Title: A MOULD AND A METHOD OF MAKING A MOULD

Abstract: A method of making an Investment Casting mould for Directionally Solidified components comprises: dipping a pattern for forming the mould into a slurry, the pattern having a first end and a second end defining the ends of the cavity in the mould, the first end being the end which, on casting and solidification into the mould, will contain the molten material which solidifies last and the second end being the end at which it is desired solidification will start. The pattern is held to drain and/or dry in a position to allow the movement of slurry towards the first end under the influence of gravity. These steps are repeated as necessary to form the mould.
A Mould and a Method of Making a Mould

The invention relates to a mould and a method of making a mould, particularly but not exclusively to a method of making a mould for use in casting Directionally Solidified Single Crystal components, such as Directionally Solidified and Single Crystal turbine blades.

Use of Directionally Solidified (DS) turbine blades within aero gas turbine engines results in significantly improved properties of the blades, in particular improved thermal fatigue life and creep strength. This is due to the elimination of grain boundaries transversely oriented to the blade reference axis; the blade reference axis being that which is subjected to the most stress when the blade is in service in the engine. The use of Single Crystal turbine blades results in yet further improved mechanical properties with the elimination of all grain boundaries in the component and the opportunity for control over the orientation of the single grain.

DS and Single Crystal turbine blades are traditionally produced by Investment Casting. A disposable wax replica of the required casting is produced. This can be formed by injection moulding and generally replicas of several castings are assembled in groups with a wax sprue and gating system. The assembly can then be coated in investment slurry before ceramic consolidation and wax removal via heating. The ceramic mould then receives the molten alloy, before being broken up to extract the solidified product. The mould is preheated before receiving the molten alloy so as not to induce the formation of columnar chill grains at the cast surface. Where a controlled, crystallographic orientation is desired in the casting, Directional Solidification must be employed. For nickel-base Superalloys, which have a face centred cubic structure, the natural growth direction is normal to the (001) plane, which happens to coincide with the optimum mechanical properties and so the normal 200 to this plane is selected to be aligned parallel to the reference axis 202 of the blade 204, which is illustrated in Figure 1.

In order to achieve a casting with this structure, the "high speed withdrawal" technique is employed to achieve an initial array of columnar grains in a starter block 206 beneath the component cavity, growing in the <001> preferred direction. The starter block 206, where competitive crystal growth occurs, comprises a mould cavity
directly above the furnace chill plate but beneath the component cavity. For the production of DS castings, this columnar grain structure is allowed to progress into the component cavity resulting in a multi-crystalline component where the preferred orientation of each grain is such that the <001> pole is aligned parallel to the blade reference axis. For the production of Single Crystal castings, selection of a Single Crystal is required at the top of the starter block 206. A crystal selector is incorporated between the component cavity and the starter block. Examples of known crystal selectors are illustrated in Figure 2 and comprise a series of steps or angles 208, a ramp 210, a 360° helix 212 or a constriction 214. Such geometric shapes permit the natural columnar growth of the <001> oriented grains whilst selectively eliminating all except the one grain most suited for survival by orientation with respect to the direction of heat flow. The use of an upwardly inclined passage such as a ramp 210 or helix 212, means that dendrites must branch in order to grow within the geometry of the selector. As the grains branch sideways to progress into the selector, they quickly annihilate until a single grain remains. Growth of the single grain continues into the blade's cavity until the mould is completely withdrawn from the furnace. The use of a fine constriction 214 above the columnar structure, the base of the constriction 214 being substantially less than the transverse dimension of the columnar grains, permits only one grain to progress into the blade cavity.

A temperature gradient is created by providing a chill plate in contact with the bottom of the mould where the starter blocks are located, and withdrawing the mould from the furnace from the starter block end, to ensure that solidification progresses from the starter block to the tip of the blade.

There are a number of defect tolerances to which cast blades must conform if they are to perform with the physical and mechanical properties demanded of them during their service in the engine. Two particularly important properties are the crystal orientation tolerance and the high angle boundary tolerance.

Crystal orientation tolerance for both DS and Single Crystal components, it is preferable that the <001> poles 200 are perfectly aligned with the blade reference axis 202. However, crystal orientation less than or equal to 20° from the blade reference axis 202 (angle θ (see Figure 1) is an acceptable industry standard.

High angle boundary (HAB) tolerance - the effect of secondary grains on the properties of Single Crystal components, together with the absence of grain boundary
strengthening elements is deleterious. In reality, blades that contain a single grain are rare, and more often "Single Crystal" is classed as a component that contains a number of grains with low relative orientation mismatch, as there is a critical atomic mismatch between adjacent grains above which the component is unacceptable.

