Analysis of Grain Selection during Directional Solidification of Gas Turbine Blades

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Abstract — **In this paper the evolution of grain structure and the control of crystal orientation in gas turbine blades are presented. The conditions leading to the solidification of columnar grain and single crystal blades are analysed, and techniques for producing columnar grain and single crystal blades in industry are reported.**

Index Terms — **Directional solidification, Grain selection, Nickel-base alloys, Turbine blade.**

I. INTRODUCTION

The operating temperature of turbine blades in jet engines has been demanded to increase because of the demand for ever higher turbine entry temperatures in the engine for saving energy and increasing thrust. Turbine blades are made of nickel-base superalloys. It is well known that theses alloys are difficult to forge, in particular when the blades have complex geometries with intricate channels which allow cooler air flow within and along the blades during operation [1]. Therefore, turbines are usually produced by investment casting. During casting two types of grain structures are formed in the blades: columnar grains and equiaxed grains [2] (see Fig 1). Fig 1(a) is a nickel-base superalloy turbine blade which was produced by investment casting, i.e., by pouring the molten metal into a consolidated ceramic mould. After proper chemical etching, the grain structure of this blade is clearly revealed by zones of different grey levels. As can be seen, the crystals grow equally in its preferred growth directions, forming roughly round-shaped, equiaxed grains. Fig 1(b) is a turbine blade which was produced by directional solidification, an array of parallel aligned dendrites grow from bottom of the blade to the top of the blade. The parallel dendrites eventually form a large region of long and thin columnar grains with long parallel boundaries. It has been found that the mechanical strengths at elevated temperature of the directionally solidified gas turbine blades are better than those of blades with equiaxed grains [3]. Over the past 30 years grain structures in gas turbine blades have progressed from equiaxed to columnar grains through the introduction of directional solidification to achieve higher temperature capabilities. Recently it was found that mechanical

properties of the Ni-base alloys are not isotropic. For example, high temperature creep strength for the blades with <001> crystals grown along the direction of combined force in-use are usually favourable compared to those with <011> or <111> crystals [4]. The orientation of columnar grains in a blade can be controlled during directional solidification using specially designed grain selector so that the columnar grains have the same orientation. Blades with such grain structure are called single-crystal blades. Fortunately, the preferred growth direction of Ni-base alloys, <001>, can be aligned with the direction of the combined force in blade during operation. So single crystal Ni-base alloys have found such wide use in recent years for improved high temperature capability.

In this paper the grain selection during directional solidification of Ni-base superalloys will be analysed. In the first part of this paper, the selection of columnar grains during casting is discussed and directional solidification techniques for producing columnar grains are introduced. In the second part, the selection of crystal orientation is presented and techniques for producing single crystal blades are reported.
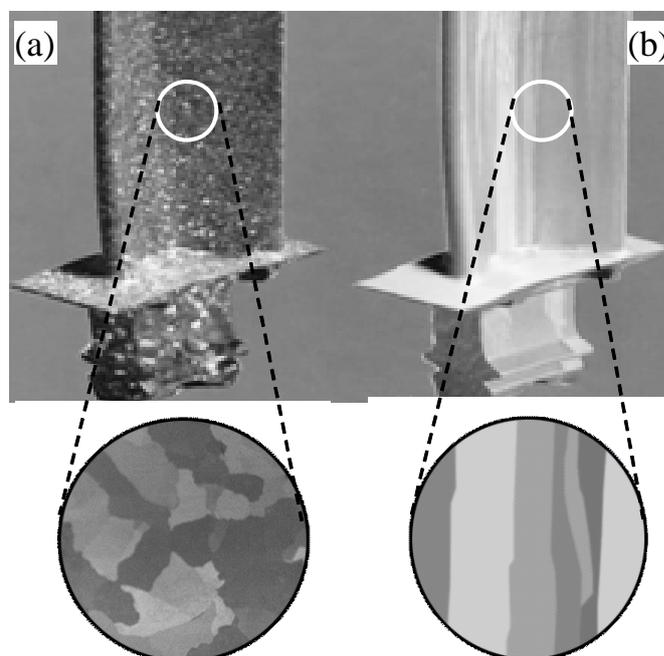
Fig 1. (a) A turbine blade with equiaxed grains, (b) a turbine blade with columnar grains

