

[54] **METHOD OF CASTING A DIRECTIONALLY SOLIDIFIED ARTICLE HAVING A VARIED COMPOSITION**

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[56] **References Cited**

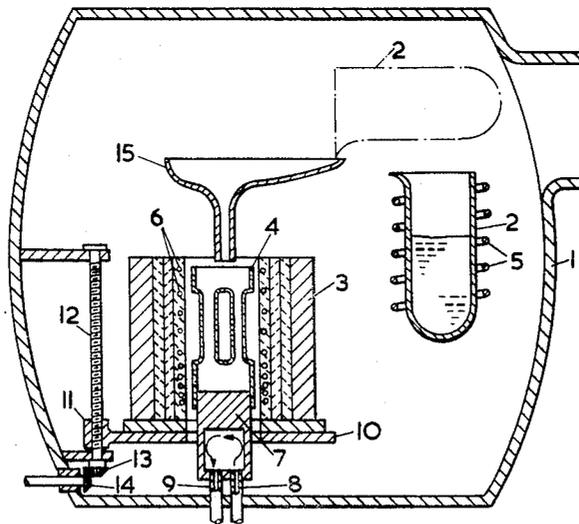
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[57] **ABSTRACT**

A first molten alloy is poured into a mould and progressively cooled to produce a vertical columnar crystal growth. A second molten alloy is then poured in while the surface of the first alloy is still liquid. The progressive cooling is then continued. A suitable mould is made of ceramic material and has an overflow tube formed in the wall of the mould so that any excess of the first alloy will run off. Two pairs of alloys, suitable for casting turbine blades, are described. The advantage of this method is that different parts of the casting can be formed from different alloys and that the known advantages of controlled columnar crystal growth are substantially maintained right across the join.

**6 Claims, 3 Drawing Figures**



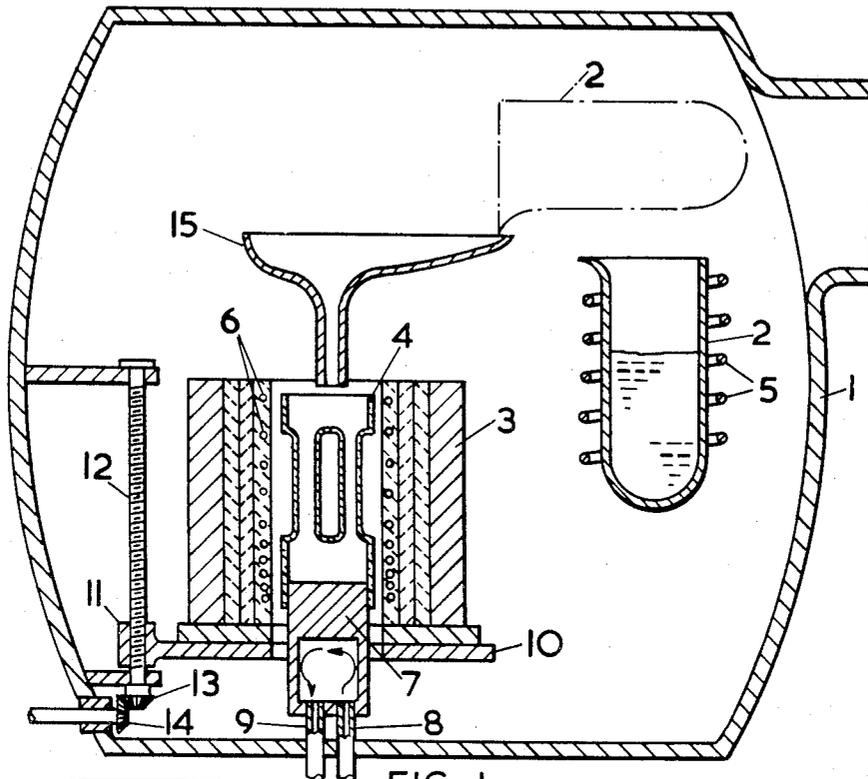


FIG. 1.

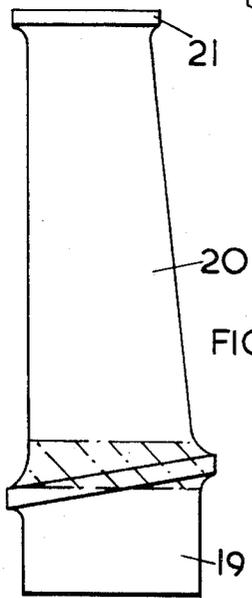


FIG. 3.