Generally an R-value of greater than 7.5° is classified throughout the industry as an unacceptable high angle boundary (HAB). For DS components, it is preferred that the nucleation of grains does not occur anywhere other than at the chill plate. An essentially planar solidification front is required for DS and Single Crystal solidification. In instances where isolated areas further up the casting mould are cooler than desired, and more in line with the alloy liquidus, nucleation and solidification of secondary grains can occur. This secondary grain occurrence can be suppressed by the application of an increased number of concrete slurry layers to the mould in order to increase the thermal mass of shell in contact with adjacent alloy and so suppress the local undercooling at the mould walls until the point that the liquidus passes, during withdrawal from the furnace chamber.

In the known casting method, the wax pattern assembly is provided as described which comprises patterns for a plurality of blades, each with an associated starter block all mounted on a base. For Single Crystal only, a crystal selector would also be associated with each component. A robot dips the assembly, base downwards, in a bath of slurry, then lifts it out, still in the same orientation, to drain and dry. This is repeated until a ceramic investment mould of the required strength and thickness has been formed on the pattern.

According to a first aspect of the present invention there is provided a method of making a mould, the method comprising:

applying slurry to a pattern for forming a mould, the pattern having a first end and a second end defining the ends of the cavity in the mould, the first end being the end which, on casting and solidification into the mould, will contain the molten material which solidifies last; and, the second end being the end at which it is desired solidification will start;

holding the pattern to drain and/or dry in a position to allow the movement of slurry towards the first end under the influence of gravity; and

repeating as necessary to form a mould.
Thus, the pattern is held for draining and/or drying in the opposite orientation from the known method. As a result of the orientation of the pattern during drainage and/or drying, a greater build up of slurry on the first end of the mould will occur than if the mould was drained and/or dried in the opposite orientation and indeed the thickness of the mould will in general increase from the second end to the first end. The thicker mould around the component cavity will hold the heat better, suppressing local undercooling and preventing the nucleation and solidification of secondary grains in the component cavity. The thinner shell around the starter blocks promotes a uniform, planar liquidus as it travels up the starter blocks, which promotes a low average $\Theta$ across the distribution of grains ready to progress into the component cavity, in the case of DS components and, in the case of Single Crystal components, across the distribution of grains available for selection by the crystal selector. As previously discussed, HAB tolerance allows the application of as many coats as necessary to control HAB (dependent on the differing thermal properties of individual shell systems) whilst always maintaining minimal shell thickness at the starter block end of the mould to control crystal orientation tolerance.

The pattern is preferably held with the axis of the mould between the first and second ends at an angle of 75° or less to the vertical during slurry drainage and/or drying, more preferably at 60° or less, more preferably at 30° or less. The pattern may be held stationary to drain and/or dry. It is preferred that the pattern is rotated about the axis of the mould during drainage and/or drying to prevent asymmetrical slurry build up. The pattern preferably includes means to enable the pattern to be lifted in the described orientation. The pattern may thus include at least one handle at the second end.

The mould is preferably for casting a Directionally Solidified component and may be for casting a Single Crystal component.

Preferably, the pattern comprises a component pattern extending from the first end, and a starter block pattern at the second end. More preferably, the pattern includes a base plate pattern, the starter block pattern extending from the face of the base plate pattern. The base plate pattern is arranged such that the resulting base plate cavity in the mould can be located on to a chill plate in the furnace. In the case of DS components, the component pattern is mounted directly on to the starter block. For single crystal components, a crystal selector pattern may be provided between the
starter block pattern and the component pattern, for selecting a Single Crystal of the desired orientation. The crystal selector pattern may take any suitable form and may take the form of an angled passage, an inclined ramp, or a constriction, but preferably is a helix, most preferably a 360° helix.

In use, the base plate cavity can be mounted on to a chill plate in the furnace to aid solidification. The orientation of the mould during slurry drainage and/or drying leads to a reduction in preferential build up of mould material around the starter block. For example, when draining and/or drying in the known orientation, with the starter block 206 lowermost, the build up of slurry would be greater at the base of the starter block 206, as slurry 216 flowing from the component mould will collect there, as illustrated in Figure 3.

In a preferred embodiment, the pattern comprises at least two component patterns fed by a common gating system. This is more efficient, but in the known method can lead to greater build up of slurry material and hence mould thickness in the area 217 between the pair 207 of starter blocks 206 of adjacent component patterns, in other words the mould will be of differing thickness around a starter block 206, being thicker 218 adjacent the neighbouring starter block 206 with the shared gating system than elsewhere, as illustrated in Figure 4. Furthermore, when a system is used containing a radial gate system 20, each gate 20 forking to supply a pair 207 of blades with molten metal, as shown in Figure 5, as well as the build-up 218 of slurry 216 in the area 217 between starter blocks 206 in a pair 207, there is also, although to a lesser extent, build-up 218 of slurry 216 in the area 219 between adjacent pairs 207 of starter blocks 206, in the same way as illustrated in Figure 4. This leads to uneven shell build up around the starter blocks 206. By draining and/or drying the moulds in the orientation according to the invention, less asymmetric build up of mould material around the starter block is achieved as slurry material will not "pool" at the base of the starter blocks.

