base alloys by Deloro Stellite Ltd.

Contents

The Metallurgical Background

Castings and the foundry process

The pouring of molten metal into moulds is used both for the manufacture of shaped castings and as a first stage in the manufacture of wrought products, for which static and continuously cast ingots provide the starting material for most deformation processing sequences. Thus most metals are cast in the first instance and it is with the many variations of microstructure intrinsic to the cast condition that this work is concerned.

Forming from the liquid affords the most direct route to the shaping of components close to the dimensions required by the designer. For some alloys, for example those which lack the plasticity or machinability for alternative manufacturing processes, casting is the only practicable means of developing shape: such materials include important wear, heat and corrosion resisting alloys and embrace the entire family of the cast irons. In many cases, however, the choice between cast and wrought products is available and is most commonly made on economic grounds, which should, ideally, be based on the overall cost effectiveness of the end product. This economic basis of process selection applies not only between the two major categories of cast and wrought products but to the many process variations within each of these groups and to the whole range of alternative routes to finished com-.ponents, which are summarised in Fig. A.

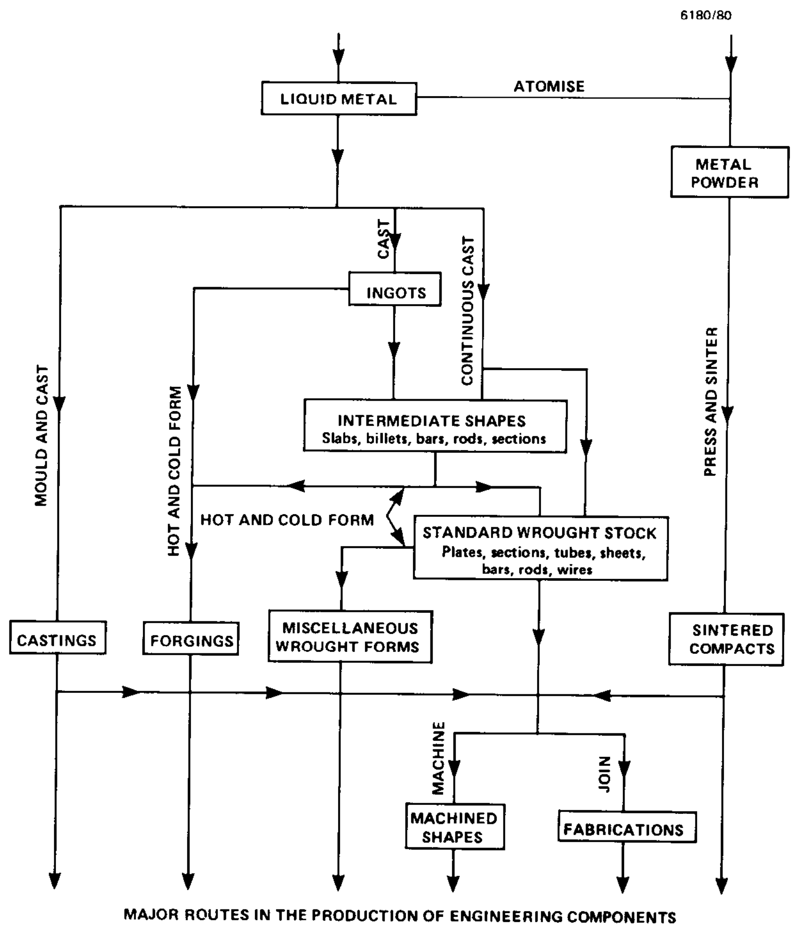

Fig. A.

(Courtesy of Foundry Technology, P.R. Beeley, Butterworths 1972.)

Whilst static ingots and continuously cast forms are themselves castings, albeit of relatively simple shape, the fact that they will undergo extensive subsequent deformation reduces the significance of their initial microstructure whilst, in many cases, even soundness itself is subordinated, in the as-cast form, to the eventual achievement of a high yield of saleable metal, expressed as a proportion of the original melt. In castings, by contrast, the properties required by the designer are heavily dependent on both soundness and microstructure of the original casting, even in those alloys in which the structure can be modified by subsequent heat treatment. The achievement of soundness and the control of as-cast microstructure are therefore central objectives in metal founding technology.

The present book is primarily concerned with microstructures of shaped castings and with alloy compositions corresponding to particular cast metal service requirements. Similar structures would, nevertheless, be frequently found in the analogous primary cast shapes destined for mechanical working.