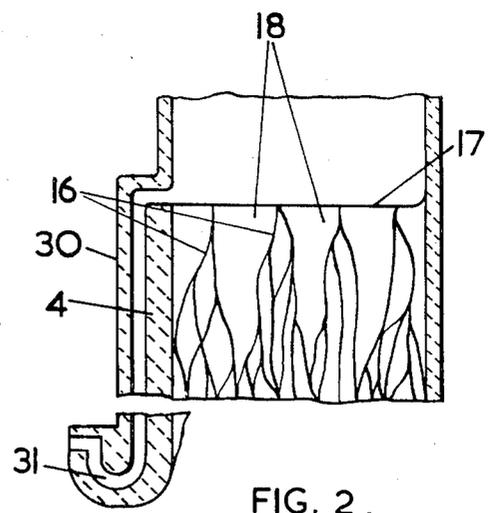


FIG. 2.

## METHOD OF CASTING A DIRECTIONALLY SOLIDIFIED ARTICLE HAVING A VARIED COMPOSITION

This invention relates to casting of metal articles.

Metal articles are not infrequently used in circumstances where different parts of the articles are subjected to widely varying operating conditions. Typical examples are blades for use in fluid flow machines such as gas turbine engines. These include rotor and stator blades for compressors and turbines, and inlet (or nozzle) guide vanes. Generally the blades comprise two main parts, namely a working portion and a root portion. The working portion, normally of aerofoil section, is subjected to impingement by gases and is attached to supporting structure by the root portion. Rotor blades are additionally subjected to centrifugal forces, while turbine blades operate at high temperatures. A gas turbine rotor blade will thus be seen to require a wide combination of properties and these differ between the working portion and the root portion.

The working portion of a gas turbine rotor blade needs good stress/rupture strength at elevated temperatures, must exhibit a minimum of creep deformation under centrifugal loadings at such temperatures and be resistant to oxidation by hot gases and to the effects of thermal fatigue. The root portion should have good ductility at somewhat lower temperatures, a high tensile strength and be fatigue resistant. The change in section usual between a working portion and a root portion through which bending and vibrational stresses must be transmitted gives rise to stress concentrations which make a low notch sensitivity also desirable. Again, whilst it may be possible to provide an oxidation-resistant coating on a working portion, this is not usually practicable with a root portion which thus preferably should be inherently resistant to oxidation at the operating temperatures involved.

It has been proposed to make blades by forging from a composite blank produced by the welding together of different metallic materials, such as niobium and titanium-based alloys, to form working and root portions, respectively.

Precision casting processes with their finer control of dimensional accuracy reduce the amount of subsequent machining required. Nickel-base alloys are in general easily cast and intrinsically possess many desirable properties which make them eminently suitable for gas turbine blading. Continuing development has resulted in alloys having high creep strength at the high operating temperatures which have become prevalent. Many of these alloys moreover do not lend themselves to forging.

Some loss of ductility has been experienced due to the existence of grain boundaries extending perpendicularly to a main stress axis, giving rise to intergranular fracture. This can be largely overcome by unidirectional solidification during casting to give a columnar structure of crystals aligned substantially parallel to the main stress axis with consequent elimination of grain boundaries perpendicular to that axis. It has been shown that improved strength, ductility and thermal fatigue resistance can be provided in turbine blades having a unidirectional grain structure extending in a spanwise direction. Compared with similar items conventionally cast, strong high strength alloys have been found to have excellent ductility with greatly improved

high temperature properties (eg longer stress/rupture times); unnotched Charpy impact tests have shown marked variation in impact strength with orientation of crystal growth (up to twice as much at right angles to the grain growth direction as with it). Nevertheless, the choice of an individual alloy to meet the sometimes conflicting requirements for the two main parts of gas turbine rotor blades remains something of a compromise. It has also been proposed that cast metal articles be produced with differing grain structure (columnar and equi-axed) at varying locations to meet prevailing conditions.

The present invention provides a method of casting a metal article comprising introducing a first molten alloy into a mould having means for progressive cooling of the mould, whereby crystal growth in the molten alloy can be controlled to form a vertical columnar structure, introducing a second molten alloy of compatible nature into the mould while maintaining the surface of the first alloy in a liquid state and subsequently continuing progressive cooling of the mould.