Asymmetrical build up of mould material around the starter block creates an asymmetrical temperature gradient which will lead to an asymmetrical liquidus in the starter block. Figure 6 illustrates the liquidus 222 in a starter block with a) asymmetric shell build up; and b) symmetric shell build up. This is because alloy in contact with thinner shell walls will lose heat at a faster rate and grain growth will be allowed to progress in this localised area. The array of grains in the central area of the
starter block should have a distribution of orientations that reflect the form of the liquidus 222. Grains growing normal to the liquidus 222 grow at a faster rate, pinching off those less favourably aligned with the temperature gradient.

In the starter block of Figure 6a, more grains possess orientations towards the thicker shell walls 218 than the thinner walls, due to the fact that the gradient of the liquidus 222 adjacent to the thicker walls 218 is steeper covering more area of the cross section up to where it intersects with the horizontal, planar section of the liquidus at the centre. The simplified diagram of Figure 6a suggests that there would be a 20% chance of the crystal selector selecting a grain oriented towards the thicker shell (as this covers 20% of the area of the cross section), a 10% chance of selecting a grain oriented towards the thinner section of shell and a 70% chance of selecting a grain oriented in line with the blade reference axis. If this example is applied to DS components, then of the array if grains that enters the component cavity, 20% of grains would be oriented towards the thicker shell, 10% towards the thinner shell and 70% in line with the blade reference axis.

In the present invention, by producing a starter block with less asymmetrical build up of slurry, the liquidus 222 that is travelling up the length of the starter block is more likely to be uniform and planar, therefore reducing the average Θ distribution of grains in DS components and increasing the chance of a grain being selected which possesses a low Θ orientation in the case of Single Crystal, as shown in Figure 6b. Therefore, the number of components rejected as a result of crystal orientation misalignment for both DS and Single Crystal manufacture will be reduced.

Preferably, the geometry of the starter block should be such that it has a wider diameter than its length. This will further promote a planar liquidus at the central grain selection area. This is due to the diminished effect of the shell at the starter block walls as it is spread over a relatively larger volume of alloy within, compared to the conventional starter blocks that are taller than they are wide.

The slurry may be applied in any suitable way, but conveniently the slurry is applied to the pattern by dipping the pattern in slurry. Preferably, the pattern is dipped in slurry first end first. The pattern is preferably dipped in the slurry with the axis of the mould between the first and second ends at an angle of 75° or less to the vertical, more preferably at 60° or less, more preferably at 30° or less to the vertical. In another embodiment, the pattern may be dipped in the slurry in any orientation,
including with the second end first, but turned to be held in the desired orientation to drain and/or dry.

Preferably the method further includes applying a number of concrete layers, more preferably, the number of concrete layers is sufficient to control secondary grain nucleation. Preferably the application of every layer of slurry is as described in the present invention, i.e. holding the pattern to drain and/or dry in an orientation to allow the movement of slurry towards the first end under the influence of gravity.

Preferably the method includes a further step after the step of drying the mould, of removing the pattern from the mould. The pattern may be made of a material which can be burnt out of the mould, preferably wax or a plastics material. Preferably the step of removing the pattern from the mould comprises burning out the pattern.

The method may comprise applying a plurality of slurry layers, preferably a plurality of concrete layers. The first two layers of slurry may be prime slurries. The mould preferably comprises at least one layer of stucco in between two slurry layers, preferably between all slurry layers. Preferably, the stucco layer is applied by rain sanding the mould immediately after slurry drainage. The mould is preferably for casting Superalloy, such as nickel-based Superalloy.

According to a second aspect of the present invention there is provided a mould made using the method of the first aspect of the present invention.

According to a third aspect of the present invention, there is provided a Directional Solidification Investment Casting mould, the wall of the mould being thicker at the end which, on casting, is the last to solidify.

Preferably the mould is made at least partially of prime slurry. The mould may further include layers of concrete, preferably a plurality of concrete layers.

The mould preferably includes a component cavity and a starter block cavity, the starter block cavity being at the end of the mould which, on casting and solidification into the mould, will contain the molten material which will solidify first.

The Directional Solidification Investment Casting mould may be a Single Crystal Investment Casting mould.

For such a mould, preferably the component cavity and the starter block cavity are connected by a crystal selection cavity. Preferably the crystal selection cavity is helical, preferably a 360° helix.
The mould may comprise a plurality of component cavities. Preferably at least one of the component cavities is for casting a turbine blade.