The basic principles of metal casting and the more detailed treatment of foundry processes and technology are to be found in the literature, of which a short bibliography is given at the end of this Introduction. For the present it will suffice to review the principal steps in the manufacture of a casting, as a prelude to a more detailed examination of factors that govern or influence the development of its microstructure.

The greatest proportion by weight of castings production is made by pouring molten metal into expendable refractory moulds, produced from patterns which are essentially replicas of the required cast forms. The commonest and most flexible single process is sand casting, in which the appropriate mould cavity is generated in a sand-based medium of sufficient refractoriness to withstand the pouring temperature. Strength to retain the pattern impression is provided by clay or chemical binders, although unbonded material too can be employed in modern variants such as the V or vacuum moulding process. A different class of refractory mould is the finer, slurry based type as used in investment casting, a process also distinguished by the use of expendable patterns, normally of wax and melted out to leave the shaped cavity in the consolidated refractory.

The other important family of processes is based on permanent mould or die casting, in which molten alloy is introduced directly into metal moulds, themselves carrying the impressions with the required shape features and thus replacing the patterns that serve as the permanent tooling in most other casting processes. These processes involve higher tooling costs and more shape limitations than those based on refractory moulds; they are also more restrictive with respect to alloy composition, but are especially advantageous for the rapid production of relatively small cast components required in large quantities. Die casting processes are particularly important in zinc and aluminium alloy production.

More specialised foundry processes, for example centrifugal and duplex casting as used for the manufacture of hollow cylinders and rolls, can combine features of sand or die casting with characteristics of their own: certain examples of structure from these products are also included in the book.

The complete sequence for producing a casting involves preparation of a melt of the appropriate composition and quality, provision of the mould or die with its integral gating and feeding system, the pouring operation, solidification and cooling of the casting within the mould, and the finishing sequence, which involves stripping, removal of heads and runners, fettling and frequently heat treatment. Machining, surface treatment or other ancillary processes may follow to meet particular product design requirements.

Several of these stages of manufacture influence the microstructure of a casting made to a particular compositional specification. Melting conditions and melt history and treatment have a potent effect on the development of microstructure during freezing. This is further affected by the cooling rate in the mould, itself influenced by casting mass and by the nature of the moulding medium. Structural differences would thus be expected between sand cast and die cast products in a particular alloy and numerous such examples are illustrated.

With the development of microstructure during solidification are coupled the equally vital phenomena of feeding, on which depend the soundness of the casting, that is its freedom from gross or dispersed shrinkage porosity: microstructure and soundness are thus closely interrelated.

In many cast alloys further development of the microstructure occurs after solidification, during cooling in the mould or in subsequent heat treatment, either through solid state transformations or simple diffusion, so that the final microstructure is the result of the entire history of the cast metal from melting stock to finished component.

The significance of microstructure in relation to the end product lies mainly in those structure-sensitive properties which, together with cost, influence the selection of a cast alloy of particular composition. It should, however, be emphasised that although there is scope for microstructure control through adjustment of several variables, it is also influenced independently by other variables that are less easy to control, so that freedom to select a specific microstructure is limited: such freedom is enhanced in those alloys which respond to heat treatment.

Cast alloys in relation to process requirements

Despite the availability of both cast and wrought products within most of the alloy families, significant differences exist between the individual compositions selected for the two processing methods, which explains the existence of separate sets of specifications. These differences have arisen in part from the special needs of the casting process. The response of an alloy to the conditions imposed in founding is determined partly by its constitution, especially as affecting its mode of freezing, whilst in some cases the microstructure itself bears on the problems of manufacture. The role of alloy composition in founding will be briefly reviewed before further consideration of the development of microstructure in cast materials.

The requirements of an alloy in the foundry can be related to three successive stages of the casting operation. At pouring the metal requires fluidity to achieve satisfactory mould filling and reproduction of surface detail, and to avoid cold laps or poor definition. The second stage involves the progress of solidification through the body of the casting, when the requirement is to achieve internal soundness concurrently with the initial development of the as-cast structure. The problems of feeding and the nature of the structure are determined largely by the solidification characteristics of the alloy. Some control of solidification can be achieved through thermal conditions, although these depend also on the mass and shape of the casting and the properties of the moulding material associated with the particular process.