Preferably the first and second alloys are nickel-base alloys.

The mould may be of ceramic material having a part in contact with a highly conductive cooling surface and with heating elements arranged about the mould so as to vary the axial location at which heat may be applied to the mould, either by relative movement between elements and mould or by selective use of elements.

The mould may include an overflow into which excess first molten alloy may flow, the vertical location of the overflow inlet in the mould determining the depth of first molten alloy in the mould and hence the position of the interface between the two alloys.

The invention also provides a cast metal article comprising adjacent parts formed of different alloys and having a common columnar crystalline structure.

One such article is a turbine blade in which the adjacent parts are respectively a working portion and a root portion.

The invention will now be described, by way of example only, with reference to the accompanying diagrammatic drawings, of which:

FIG. 1 is an axial section through an assembly of apparatus for metal casting,

FIG. 2 is an axial section through part of a mould containing molten metal, and

FIG. 3 is an elevation of a turbine blade.

FIG. 1 shows a chamber 1 enclosing a crucible 2 and a furnace 3 which in turn encloses a mould 4. The crucible is surrounded by a high frequency induction heating coil 5 and can be raised and tilted by conventional means (not shown) to a pouring position as indicated in dotted lines. The furnace 3, of the well-known electrical resistance type, comprises heating elements 6 supported in refractory insulating material surrounding a central axially extending aperture. The furnace is mounted with the central aperture extending vertically (according to the Figure) and the heating elements extend around the aperture as a coil having its windings pitched closer together towards the bottom than higher up, to give greater heating capacity in the lower portion of the furnace. The mould 4 is located centrally within the aperture and is formed of ceramic or other refractory material built up in known manner around a wax pattern which is subsequently burned out during firing of the mould to leave a cavity defining the shape of the

article to be cast. The mould, which may contain a core if desired, is open-ended and is mounted at its lower end on a chill-plate 7 which also closes the bottom of the mould. The chill-plate 7 comprises a block of metal, preferably copper or a copper alloy, having good thermal conductivity and has an internal cavity through which water can be circulated for cooling by way of pipes 8, 9. The furnace 3 is supported by a platform 10 connected by a die-block 11 to a lead-screw 12. The lead-screw can be driven through gearing 13, 14 by an electric motor (not shown) to raise or lower the furnace 3 relative to the mould 4. Formed in the wall of the mould is an overflow 30 (shown in FIG. 2 only) into which excess first molten alloy may flow. The overflow is provided with a U-shaped trap 31 to retain excess first alloy.

In a casting operation the chamber 1 is first evacuated by means of a vacuum pump (not shown). The mould 4 is then pre-heated by the furnace 3, which is set at its lowest position, to a temperature in excess of the melting temperature of the metal to be cast, usually 150° to 200°C above the alloy liquidus temperature, and cooling water is circulated in the internal cavity of the chill-plate 7 in order to maintain the upper surface of the chill-plate well below the solidification temperature of the metal to be cast. A quantity of metal (a nickel-base alloy, for example) is melted in the crucible 1 by the agency of the heating coil 5. The crucible is then raised and tilted to pour the molten metal into the mould 4 by way of a tundish 15, after which the crucible is restored to its normal position and charged with another metal (e.g. another nickel-base alloy of different composition to that first mentioned), which is melted in turn. Excess first alloy flows into the overflow 30 until the surface of the alloy reaches the bottom of the overflow inlet. Some of the excess first alloy is retained in the overflow trap 31 and solidifies therein on cooling, thereby preventing second molten alloy from flowing through the overflow.

The chill-plate 7 extracts heat from the metal in contact with it and solidification commences in this zone. The furnace 3 is slowly raised by rotation of the lead-screw 12 to give progressive cooling of the molten metal whereby solidification proceeds at a solid-liquid front moving up the mould. The furnace is stopped in such a position as will maintain the upper surface of the metal in the mould in liquid state, whereupon the second metal is poured from the crucible to fill the mould completely, after which the furnace is raised once more to continue the progressive cooling of the mould and its contents. The unidirectional temperature gradient established by the progressive cooling ensures that the solidification process proceeds gradually upwardly from the bottom of the mould. Subsequently the furnace is switched off to permit final cooling.

The cast article, after removal from the mould will have a columnar crystalline structure in which the crystals are unidirectionally aligned substantially parallel to each other in the direction of the mould axis, individual columnar grains usually comprising more than one dendrite arm.