According to a fourth aspect of the present invention there is provided a Directional Solidification Investment Casting mould, the mould including a part defining a cavity for a starter block, that part being of substantially constant wall thickness.

The Directional Solidification Investment Casting mould may be a Single Crystal Investment Casting mould.

According to a fifth aspect of the present invention there is provided a method of making a mould comprising the steps of:

- applying slurry to a pattern;
- holding the pattern in an inverted position to drain and/or dry;
- repeating as necessary.

The term "inverted" as used above may suitably be defined with respect to the mould's orientation during casting therein.

Two embodiments of the invention will now be described by way of example and with reference to the accompanying drawings, in which:

Fig. 1 is a perspective view of a blade illustrating the reference axis, and the reference plane;

Fig. 2 shows examples of known crystal selectors which are a) a series of steps or angles; b) a ramp; c) a 360° helix; and d) a constriction;

Fig. 3 illustrates build up of slurry around the base of a starter block dried in the known orientation;

Fig. 4 illustrates asymmetric build up of slurry around the starter block as a result of the proximity of one starter block to another starter block in a system where both starter blocks are fed by a common gating system;

Fig. 5 is a plan view illustrating an arrangement with five radial gates, each gate forking to supply two blades with molten metal;

Fig. 6 is a schematic representation of the liquidus in a starter block with a) asymmetric shell build up, b) symmetric shell build up;

Fig. 7 is a perspective view of the pattern of the first embodiment;

Fig. 8 is a plan view of the pattern of Fig. 7;
Fig. 9 is a schematic representation in cross-section of a pattern with handles attached hanging from a dipping hanger a) before dipping in the slurry; b) whilst dipping in the slurry; and c) whilst draining, after dipping in the slurry, according to the method of the first embodiment;

Fig. 10 is a cross-sectional view of a mould of the first embodiment;

Fig. 11 is a schematic representation of the furnace used for casting and Directional Solidification in the method of the first embodiment;

Fig. 12 is a cross-sectional view of the mould of the first embodiment, containing a casting located on the furnace chill plate;

Fig. 13 is a cross-sectional view of the mould of the second embodiment; and

Fig. 14 is a schematic representation of a) a component with columnar grains as a result of Directional Solidification along the component; b) a Single Crystal component (arrows represent cube axes).

First Embodiment

In the method of the embodiment, a mould for Single Crystal Investment Casting is made as follows. A pattern 10, as illustrated in Fig. 7, is produced by injection moulding of wax. The pattern 10 is arranged to form moulds for ten turbine blades. The pattern 10 includes a base plate pattern 12. A down sprue pattern 14 extends perpendicularly from the centre of the base plate pattern 12. A pourcup pattern 16 is positioned at the top of the down sprue pattern 14. Ten starter block patterns 18 are positioned on the base plate pattern 12. The starter block patterns 18 are grouped in pairs via a common gating system, the pairs being equally spaced and all ten starter block patterns 18 being equally spaced on the base plate pattern 12.

Five equally spaced gate patterns 20 extend from the bottom of the down sprue pattern 14, perpendicularly to the down sprue pattern 14. Each gate pattern 20 splits into two sub-gate patterns 22, each sub-gate pattern 22 being connected to a starter block pattern 18. The gating system arrangement is the same as that illustrated in Fig. 5. A crystal selector pattern 24 extends from the top of each starter block pattern 18. The crystal selector pattern 24 is connected to a turbine blade pattern 26. Thus, the pattern 10 can be seen to comprise a first end 28 with the patterns for the tips 30 of the blade.
patterns 26, and a second end 29 defined by the base plate pattern 12 and the starter block patterns 18.

The wax pattern 10 dimensions are enlarged by 2% relative to the desired final cast dimensions to accommodate both wax contraction on cooling and metal contraction on solidification and cooling.

The crystal selector pattern 24 on each starter block pattern 18 is a 360° helix. The position of the helices is such that each helix evolves from starter block patterns 18 in an anti-clockwise orientation (from a plan view).

Handles 32 are fixed to the base plate pattern 12, as shown in Fig. 9. The wax pattern 10 is then fixed to the dipping hangers 34 via the handles 32. Before shell moulding, the wax patterns 10 are dipped in a degreasing agent to promote first prime coverage of the wax by decreasing the surface tension. The wax patterns 10 are then loaded into a drying tunnel adjacent to the dip room which contains the slurry tanks and rain sanders. The drying tunnel contains an overhead conveyor supporting six-arm cruciform hangers 34, from the ends of which the wax patterns 10 are suspended at a radius of 250 mm from the centre of the hanger 34. Six patterns 10 may be fixed to a hanger 34 with the handles 32 by a locking pin system allowing two rotational orientations of each pattern 10.