The third stage of the casting sequence involves completion of solidification and cooling to ambient temperature. Feeding continues throughout freezing, but during the later stages cohesion is established and the emphasis moves to the behaviour of the cast material under stress. The casting now contracts as a continuous solid body and cohesion must be maintained as resistance is encountered from the mould or through the differential cooling of casting sections. If contraction strain cannot be absorbed within the metal-mould system hot tears or cracks are formed. For a given mould the behaviour of the alloy during this stage of cooling depends upon its specific contraction and its structure-mechanical properties relationships at successively lower temperatures.

Basic alloy constitution is relevant to the requirements of all the above stages of the casting sequence. It will be seen that a narrow freezing range is the crucial characteristic and this accounts for the customary association of good foundry qualities with alloys approximating to eutectic composition. Systematic variations in fluidity conform to this behaviour, since this property is closely associated with the mode of solidification in the mould passage. For constant superheat above the liquidus temperature, maximum fluidity is generally obtained in pure metals and in alloys close to eutectic composition, whilst alloys freezing over a long temperature range usually require much greater superheat for satisfactory mould filling.

The feeding characteristics of alloys are similarly related to the mode of freezing. Ideal feeding conditions are usually obtained with progressive or directional solidification, which ensures constant access of compensating liquid to the contraction sites at the solid-liquid interface. This is most readily achieved in alloys of short freezing range, which tend to solidify by the convergent growth of a sound skin towards thermal centres situated in feeder heads. Alloys of long freezing range, by contrast, tend to freeze in a pasty manner, with intercrystalline residual liquid present through an extensive zone: the mass transfer of feed metal is in this case severely restricted in the later stages, producing a tendency to dispersed porosity unless steep temperature gradients can be induced. These alloys are also susceptible to the segregation of low melting point constituents by the intercrystalline movement of solute rich liquid under the influence of contraction and convective forces.

Feeding in most cast alloys can be related to one or other of these contrasting types of behaviour, depending on freezing range, but graphitic cast irons are a major exception, undergoing as they do an expansion stage during freezing. Solidification in these alloys involves precipitation of two phases, austenite and graphite, sequentially or simultaneously according to composition, temperature and location in the casting. Contraction accompanying the growth of austenite is offset by expansion resulting from the precipitation of the lower density graphite phase, reducing the need for an external feed supply. Self feeding is, however, bound up with the need for mould rigidity to contain the expansion pressures. Apart from highly specialised type metals containing bismuth and antimony, these cast irons are the only commercial alloys undergoing expansion on freezing.

Finally, the ability of a casting to resist contraction restraint without hot tearing is again associated with the freezing range of the alloy. The crucial factor in this case is the length of the temperature range over which the particular alloy retains a liquid fraction after solid cohesion has developed. This determines the total linear contraction accumulated in a casting section whilst the alloy is in a weak and brittle condition: a short freezing range is thus again beneficial, although not the sole factor concerned.

Notwithstanding the association of good foundry qualities with near-eutectic compositions, cast alloys of other types are widely and successfully used, given appropriate attention to design and foundry technique.

The significance of structure in the manufacturing process

The metallographic structure in a cast product is frequently the outcome of physical conditions sought primarily to meet other needs of the foundry process. To quote one example, the directional freezing which assists feeding may also produce zones of columnar grains. Although such structures sometimes undergo subsequent recrystallisation, alignment of microstructural features may persist in the final material, inducing varying degrees of anisotropy. The pasty mode of freezing, on the other hand, is commonly associated with equiaxed macrostructures. Refinement of these is often sought, not only for beneficial distribution of microconstituents, but to achieve readier mass flow for feeding in the pasty stage; the hot tearing tendency is also then reduced by delayed cohesion and by dissipation of the strain over more residual liquid sites. Heat treatment times too can be greatly reduced by prior refinement, through reduction of the critical diffusion distances involved.

In other cases foundry conditions are directed primarily at structure control for the optimisation of mechanical properties in the product. Processing and product characteristics are thus seen to be interdependent through the medium of macrostructure and microstructure.

Cast alloy groups

Although cast alloys can be classified in various alternative ways, for example by structure type, properties or areas of application, the organisation of manufacture cuts across such groupings: the foundry industry consists mainly of units specialising in cast iron, steel, light alloys or copper alloys, with a few limited areas of overlap. This book has been compiled in a similar manner, which also corresponds to the main groups of standard specifications for cast materials. Part of the purpose of the present introduction is to knit together the separate sections by emphasising common features and contrasts, between as well as within the respective alloy groupings.