FIG. 2 shows the nature of the crystalline growth concerned, and shows an overflow 30 formed in the mould wall 4. Tongues of skeleton crystal (dendrites) 16 form in the liquid metal at the bottom of the mould 4 as a result of the solidification due to the chill-plate. The temperature gradient induced leads them to grow

upwardly in parallel formation towards the top surface 17 of the gradually cooling liquid metal. The growth continues until cooling is arrested prior to pouring of the second metal, the interstices 18 at this stage still containing small amounts of liquid metal. When the second metal is introduced, there is mingling between the respective liquids (assuming proper compatibility), with possibly some remelting of the tips of the dendrites. Consequently there is virtually complete fusion between the two metals in the transition zone between them. On resumption of progressive cooling, the upward dendrite growth continues once more, and the growing dendrites rapidly attain the composition of the second metal. Initially, the composition of the interdendritic material is partly governed by the amount of liquid present when the second metal is introduced. The extent of the transition zone is governed by this and by the rate of cooling in this particular region and is controllable.

There will almost certainly be some initial formation of randomly oriented crystals before growth in a preferred orientation becomes established but provision can be made for this by making the mould sufficiently deep at its lower end as to include a "growth zone" which can be removed from the finished article if desired.

The heating of the mould above the pouring temperature of the metal is to prevent random crystallization, or nucleation, in advance of the controlled solidification which would otherwise spoil the desired structure of the cast article.

The cast article may of course be subjected to subsequent heat treatment so as to improve its physical properties in known manner, or be provided with protective coatings.

A gas turbine rotor blade produced by the process described is shown in FIG. 3. The blade comprises a bulbous root portion 19 by which it can be attached to a rotor disc, a working portion of aerofoil section 20 and a shroud 21 at the tip of the working portion. The root portion 19 is composed of an alloy having high ductility at the root operating temperature while the working portion 20 is composed of a second alloy having good creep resistance at operating temperatures, some reduction in ductility being acceptable. The transition zone between the two alloys occurs at the junction between the root and working portions as indicated by cross-hatching. The root portion would normally be cast first followed by the working portion in the manner previously set out. The lower part or growth zone of the blade as cast is then machined away to remove random crystal growth. Subsequently, continuous crystals will extend through the root portion, through the working portion and into the shroud to give a parallel columnar structure throughout. Unwanted growth at changes of section can be prevented by the provision of smooth curves at these points.

The production of integrally bladed turbine rotors by similar methods can be envisaged, the blades being composed of a different alloy to the turbine disc.

The sequence of operations in the process as previously described is not completely exclusive and may be varied in so far as the invention is not affected. For instance, casting can take place in an inert atmosphere, such as argon or helium, rather than in a vacuum: it can even be carried out in air where adverse considerations are not involved. The different metals or alloys can be

melted in separate crucibles and instead of physically moving the furnace relative to a mould there can be provided means for selectively energising furnace heating elements so as to vary the position of the main heating zone.

So far as the casting process itself is concerned, a change from one metal to another can be repeated, with the introduction of a third metal or alloy or even a reversion to one used earlier in the sequence. Again, controlled cooling can be dispensed with at a final stage, to permit the formation of randomly oriented crystals at one end of the cast article where this might be desirable, or unimportant.

The metals or alloys used need not both be of the same metal base, for example one may be nickel-base, another cobalt base, or another iron-base, but in all cases, the metals or alloys used (chosen for some specific property or properties in a particular area) must be properly compatible. They must not, for instance, form harmful transition compositions likely to give a zone of weakness, while the process may be difficult to operate if alloys have widely differing melting points. (Most nickel-base alloys melt in the range 1,300° to 1,400°C and so are generally suitable in both these respects.)

Castings according to the invention have been manufactured from nickel-base alloys having the following nominal percentage compositions:

Alloy	C	Cr	W	Mo	Al	Ti	Ta
I	0.05	12.0	—	4.5	5.9	0.6	2.0
II	0.13	5.7	11.0	2.0	6.3	—	3.0
III	0.11	19.5	—	—	—	0.4	—
IV	0.15	9.0	10.0	2.5	5.5	1.5	1.5
V	0.15	19.5	—	—	1.5	2.5	—

The percentage values for Alloy V for carbon, boron and zirconium are maximum values.