The shell moulding procedure involves the cyclical application of coats of slurry 35 and dry alumina sand (stucco) to the wax patterns 10 with sufficient intermittent drying to receive the subsequent coat. The moulds 36 consist of eight shell coats, i.e. a first prime slurry coat followed by stuccoed sand, a second prime slurry coat followed by stuccoed sand, five concrete coats each followed by stuccoed sand, then an eighth coat which is a dipseal consisting of slurry only. The first prime slurry is a proprietary mix of 19% by mass colloidal silica liquid and 81% by mass zircon flour of particle size distribution sub 65 µm. Prior to product dipping, deionised water is added to the mix to attain a nominal plate weight of 10 g after a fixed time of 2 minutes, i.e. 10 g of material remaining on a vertically suspended brass plate after being submerged in the slurry and drained for a total of 2 minutes.

The second prime slurry consists of a 20:80% mass mix of colloidal silica liquid to zircon flour (sub 65 µm). Sufficient deionised water is then added to attain a nominal (2 minute) plate weight of 8 g. The layer of fused alumina sand following the first and second coats has a particle size distribution sub 200 µm. The concrete coats
are a mix of colloidal silica liquid and zircon flour (sub 65 µη). The tabular alumina in suspension in the slurry is of particle size distribution 250-500 µη. This is also the same dry mix used to coat the layers of concrete. The concrete is set to a nominal plate weight of 18 g, prior to dipping, via liquid additions of 75% colloidal silica / 25% deionised water.

To compensate for water evaporation from each of the slurries, the specified plate weights are maintained by replenishment with deionised water, prior to the dipping of any wax patterns 10. In the case of the first and second prime slurries, 2 litres of deionised water is added for every 1 g plate weight above nominal. In the case of the concrete slurry, 0.5 litres of 80/20 colloidal silica/deionised water additions are made for every 0.1 g plate weight above nominal. All the slurries are held in mixing tanks under constant motion to keep the particles in the slurries in suspension. The variabilities of other slurry parameters are monitored and recorded once the slurries have been set at the specified plate weights. Such parameters include viscosity, temperature, pH and relative density, commonly referred to as "specific gravity". In standard production, slurries can be used up to the point when the monitored parameters exceed their specified limits, at which point the slurry is taken out of use and replaced by a new mix.

The patterns 10 are static relative to the hanger 34. However the hanger 34 rotates relative to the conveyor (not shown) to attain more uniform drying of each mould from the fans (not shown) at the centre of the drying tunnel (not shown). A maximum of twenty hangers 34 can be suspended from the conveyor for dipping in any one batch of moulds and dipped in the same cycle over the same time period. This is commonly referred to as a "dip run". The circular conveyor transports the rotating hangers 34 around the fans. The fans run axially, within reducing conical sections to achieve the same exit air velocity at the base as at the top and hence controlled drying conditions are imposed in the tunnel on every dip run.

During loading of the wax patterns 10 on to the conveyor, a relative humidity of 67% is created in the tunnel with an air velocity of ~6 m s⁻¹. The patterns 10 experience these conditions for a minimum of 2 hours prior to dipping in order to bring the wax to the same temperature as the drying tunnel to minimise the risk of wax expansion following dipping, causing the splitting of the initial shell coats. Following the application of four coats all via the described method of 'inverted drainage', the
shell green strength has increased sufficiently that subsequent shell coats can be dried more rapidly under more aggressive conditions, so the relative humidity is reduced to 57% and the air velocity is increased to ~8 m s⁻¹. After the sixth coat, the relative humidity is again decreased to 47%. Each shell coat is allowed to dry in the tunnel for a minimum of 2 hours. Throughout the dip run, the dry bulb temperature in the drying tunnel remains constant at 26 °C, while the dry bulb temperature in the dip room is at 24 °C, with a relative humidity of 57%.

Each hanger 34 of six patterns 10 is dipped in turn by a 3-axis robot. With the hanger 34 having a T-shaped handle, there are two potential orientations on robot pick-up. The hanger 34 being static relative to the robot head means it is set down in the same orientation as it was picked up. The robot executes a preset program of movements for the dipping, draining and sanding of each shell coat. The program sequence varies slightly between the first prime, second prime and the concrete coats.

Following pick up, the hanger 34 is rotated anticlockwise looking down from the robot head, whilst being submerged first end down into the slurry tank. The hanger 34 is held at an angle slightly off vertical so as to ensure any air pockets come into contact with slurry. The patterns 10 are immersed in the first prime slurry for 120 seconds, and in the case of the second prime and concrete slurries, for 70 and 90 seconds respectively. The hanger 34 changes direction of rotation in each slurry, 30 seconds after immersion. The hanger 34 is then withdrawn from the slurry tanks vertically whilst rotating clockwise. After 5 seconds, it indexes to a position 30° from the vertical in a hanging position whilst maintaining the clockwise rotation for 45 seconds. This sequence is the same for each coat. The fully drained hanger 34 then indexes to a vertical hanging position and over a period of 30 seconds, moves towards the rain sander where sand is then applied to the assemblies which move to adopt a horizontal orientation in the sander whilst continuing to rotate clockwise. The two prime and the concrete coats are sanded for 70 and 60 seconds respectively, before being returned to the vertical orientation (first end down) to dry.