Where the illustrated microstructures are of materials made to particular specifications, these are given in the commentaries and reference can be made to the full specifications if required. In the case of the cast irons, chemical composition is not normally specified except for the high alloy types: the grey irons are graded by the tensile strength applicable to a particular section thickness, whilst combinations of tensile strength and elongation are specified for the ductile irons. For the steels and non-ferrous alloys composition ranges are normally designated and most specifications also give values for mechanical properties, including tensile properties, with proof or yield stress, impact, bend, hardness and other values where appropriate. General clauses cover various inspection and testing procedures and quality requirements, for which numerous separate specifications also exist. For particulars of these reference should be made to the British Standards Yearbook, ASTM Standards Annual Index and other compendia.

Some characteristics of cast microstructures

Cast alloys exhibit many different microstructures and the characteristics crucial to the particular properties and application vary greatly with alloy type. Certain structural features are, however, common to alloys with widely differing compositions and can thus be reviewed in general terms.

Macroscopic features include contrasting zones of differing grain structure, for example the columnar and equiaxed zones most commonly discussed in the context of ingots for further working. Various forms of macrosegregation are also encountered and result from several different and complex mechanisms. Anisotropy and local property variations sometimes accompany such features. The duplex structures used in certain special cast products such as rolls illustrate the practical exploitation of the ability to develop differential structures within a cast material. These various forms of macrostructure are normally visible to the naked eye or at very low magnifications and specific examples will be examined.

The grain structure itself is frequently observed on either macro- or micro-examination; This may consist of primary grains formed on freezing but is in other cases the product of solid state transformation. Multi-phase systems are characterised by widely varying distributions of the separate phases around and within the principal grain structure. Where this results from a solid state transformation the distribution of constituents may still retain characteristics derived from an earlier stage, as exemplified in Figs. 279 and 281, in which transformed steel exhibits features from the solidification and high temperature solid stages respectively.

Two important types of feature associated particularly with cast alloys result from dendritic and eutectic growth, which will be discussed in more detail. Within the actual grains, these features often predominate in the microstructure.

On the scales of the grain and of these immediate sub-structures, segregation is again a common occurrence: the dendritic segregation of alloying elements is observed as coring in solid solutions and as characteristic second phase morphologies in more complex systems. Several examples will be highlighted in the section dealing with the development of cast microstructure.

Structural features consequent on heat treatment are not peculiar to cast alloys but are particularly important in high strength cast constructional materials. They include the products of martensitic transformations and of precipitation processes following solution treatment. It should be emphasised that some of the most significant features developed in heat treatment cannot be resolved by optical microscopy but require the higher magnifications attainable in the electron microscope: typical examples are shown in Figs. 41 and 42. It might be noted here that the useful role of electron microscopy in revealing features of cast microstructure is not confined to the magnification aspect but includes the capacity to elucidate the three-dimensional characteristics of certain components, as exemplified in the scanning electron micrographs in Figs. 53, 54, 92 and 390.

Other features encountered in cast alloy microstructure include non-metallic inclusions, of which the indigenous type are derived from the characteristics of the melting practice and the purity of the initial melting stock: manganese sulphide inclusions in steel fall into this category and their morphology is both important to properties and sensitive to small changes in deoxidation practice, (Figs. 373, 374 and 375). Exogenous inclusions, usually much larger, originate mainly from furnace, ladle and mould refractories. Microporosity resulting from gas precipitation or from shrinkage may also be observed. The incidence and tolerance of inclusions and porosity in castings is examined more fully in the literature relating to defects.

For the proper understanding of microstructure and its development, alloy phase diagrams should also be consulted. This aspect is featured frequently in the texts listed in the Bibliography, especially in that by Chadwick, as well as in more comprehensive and general works on metallography.

The development of cast microstructure

The strong preliminary influence of melt condition on the development of cast structure has previously been emphasised and arises mainly from its effects in the solidification process. Major structural characteristics are developed during freezing, which has already been shown to exert a residual influence even in those cases where the structure is modified by phase transformations during further cooling or heat treatment. Wrought products similarly originate in the molten state and, although the cast structure is in this case drastically modified by subsequent mechanical working, the original "as-cast" size and distribution of constituents and segregates can still profoundly influence the phenomena of homogenisation and heat treatment.