II. SELECTION OF COLUMNAR GRAIN AND DIRECTIONAL SOLIDIFICATION

A. Columnar and Equiaxed Grains

To create the designed shape of a turbine blade, liquid metal is poured into a mould cavity, where the liquid metal transforms or solidifies into a solid of the desired shape. This process is called solidification. During solidification there are two distinguished steps: nucleation and growth. The first step of solidification is the creation of tiny, stable, solid crystals called nuclei in the liquid metal when the temperature of the melt cools down below its equilibrium temperature (T_E in Fig 2). Once nuclei have been created, solidification proceeds by growing the nuclei into grains. The growth process usually generates heat because the enthalpy of the solid is less than that of the liquid, meanwhile solute partitions into the liquid if its solubility in the solid is less than that in the liquid. As an example shown in Fig 2, at the solidification front or solid/liquid interface, solute concentration in liquid (C_L) is greater than that in solid (C_S) when the partition coefficient k, ($k = C_S/C_L$), is less than 1. The accumulation of solute and heat ahead of the interface leads to circumstances in which the liquid in front of the solidification front is undercooled (temperature of the melt is below its equilibrium temperature). The solid/liquid (S/L) interface thus becomes unstable and in appropriate circumstances the morphology of solid becomes dendritic. Dendrite (from Greek *dendron*, tree-like structure) is the most prevalent structure in crystal grains, and the pattern of dendrites determines the final properties of castings. Two distinct forms of dendrite structures, columnar and equiaxed dendrites, exist in castings (see Fig 3).

The crystal grains, either columnar or equiaxed, are the result of mechanisms of nucleation and growth of a primary phase solidified in a thermal gradient [5]. During equiaxed growth, latent heat is extracted through the undercooled liquid. The temperature gradient in the liquid ahead of the dendrite tip will be negative. In this case, there is little interaction between the growing dendrite tips and the dendrites can grow freely into the melt as rapidly as the undercooling permits. The controlling parameter for the growth velocity is simply the undercooling of the bulk liquid below its liquidus temperature, ΔT (as indicated in Fig 2).
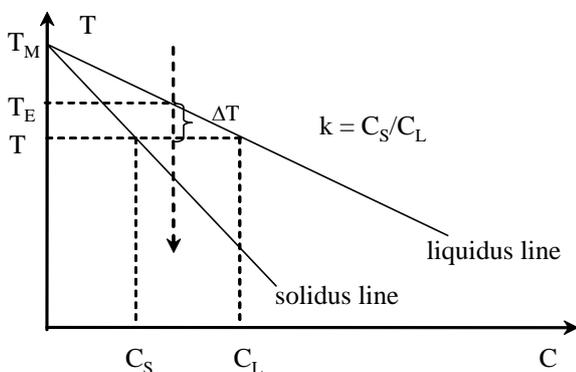
Fig 2. A typical phase diagram for a two component alloy ($k < 1$). The solidus and liquidus are assumed to be approximately straight lines.
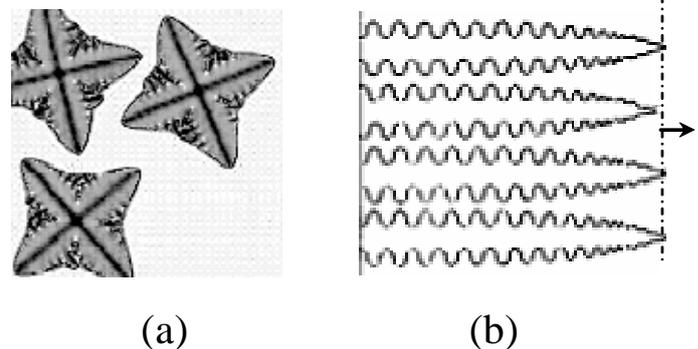

(a)   (b)

Fig 3. Schematic diagrams showing typical equiaxed grains (a) and columnar grains (b)

During columnar growth (also called directional solidification), heat is extracted through the solid from the left hand side, in the opposite direction to the growth direction. The temperature gradient in the liquid ahead of the tips will be positive. Dendrites will be arranged parallel to each other in arrays and there will be an interaction between the growing dendrites. This is also known as constrained growth because the growth velocity is fixed by the imposed temperature gradient and pulling velocity.