After completion of the dipping process, all complete moulds 36 are then dehumidified in aggressive conditions for a minimum of 24 hours (fan assisted 26% relative humidity, 22 °C dry bulb), to ensure minimal moisture retention in the shell, which would cause the shell to crack on de-wax.
The moulds 36 are de-waxed in an autoclave via the application of steam at a pressure of 0.6 MPa, for 12 minutes, after wax exit holes have been brushed into the ceramic at the base and pourcup using a high speed revolving wire brush. The moulds 36 are placed in a freezer at 0 °C for 12 hours prior to de-wax. This assists the high pressure steam in minimising the potential for wax core expansion and hence shell cracking, by enabling the melting of the outer layer of wax at a rapid rate. To ensure this, a pressure of 0.6 MPa must be attained in the vessel within 11 seconds and held for a minimum of 12 minutes.

Following de-wax, the moulds 36 are fired in a kiln with an oxygen supply to enable the sintering of the ceramic and complete combustion of wax residue from the moulds 36. The heating regime includes a ramp up to 930°C over 40 minutes, where the temperature is then held for 30 minutes before partial furnace cooling. Prior to casting, moulds are fitted with a ceramic filter (not shown) in each starter block to minimise the risk of inclusions in the cast product.

Each mould 36 comprises a shell 38 which is made from dried silica and zircon slurry, alumina and concrete. The shell 38 defines the casting cavity 40. The casting cavity 40 has the same form as that of the pattern 10. Thus, it includes a base plate cavity 42. A down sprue cavity 44 extends perpendicularly from the centre of the base plate cavity 42. A pourcup cavity 46 is positioned at the end of the down sprue cavity 44. Ten starter block cavities 48 are positioned on the base plate cavity 42. The starter block cavities 48 are grouped in equally spaced pairs. Five equally spaced runner cavities 50 extend from the bottom of the down sprue cavity 44, perpendicularly to the down sprue cavity 44. Each runner cavity 50 splits into two sub-runner cavities 52, each sub-runner cavity 52 being connected to a starter block cavity 48. The starter block cavities can be wider than they are tall. The runner arrangement is the same as that illustrated in Figure 5. A crystal selector cavity 54 extends from the top of each starter block cavity 48. The crystal selector cavity 54 is connected to a turbine blade cavity 56. Thus, the mould 36 can be seen to comprise a first end 58 and a second end 59 in a similar way to the pattern 10, the first end 58 being the portion of mould 36 which surrounded the first end 28 of the pattern 10, and the second end 59 of the mould 36 being the portion of the mould which surrounded the second end 29 of the pattern 10.
The resulting moulds 36 are thicker at the tips of the blade cavities 56, that is, the first end 28/58 of the pattern/mould than at other places in the mould as seen in Fig. 10. The thicker shell around the component cavity, will hold the heat better suppressing local undercooling and preventing the nucleation and solidification of secondary grains. In addition, the build up of slurry around the starter block pattern 18 is thinner and more uniform than for patterns dipped in the opposite orientation, as shown in Fig. 6b. This promotes a liquidus which is more likely to be uniform and planar, therefore increasing the chance of a grain being selected which possesses a low Θ orientation. In addition, the starter blocks can be wider than they are tall, further promoting a planar liquidus at the central grain selection area.

The mould 36 can then be used for casting turbine blades. Casting takes place in a 3-chamber, small bore type, Directional Solidification furnace 60, as shown in Fig. 11. The furnace comprises a melt chamber 62, within which the alloy charge 64 is melted, a furnace chamber 66 within which the pre-heated mould 36 sits ready to receive the molten alloy 64 and below that a mould chamber 68, into which the mould 36 is retracted during melt solidification. The melt chamber 62 is induction heated and houses the facility for a disposable alumina crucible 70. The crucible 70 is a one-shot bottom pouring type. The furnace chamber 66 possesses a water-cooled stainless steel shell 72, housing a graphite resistance element 74. The mould chamber 68 houses a motor driven ram 76, with a 6-inch diameter water-cooled copper chill plate 78 on to which the mould 36 is mounted.

The system is evacuated in preparation for casting to avoid the formation of metal oxides, dross formation or air in the moulds themselves, which could restrict the flow of molten alloy and give rise to porosity or gas hole defects. A maximum standard casting pressure of 0.7 Pa is achieved. Furnace temperature is controlled by a pyrometer. A k-type thermocouple is used as a low/high temperature 'Policeman Gauge'.