Crystallisation of an alloy melt involves the separate stages of nucleation and growth, the locations and relative rates of which affect both the general progress of freezing and the nature of the as-solidified structure. Nucleation is the initial step and it is generally accepted that heterogeneous nucleation on foreign substrates is the normal occurrence in commercial castings. For a particle to serve as a nucleus, it must be readily wetted by the liquid metal. A close epitaxial relationship is beneficial and substances having lattice parameters closely matching those of the alloy fulfil this function. The identities of some nuclei found to be effective in particular alloys have been established, although many other indigenous nucleants remain to be identified.

The number of operative nuclei is directly related to the number of primary grains in the cast material, although in alloys of eutectic composition, for example, it is both convenient and logical to regard the primary grain as that multi-phase unit within which two separate phases grew in association from a single centre. Such a unit must contain at least two original nuclei, although much of this duplex structure can subsequently be developed by branching.

It is important at this stage to note that the significance of grain size in cast alloys is not always related to the primary grains but may be attributed to such features as dendrite arm spacing or to grains developed by solid state phase transformations in the alloy.

Nucleation can be allowed to occur spontaneously on particles already present in the melt, or can be induced by added nucleants or inoculants: such additions are the commonest form of structure control applied to castings. The phenomenon of heterogeneous nucleation also accounts for the major significance of melt condition in determining the structure of cast alloys and accounts for the frequent sensitivity of the microstructure to small changes in composition. The nature of the available nuclei depends on the presence of impurities derived from furnace charge, refractories, slags, fluxes and atmosphere, and depends also on the thermal history of the melt, including holding time and degree of superheat: these conditions affect the formation, solution and precipitation of nucleating compounds at temperatures near the alloy liquidus.

Once nucleation has occurred, the structure of the primary grains is determined by growth processes. Two broad patterns of growth are observed, depending upon alloy constitution and thermal conditions: these are associated with the two main types of macrostructural zone encountered in castings and exhibited in the aluminium and steel examples in Figs. 25 to 28 and 239 to 242 respectively. Growth may occur, at least macroscopically, in approximately a single direction, as observed in the advance of a solidification front from a mould surface under a pronounced temperature gradient. These conditions favour the formation of a columnar zone, normally characterised by a preferred crystallographic orientation. Some of the research into growth processes has been conducted under similar but more idealised conditions of controlled unidirectional freezing.

Alternatively, growth may occur from centres within the undercooled liquid, proceeding radially from each centre to form a primary grain. These free grains can originate in several ways. They may grow from independent nuclei or from fragments of previously formed crystals transported from other zones. Small crystals may also be initially formed at the cool mould surface or at the upper free surface of the liquid, to be transported to the interior by gravity, turbulence or convection. These grains are approximately equiaxed, randomly orientated and again form characteristic zones in the macrostructure. Very fine equiaxed grains may also be induced as a structure control measure, by the addition of nucleants or growth inhibitors to the melt.

Depending on the alloy and the solidification conditions in the particular casting, the macrostructure may be wholly columnar, as in Figs. 25 and 240, with growth proceeding until the grains impinge on those growing from other mould surfaces; it may be wholly equiaxed as in Figs. 28 and 242(c) or both types may be present as in Figs. 239 and 242(b) Apart from the steep temperature gradients as mentioned above, all-columnar structures are promoted by high pouring temperatures and low alloy contents, and are the normal occurrence in castings of pure metals. In special cases solidification may be so controlled as to produce columnar growth in a single direction throughout the casting, or even to form a single crystal: a gas turbine blade casting embodying the former principle is illustrated in Fig. 380.

In these illustrations of macrostructures it will be noted that very low magnifications are employed. At the much higher magnifications used in microexamination, dendritic, eutectic and other features predominate but a superimposed macrostructure may well still be present, even though unobserved under the same conditions.

Whether the macroscopic growth pattern is unidirectional or radial, the actual interface may be smooth and non-crystallographic, i.e. flat or spherical as the case may be, or may be characterised during growth by irregularities in the form of projections or leading phases. The nature of the growth interface and its influence on the microstructure will now be briefly considered, since growth phenomena are largely responsible for the two most familiar groups of microstructural features in cast alloys, those associated with dendritic and eutectic freezing.