B. Selection of Columnar Grains

The selection of the grain structure is a key issue for the optimisation of casting properties. In direct-chill and continuous casting, columnar grains grow from the mould surface perpendicular to the isotherms, with a transition to equiaxed grains occurring near the centre of the ingot. To obtain a casting ingot with fine equiaxed grains, inoculation of the melt by adding other high temperature particles (called grain refiner) is widely used to promote the formation of equiaxed grains. While in directionally solidified or single crystal castings, columnar grains are desirable, with equiaxed grains being treated as casting defects when high angle boundaries must be avoided in turbine blades.

In Fig 4 (a), the solid is produced by slowly drawing an initially liquid specimen from a furnace (so that all the heat is extracted from the left end). If a planar solid/liquid (S/L) interface is assumed, i.e. curvature undercooling is negligible ($\Delta T_\gamma = 0$) and a local equilibrium occurs at the interface, i.e. kinetic undercooling is zero ($\Delta T_K = 0$), then the undercooling and compositions at the interface (ΔT) will be given by the equilibrium phase diagram which is shown generically in Fig.2 for the case $k < 1$. The solute rejected by the growing solid 'piles up' in the liquid ahead of the S/L interface, and 'defuses away exponentially' from the interface (see Fig 4 (b)). Equilibrium temperatures for the melt ahead of the S/L interface are plotted in Fig 3 (c). The lowest equilibrium temperature occurs at the S/L interface due to the maximum solute 'piled-up', and the equilibrium temperatures rise up

exponentially due to the solute 'defused away exponentially' from the interface.

$$G_{CRIT} = \left.\frac{dT_L}{dz}\right|_{z=0} = m\left.\frac{dC_L}{dz}\right|_{z=0}$$

where m is the slope of the liquidus line as shown in Fig 2. For the imposed thermal gradient G2 where $(dT/dz)_{z=0} > (dT_L/dz)_{z=0}$, the equilibrium temperature of the melt is lower than the temperature in the melt and the melt is not undercooled. Therefore even if a nucleus appears in the melt, it can not grow into a grain.

The existence of a constitutional undercooling (CU) ahead of the S/L interface provides a driving force for the nucleation and growth of new grains. Grains formed ahead of the S/L interface usually have equiaxed grain morphology and can block the growth of columnar grains. This phenomenon is call columnar-to-equiaxed transition (CET). Based on the potential for equiaxed grains to nucleate and grow in the constitutionally undercooled region ahead of the columnar front Hunt proposed that if the volume fraction of equiaxed grains exceeds 0.49 then the grain structure is equiaxed, otherwise the columnar grain will continue to grow [7]. To remove the CU ahead of the growth front, a high thermal gradient is required, $(dT/dz)_{z=0} < (dT_L/dz)_{z=0}$. Alternatively to minimize the CU, a slow growth rate can be applied at the S/L interface (solidifies at a low rate), which allows the 'piled up' solute to diffuse away. Therefore, to grow the columnar grains, high temperature gradients in front of the S/L interface and low solidification velocities are desired.

C. Technological Consequences – Growth of a Blade with Columnar Crystals

As discussed above, to grow the columnar grains, a positive thermal gradient should be imposed at the growth front. This is achievement by the directional solidification where heat is extracted through the solid, in the opposite direction to the growth direction (see Fig 5 (a)). The temperature gradient in the liquid ahead of the S/L interface is positive. In this case, columnar dendrites will be arranged parallel to each other in arrays. For Ni-base superalloys, the most rapid dendritic growth direction, <001>, is selected as the long axis for the blades. This is fortunate because the alloy also has a high elastic anisotropy with the minimum value along this axis. This minimizes the strain produced during thermal cycling when blades are in operation in aero-engines.