Once located on the chill plate 78, sealed in the furnace 60 with the specified pressure achieved, the mould 36 is rammed up into the furnace chamber 66 where it is heated to 1470°C, 81°C above the alloy liquidus. The charge of SRR99 Single Crystal alloy in the melt chamber is then high frequency induction melted. The alloy pouring system is achieved with the use of a solid disc or "penny" of SRR99 in a recess 80 at the base of the crucible retaining the charge of alloy 64 above, until it is molten. The
induction coil is located such that the penny is the final stock to melt, allowing the alloy 64 to fill the mould 36 via the pourcup cavity 46. Once the alloy 64 is poured, the mould 36 remains in situ for 90 seconds while the aperture 82 between the melt chamber 62 and furnace chamber 66 closes. The mould 36 is then withdrawn out of the furnace chamber 66 through baffles into the mould chamber 68 beneath at varying rates dependent on blade section thickness. This provokes Directional Solidification up the length of the casting 83 and ensures a uniform solidification rate along the axis of the blade cavity 56 to form blades 84. Once fully solidified, the casting 83 and mould 36 are removed from the furnace 60 and left to cool in an insulated cabinet.

Once cooled, excess shell is removed from the blades 84 through the application of a high frequency pneumatic hammer to the base of the starter blocks 86. The blades 84 can be cut from the ends of the helices 88. The blades 84 are heat treated in an argon atmosphere at a partial pressure of 50-70 Pa and a maximum temperature of 1305 °C. The temperature is elevated at increments and held for soak periods to promote a more homogenised grain structure. After non-destructive testing all conforming blades 84 are polished and machined to an engine ready state.

In another embodiment, the crystal selector may be another suitable shape, other than helical. For example, it may be an angled passage, an inclined ramp, or a constriction, as illustrated in Fig. 2a, b and d respectively.

Second Embodiment

In the method of this embodiment, a mould for Directional Solidification Investment Casting is made. This embodiment is similar to the first embodiment, and so the same reference numerals will be used for similar features, and only the differences between the two embodiments will be described. The wax pattern 10 does not include a crystal selector pattern 24, and thus the starter block pattern 18 is connected directly to the blade pattern 26. Thus, in the mould, the starter block cavity 48 is connected directly to the blade cavity 56. The resulting mould is shown in Fig. 13. On casting, an alloy suitable for Directional Solidification, with grain boundary strengthening elements, is used. Fig. 14 schematically illustrates Directional Solidification within a component.
In the above two embodiments the slurry parameters may vary from those described, but within suitable parameters as could be deduced by the skilled man, with the number of coats for the particular slurry type used being sufficient to control secondary grain occurrence sufficiently.

In both embodiments, the pattern was dipped with the first end first. However, the pattern could be dipped in any orientation, including second end first, and then drained in an 'inverted' position, i.e. with the first end lower than the second end.

A pattern with ten blades, fed by five gates, has been described but any suitable number of blade patterns, fed by any suitable gating system, as could be readily devised by the skilled man, may be used. The size of the starter block, and the size of chill plate it can accommodate may also be varied.
Claims

1. A method of making a mould, the method comprising:
   applying slurry to a pattern for forming a mould, the pattern having a first end and a second end being for defining the ends of the cavity in the mould, the first end being the end which, on casting and solidification into the mould, will contain the molten material which solidifies last; and, the second end being the end at which it is desired solidification will start;
   holding the pattern to drain and/or dry in a position to allow the movement of slurry towards the first end under the influence of gravity; and
   repeating as necessary to form a mould.

2. A method of making a mould according to claim 1, wherein the pattern is held to drain and/or dry with the axis of the mould between the first and second ends at an angle of 75° or less to the vertical.

3. A method of making a mould according to claim 2, wherein the pattern is held to drain and/or dry with the axis of the mould between the first and second ends at 60° or less to the vertical.

4. A method of making a mould according to claim 3, wherein the pattern is held to drain and/or dry with the axis of the mould between the first and second ends at an angle of 30° or less to the vertical.

5. A method of making a mould according to claim 4, wherein the pattern is held to drain and/or dry with the axis of the mould between the first and second ends substantially upright.

6. A method of making a mould according to any preceding claim, wherein the pattern is held and rotated during at least part of the drainage and/or drying step.
7. A method of making a mould according to any preceding claim, wherein the pattern includes means to enable the pattern to be lifted in the desired orientation.

8. A method of making a mould according to claim 7, wherein the pattern includes at least one handle at the second end to enable the pattern to be lifted in the desired orientation.

9. A method of making a mould according any preceding claim, the mould being for casting a Directionally Solidified component.