A smooth, planar interface is only obtained when a steep temperature gradient is combined with a low growth rate. In alloys, uniform deposition of further solid on the interface is inhibited by the presence of a narrow zone of solute-enriched liquid produced by differential freezing: this has a lower freezing temperature than the bulk liquid. Under such conditions existing projections become stabilised and grow preferentially, since they come into contact with liquid which is ready to solidify at a higher temperature than that in the layer adjoining the interface. This produces progressive transition to a hexagonal cellular morphology; under most circumstances encountered in commercial castings, however, there is further development to dendritic growth. Primary dendrite arms are formed in the direction of heat flow and secondary arms can subsequently grow by a similar mechanism operating laterally: the full skeletal structure of rods or plates develops within each grain and is frequently observed in cast macro- and micro-structures, in some cases as the principal structure and in other cases as a "memory" effect by virtue of residual micro-segregation or coring. Examples of dendritic features in microstructures are seen in Figs. 52, 128, 176, 279 and 337 and many other specimens. The dendritic grains maybe columnar due to directional growth or equiaxed following growth from independent centres.

The conditions giving rise to the successive transitions in the mode of growth in solid solution alloys as outlined above are summarised in Fig. B and analogous transitions are observed in eutectic solidification.

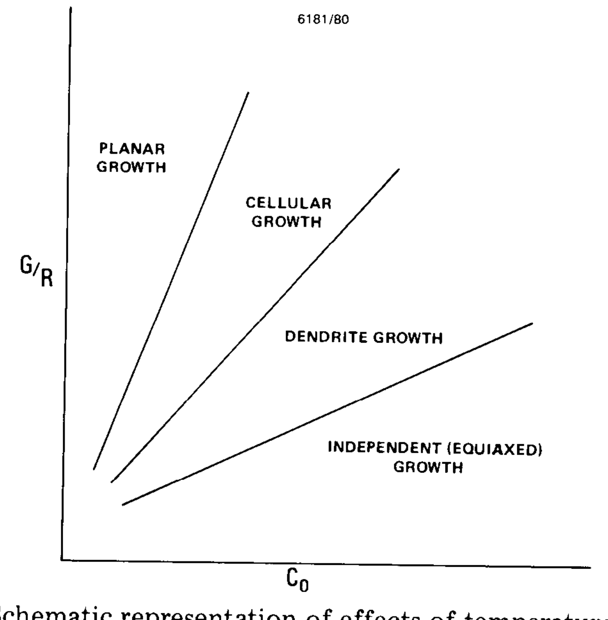

Fig.B.—Schematic representation of effects of temperature gradient G, freezing rate R and solute concentration C_0 on solidification morphology in alloys.

The main feature of eutectic freezing is the associated growth of two phases from a common origin to form duplex grains, often referred to as eutectic cells or colonies. This grain structure of a eutectic can be observed in a grey cast iron, appropriately etched, and is seen, for example, in Fig. 89. The morphologies of the individual phases within the eutectic grains depend upon their respective and comparative growth characteristics and upon thermal and chemical conditions in the casting. Contrasting morphologies in a eutectic system are again well exemplified in graphitic cast irons, in which variations in graphite flake type and the quite different spheroidal form obtained under more specialised casting conditions are seen in the range of microstructures included here (note especially Figs. 103-106, 115-117, 118-121 and 191-193). It may be noted that in the case of the nodular cast iron the eutectic cells correspond to the individual graphite nodules, unlike the flake graphite irons in which each cell or grain contains many interconnected flakes. The aluminium-silicon system provides further examples of structural variations consequent on changes in mode of solidification; both cooling rate and melt treatments produce important effects on the eutectic structure in these alloys (see Figs. 49 to 54).

Dendritic and eutectic structures are frequently seen together in cast materials, in hypo or hypereutectic alloys. Examples of such combinations can be seen in Figs. 11, 51 and 52.

It is thus seen that the macrostructure, the important dendritic and eutectic features of microstructure, and associated segregation characteristics, all originate in solidification.

Influences of subsequent solid state changes on the development of microstructure are observed in numerous examples throughout this book. The commonest case is the austenite transformation in the steels and cast irons. Ferrite and cementite in various stages of aggregation, including the eutectoid constituent pearlite, are frequent features of both groups of materials as products of natural cooling following completion of freezing.