Directional solidification (DS) furnaces have been used to grow blades with columnar grains furnace. As shown in Fig 5 (b), the DS furnace comprises 3 zones: (1) a vacuum induction-melting unit; (2) a resistance-heated furnace chamber and (3) a withdrawal chamber. The preheated ceramic mould is open at the bottom and sits on a water-cooled copper chill plate. The molten superalloy solidifies on contact with the copper chill to form a thin layer of equiaxed grains. Subsequent growth favours those grains most closely aligned with the <001> direction parallel to the thermal gradient, producing an array of columnar grains with a common vertical <001> crystal orientation. After solidification starts, the water-cooled chill plate is lowered gradually, withdrawing the ceramic shell
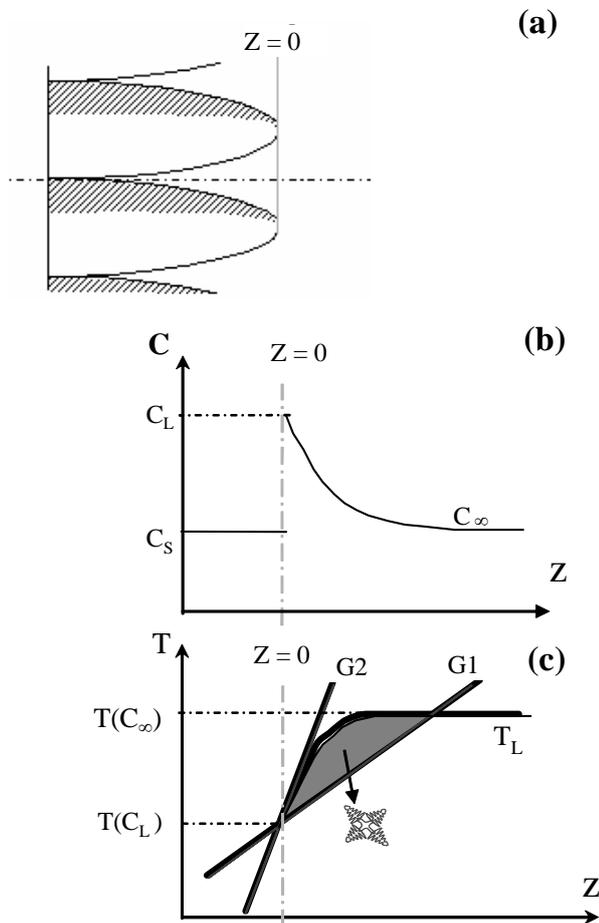

Fig.4. (a) schematic diagram of dendritic front, (b) solute concentration at the solidification front (S/L interface), (c) equilibrium temperature (T_L) at the solidification front and applied thermal gradients (*G1* and *G2*), constitutional undercooling exists if $G = (dT/dz)_{z=0} < (dT_L/dz)_{z=0}$.

Considering the imposed thermal gradients G_1, the equilibrium temperature of the melt ahead of the S/L interface (X=0) is higher than the temperature in the melt. So the liquid ahead of the interface is effectively supercooled. This undercooling is called constitutional undercooling (CU) [6] since it is formed due to the solute 'piled up' ahead of the interface. The hatched zone in the Fig 4 (c) is called constitutionally undercooled region where the equilibrium temperature of melt is higher the temperature in the melt. If a nucleus appears in the undercooled region, it may grow into grains. The critical condition for the existence of this CU can be easily derived. CU will exist when thermal gradient at the interface $(dT/dz)_{z=0}$ is less than the gradient of the equilibrium temperature at the interface, G_{CRIT}. G_{CRIT} is defined as:

mould filled with molten alloy from the heated furnace, producing a blade with columnar grains as shown in Fig 1 (b).
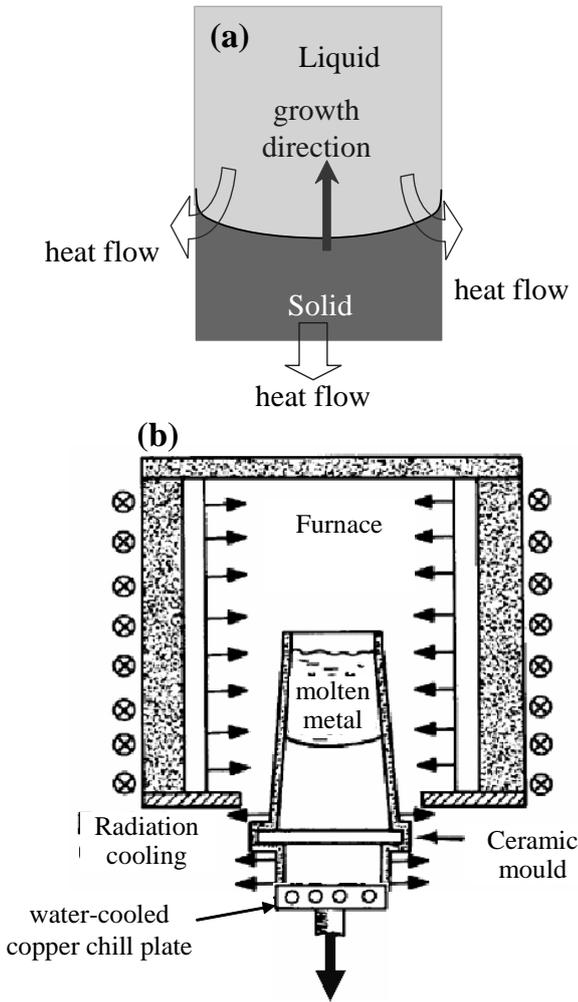

Fig. 5. (a) heat flow analysis during directional solidification, (b) schematic drawing of directional solidification of a turbine blade

III. SELECTION OF GRAIN ORIENTATION

Due to the anisotropy of surface tension, each crystal has a preferred growth direction. For Ni-based superalloy with a cubic lattice, <100> is the preferred growth direction. It has been well known that mechanical properties of the Ni-base alloys are not isotropic too. High temperature creep strength for the blades with <001> crystals along the direction of combined force in-use are favourable compared to those with <011> or <111> crystals. To achieve the higher temperature capability, the preferred growth direction <001> of Ni-base alloys is desired to be aligned with the direction of the combined stress in-use, and the selection of grain orientation is through the competitive growth mechanism.

A. Competitive growth

Fig 6 (a) shows the solidified structure of succinonitrile-1.3wt.% acetone (the succinonitrile acetone has