10. A method of making a mould according to claim 9, the mould being for casting a Single Crystal component.

11. A method of making a mould according to any preceding claim, wherein the pattern comprises a component pattern extending from the first end, and a starter block pattern at the second end.

12. A method of making a mould according to claim 11, wherein the pattern includes a base plate pattern, the starter block pattern extending from the face of the base plate pattern.

13. A method of making a mould according to claim 12, wherein the base plate pattern is arranged such that a base plate cast in the mould is arranged to engage with a furnace chill plate.

14. A method of making a mould according to claim 11, 12 or 13, wherein the starter block pattern is wider in diameter than it is tall.

15. A method of making a mould according to any of claims 11 to 14, wherein a crystal selector pattern is provided between a starter block pattern and a component pattern, for selecting a Single Crystal of the desired orientation.
16. A method of making a mould according to claim 15, wherein the crystal selector pattern may take the form of one of the group comprising: an angle passage, an inclined ramp, a constriction, and a helix.

17. A method of making a mould according to claim 15, wherein the crystal selector pattern is a helix.

18. A method of making a mould according to claim 17, wherein the helix is a 360° helix.

19. A method of making a mould according to any preceding claim, wherein the slurry is applied to the pattern by dipping the pattern in a slurry.

20. A method of making a mould according to claim 19, wherein the pattern is dipped in slurry first end first.

21. A method of making a mould according to claim 20, wherein the pattern is dipped in the slurry with the axis of the mould between the first and second ends at an angle of 75° or less to the vertical.

22. A method of making a mould according to claim 20, wherein the pattern is dipped in the slurry with the axis of the mould between the first and second ends at 60° or less to the vertical.

23. A method of making a mould according to claim 20, wherein the pattern is dipped in the slurry with the axis of the mould between the first and second ends at an angle of 30° or less to the vertical.

24. A method of making a mould according to claim 20, wherein the pattern is dipped in the slurry with the axis of the mould between the first and second ends substantially upright.
25. A method of making a mould according to any preceding claim, wherein the pattern is dipped in the slurry in any orientation, but turned to be held in the desired orientation to drain and/or dry.

26. A method of making a mould according to any preceding claim, wherein the method includes a step of drying the mould and a further step, after the step of drying the mould, of removing the pattern from the mould.

27. A method of making a mould according to any preceding claim, wherein the slurry is prime slurry.

28. A method of making a mould according to any preceding claim, wherein the mould includes a concrete layer.

29. A method of making a mould according to any preceding claim, wherein the mould comprises at least one layer of stucco.

30. A method of making a mould according to any preceding claim, wherein the steps of applying slurry and holding the pattern to drain and/or dry are repeated at least once.

31. A mould made using the method of any of claims 1 to 30.

32. An Investment Casting mould for Directionally Solidified components, the wall of the mould being thicker at the end opposite the end at which solidification starts.

33. A mould as claimed in claim 32, the mould including a part defining a cavity for a starter block.

34. A mould as claimed in claim 33, the part being of substantially constant wall thickness.
35. An Investment Casting mould for Directionally Solidified components, the mould including a part defining a cavity for a starter block, the part being of substantially constant wall thickness.

36. A mould according to claim 33, 34, or 35, wherein the starter block is wider in diameter than it is tall.

37. A mould according to any of claims 31 to 36, wherein the mould includes a layer of concrete.

38. A mould according to any of claims 31 to 37, wherein the mould is made at least partially of stucco.

39. A mould as claimed in any of claims 31 to 38, wherein the mould is an Investment Casting mould for Single Crystal components.

40. A mould according to claim 39, wherein the starter block cavity is connected to a component cavity by a crystal selection cavity.

41. A mould according to claim 40, wherein the crystal selection cavity is helical.

42. A mould according to claim 41, wherein the crystal selection cavity is a 360° helix.

43. A mould according to any of claims 31 to 42, wherein the mould comprises a plurality of component cavities.

44. A mould according to any of claims 31 to 43, wherein the mould is for casting a turbine blade.

45. A method of making a mould, the method comprising the steps of: applying slurry to a pattern; holding the pattern in an inverted position to drain and/or dry; and
repeating as necessary.

46. A method of making a mould substantially as described herein and with reference to Figures 5, 6b, and 7 to 12 or 13 and 14.

47. A mould substantially as described herein with reference to Figures 5, 6b and 7 to 12 or 13 and 14.
Figure 9 c)
INTERNATIONAL SEARCH REPORT

PCT/EP2011/057436

A. CLASSIFICATION OF SUBJECT MATTER

INV. B22C9/04 C30B11/00

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B22C C30B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of Box C.

See patent family annex.

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Date of the actual completion of the international search

21 June 2011

Date of mailing of the international search report

30/06/2011

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Hodi amont, Susanna
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