The particular distribution of constituents in a multiphase microstructure is often determined by solid state cooling conditions. One characteristic form commonly encountered in cast materials is the Widmanstätten structure. This occurs on cooling from a single phase to a two phase region when the primary structure is relatively coarse grained: the second phase is then precipitated in preferred crystallographic planes within the parent grains rather than in the more distant boundaries. Such structures are typical in the as-cast condition in steel (Figs. 244 and 290) and are also met in copper base alloys such as brasses and aluminium bronzes (Figs. 65 and 82). Widmanstätten structures do not normally occur in cast irons.

On the other hand, secondary phases may be distributed around primary grain boundaries. Their distribution can be modified by heat treatment, as in the normalising of steel: this normalising treatment is designed to refine the austenite grains from which the ferrite-pearlite distribution is derived on transformation (see Fig. 252).

More radical changes sought by heat treatment are typified in numerous cast aluminium alloys and steels and in malleable cast iron. In the heat treatable aluminium alloys the as-cast structures normally contain interdendritic particles of the vital secondary constituent: these are wholly or partially dissolved in a solution treatment stage, retained in supersaturation on quenching, and reprecipitated as ultra-fine matrix dispersions on ageing. Typical structural changes from an as-cast to a heat treated condition are shown in Figs. 35 to 42: the optimum mechanical properties are associated with the θ'' stage, before the strengthening phase becomes visible in an optical micrograph.

Fully heat treated structures in steel are mostly products of the tempering of martensite formed by transformation of austenite at relatively low temperatures through rapid cooling. The diffusionless shear transformation produces microstructures of the type shown in Figs. 269 and 270; such martensites are progressively modified by the precipitation of temper carbides on reheating, accompanied by the gradual disappearance of their lath-like features and the formation of uniform carbide dispersions (Figs. 272 and 274).

The heat treatment employed as an intrinsic step in the production of malleable cast iron is designed to bring about the decomposition of cementite in the initial white iron structure, and the precipitation of graphite: it thus involves a fundamental change in the nature of the phases present. This profound change can be observed by comparing the microstructures in Figs. 152 to 167 with those in Figs. 136 and 137, and it will be noted that the graphite form is markedly different from the more usual flake morphology; it shows greater similarity of outline to the nodular structures produced directly from the melt.

Casting conditions and the control of microstructure

The solidification stage has been shown to be crucial in the determination of microstructure in castings, in respect of the nature of the macrostructural zones, primary grain size and structural features within the grains. Considering the two major structural types previously discussed, a dendritic structure is characterised by the primary grain size itself and by the spacing of the dendrite arms, which governs the form and distribution of microsegregates and secondary constituents, whether precipitated during or after freezing. The spacing can also influence the grain size and other characteristics developed from the primary structure by solid state transformations and affects the time required to accomplish changes sought by heat treatment. The dispersion of constituents in the final microstructure has a marked effect on mechanical properties. The influence of primary structures on the distribution and morphology of secondary constituents is well illustrated in the contrasting light alloy microstructures of Figs. 13 and 14, 57 and 58, and 59 and 60 respectively.

Eutectic structures too are characterised partly by the primary grain size, inversely related to the number of cells or grains, and partly by the substructure, in this case the morphologies and spacings of the constituent phases. Mechanical properties and heat treatment are again highly sensitive to these characteristics, of which there is some degree of interdependence.

Process variables are the principal means available for the control of microstructure and properties in castings as can be largely inferred from the foregoing review of solidification, and the main parameters can now be briefly summarised.

Melt condition.—The important influence of melt condition on subsequent mechanisms has already been stressed and accounts for the sensitivity of microstructure to small changes in melt chemistry. Practical controls on structure using these effects will be discussed under the separate heading of Grain Refinement and Modification. The other aspect of melt condition relates to superheating and the influence of temperature. This operates through its effect on the presence and survival of nuclei and, with certain exceptions, notably some magnesium base alloys, high superheat produces coarsening; in cast iron it increases the tendency to produce white or chill rather than grey structures.

The pouring temperature itself exerts an influence; low pouring temperatures encourage copious nucleation on contact with cold mould surfaces and minimise the time for growth of individual grains, hence promoting finer microstructures.

Cooling rate.– A high cooling rate produces a refining effect upon both primary grain size and substructural features. The former influence is attributable to the increased number of effective nuclei with greater undercooling and to accentuated growth restriction through concentration gradients ahead of the interface; the refinement of substructure results from increased frequency of branching of dendrite arms or eutectic phases with increasing growth rate. In both cases the spacing conforms to a relation $dr^a = c$, where d is the spacing, r the cooling rate and a and c appropriate constants.