Alloys I and V have better ductility and are more suitable for root portions, and Alloys II and IV have better strength at high temperatures making them appropriate for blade working portions. Specimens containing a junction between Alloy I and Alloys II, and IV, and between Alloy IV and Alloy V between Alloy II and Alloy III have been cast by the method according to the invention.

The nickel-base alloy, Alloy III, was used with Alloy II in place of Alloy I primarily for metallographic studies since it exhibits a greater difference in micro-structure.

Micro-structural examination has revealed complete interfusion between the above alloy pairs with unidirectional solidification maintained across the transition zones. By altering the casting conditions it has been possible to vary the width of transition zones to produce narrow or wide zones. Electron microprobe analysis has indicated that the change from one alloy composition to another across the transition zone between Alloys III and I was completed in a distance of approximately 0.050 in.

Creep/rupture tests on four test-pieces containing a junction between Alloys I and II gave the following results:

TABLE I

Test-piece	A	B	C	D
Temperature (°C)	980	980	750	750
Load (tsi)	8	8	40	40
Time to rupture (hr)	530	564	721	323
Elongation (percent)	15.3	14.8	9.2	3.4

Test-pieces B and D referred to in Table I above were produced by reducing the amount of liquid alloy present when the second alloy was introduced into the mould, thereby producing a narrow interfusion zone between the two alloys — Test pieces A and C were produced without such removal of liquid alloy. Under comparable conditions the weaker Alloy I would be expected to have approximately the same life as those given in Table I. A tensile test on another test-piece from the same casting as test-piece A at 750°C gave the following results:

Ultimate tensile strength	72 tsi
0.1 percent proof stress	58.5 tsi
Elongation	7.2 percent
Reduction of area	8.0 percent

I claim:

1. A method of casting a metal article comprising the following steps:

- a. introducing a first molten alloy into a mould having an overflow means until molten alloy overflows into the said overflow means;
- b. progressively cooling the mould to produce controlled crystal growth in the form of a vertical columnar structure in the molten alloy;
- c. introducing a second molten alloy compatible with the first molten alloy into the mould while main-

B	Zr	Co
0.01	0.1	—
—	0.6	—
—	—	—
0.015	0.05	10.0
0.03	0.15	18.0

taining the surface of the first alloy in a liquid state; and

- d. progressively cooling the mould to produce controlled growth in the form of a vertical columnar structure in the second molten alloy.

2. A method of casting a metal article comprising the following steps:

- a. introducing a first molten alloy into a mould;
- b. progressively cooling the mould to produce controlled crystal growth in the form of a vertical columnar structure in the molten alloy;
- c. introducing a second molten alloy compatible with the first molten alloy into the mould while maintaining the surface of the first alloy in a liquid state; and

- d. progressively cooling the mould to produce controlled growth in the form of a vertical columnar structure in the second molten alloy; said alloys having the compositions:

	First alloy	Second alloy
Carbon	0.05	0.13
Chromium	12.0	5.7
Tungsten	—	11.0
Molybdenum	4.5	2.0
Aluminium	5.9	6.3
Titanium	0.6	—
Tantalum	2.0	3.0
Boron	0.01	—
Zirconium	0.1	0.6
Nickel and impurities	Balance	Balance

3. A method of casting a metal article comprising the following steps:

- a. introducing a first molten alloy into a mould;
- b. progressively cooling the mould to produce con-

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- trolled crystal growth in the form of a vertical columnar structure in the molten alloy;
- c. introducing a second molten alloy compatible with the first molten alloy into the mould while maintaining the surface of the first alloy in a liquid state; and
- d. progressively cooling the mould to produce controlled growth in the form of a vertical columnar structure in the second molten alloy; said alloys having the compositions:

	First alloy	Second alloy
Carbon	0.11	0.13
Chromium	19.5	5.7
Tungsten	—	11.0
Molybdenum	4.5	2.0
Aluminium	5.9	6.3
Titanium	0.4	—

8

	First alloy	Second alloy
Tantalum	2.0	3.0
Boron	0.01	—
Zirconium	0.1	0.6
Nickel and impurities	Balance	Balance

4. A method as claimed in claim 1, wherein casting is carried out in an atmosphere which is chemically inert with respect to the alloys to be cast.
5. A method as claimed in claim 1 including the step of introducing a third molten alloy compatible with the second molten alloy into the mould while maintaining the surface of the second alloy in a liquid state, and subsequently cooling the mould.
6. A method as claimed in claim 5 in which the first and third molten alloys are identical.
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