It should also be noted that analogous and direct effects of cooling rate are operative with respect to structural features produced in solid state transformations where these also occur, for example to ferrite grain size and pearlite spacing in cast steels. In such cases as these the cooling rate exerts a double influence on the final microstructure, operating through both the successive sets of transformations. The matrix structure in cast iron, including the amount and form of pearlite, is similarly dependent upon the cooling rates obtaining over the lower temperature ranges.

Pronounced cooling rate influences may be observed in the contrasting microstructures of Figs. 107 and 108, 117 and 119, 191 and 192, and 292 and 293 respectively, whilst the effect of varying cooling rate within a single casting is evident in the specimens from centrifugally cast pipes shown in Figs. 185-188, and 189 and 190. Cooling rate effects are primarily responsible for the section sensitivity of mechanical properties in some cast alloys, and for differences in structure and properties between sand and chill cast materials. The section size effect is directly illustrated in the range of grey cast iron structures and properties given for BS1452: 1977 Grade 260 (see Figs. 103-106), whilst comparisons of chill and sand cast alloys can be made for numerous non-ferrous alloys (see, for example, Figs. 51-52 and 63-64).

Apart from the size factor in structure, more drastic changes can be produced by cooling rate effects. In cast iron, changes in graphite form and the tendency for an increasing proportion of carbon to remain in the combined form gives way to the formation of mottled and with more severe chilling, white cast iron structures (see Figs. 136, 137 and 138). In some steels and alloy white cast irons equivalent conditions may produce martensite in the as-cast material.

Cooling rate is only marginally controllable at the solidification stage, except by drastic changes in the moulding medium, for example with chills or in ceramic investments: it is thus of limited value as a structure control parameter. Some refinement is nevertheless achieved by minimising pouring temperature, whilst adverse structural changes are suppressed by avoiding excessive rates. In cases requiring drastic structural modification at the casting stage, much greater use is made of compositional changes and inoculant additives.

In alloys undergoing solid state transformations, subsequent heat treatment is additionally available as a powerful, and in many cases crucial, technique in influencing the final structure and properties of the alloy.

Grain refinement and modification.—Treatment of the melt with relatively small additions can produce major changes in macro- and microstructure. Such additions can be employed to inhibit the formation of a columnar zone, decrease the equiaxed grain size and change the nature of the substructure, including the form and dispersion of second phase solid solutions or compounds, i.e. the refinement may be of the matrix, of dispersed phases or of both.

Effective refinement is achieved in many cast alloys by the use of inoculants to provide additional nuclei or barriers to rapid growth. The resulting decrease in primary grain size may, however, produce some coarsening of the substructure: this effect is seen in grey cast iron, in which an increase in the number of eutectic grains (see Figs. 111 and 112) is accompanied by reduced graphite branching, so developing a uniform dispersion of medium flake graphite (Figs. 113 and 114). Grain refining treatments are also widely employed in light alloy founding. Since the first effect is to suppress columnar growth, the structures in all the treated alloys are developed from fine equiaxed primary grains, with beneficial effects on secondary dispersions.

Whilst refining treatments are designed primarily to reduce structural spacing, other additives are employed to produce more radical changes in the microstructure. One such process is the modification of aluminium-silicon alloys (see Fig. 49, *et. seq.*). Another is the change from flake to spheroidal graphite in cast iron. In both these cases, these changes are produced by very small additions of the effective elements.

Some additives are susceptible to oxidation, evaporation or other changes, so that late addition is essential in such cases. Most additives are introduced to the furnace, tapstream or ladle, but there is growing use of techniques of application in the mould itself, through reactive mould coatings or by dispensing within the gating system, so ensuring minimum opportunity for fade.

Temperature gradients and directionality.—A converse form of structure control is employed where benefit is to be derived from directional crystallisation: this requires the suppression of independent nucleation and growth, and the generation of temperature gradients sufficiently steep to produce fully columnar macrostructures, with, in some cases, associated alignment of microstructural features. Such structures are sometimes preferred for their favourable feeding characteristics and high and reproducible standards of soundness, with resultant benefits to the general level of mechanical properties and pressure tightness.

In other cases anisotropy can be exploited in special design situations: one example is the improvement in longitudinal high temperature properties by the elimination of transverse grain boundaries, as illustrated in Fig. 380. Other developments in this area include phase alignment in multiphase cast structures.