a similar solidification behaviour as metals [8]) , illustrating the competitive growth. The growth direction is from the bottom to the top. At the start, there were three grains. The growth directions of the grains 1 and 3 are parallel to pulling direction (the direction of heat flow) as indicated in Fig 6(b), while the growth direction of grain 2 is approximately 20° off from the pulling direction. During steady state growth, the growth velocity of the grain 1 and 3 is approximate the pulling velocity V, but the growth velocity of the off-axis grain 2 is $V / \cos(\theta)$.
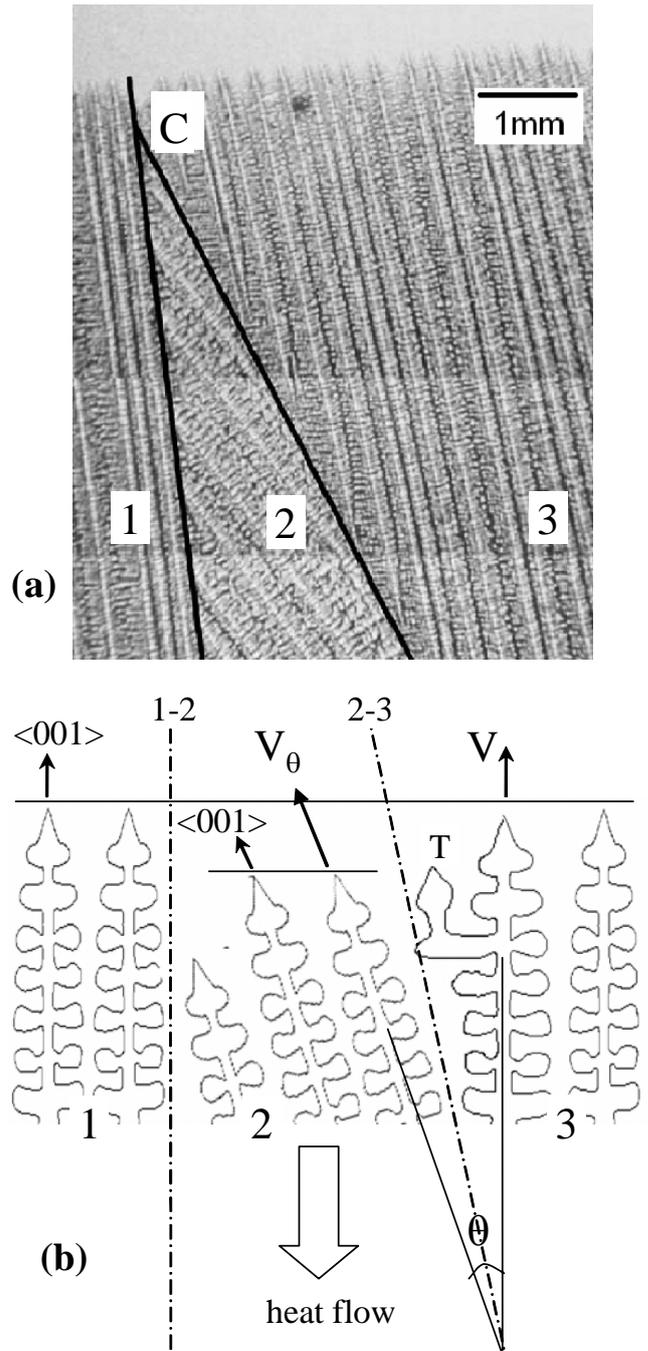
Fig. 6. (a) Grain selection observed in succinonitrile-1.3wt.% acetone alloy. Thermal gradient:1.9×10³ K/m, grown velocity: 8.66×10⁻⁵ m/s. [after ref. 10] (b) Schematic representation of dendritic growth showing the nature of competitive growth process in (a).

This means that the grain 2 grows at a higher a rate than grains 1 and 3. Under conventional casting conditions, the dendrite growth velocity increase monotonically with the square of undercooling, which is $V \propto \Delta T^2$ [9]. Therefore the grain 2 with a growth velocity of $V / \cos(\theta)$ has a higher undercooling at the front compared with the grain 1 and 3 with a growth velocity of V. Under the imposed positive thermal gradient, the growth front of the less-well aligned grain 2 falls behind that of well aligned grain 1 and 3 as illustrated in Fig 6 (b). Due to the lag of the solidification front, grain 2 will be overgrown (blocked) by the grain 1 at the converging grain boundary between 1 and 2. Thus the grain boundary between 1 and 2 is straight and parallel to the growth direction of dendrites in grain 1. On the other hand, at the diverging grain boundary between 2 and 3, branching takes place. One of the tertiary dendrite arm (indicated as T in Fig. 6(b)) becomes a new primary arm, thus the grain boundary between 2 and 3 is approximately the bisector of the growth directions of dendrites in grains 2 and 3. Due to the effect of overgrowth and branching at the grain boundaries, the less well-aligned grain 2 will disappear at the grain boundary interest points C as indicated in Fig 6(a). Selection of grain orientation is achieved through the nature of competitive growth.

In order to more effectively select the crystal orientation during solidification, specially designed grain selectors are utilised to achieve a single crystal grain orientation for a whole component, which will be analysed in next section.

B. Technological Consequences – Growth of a Blade with Single Crystal

The primary aims of producing single crystals are (1) to eliminate grain boundaries that limit creep ductility and (2) to orient the elastically soft <100> orientation parallel to the maximum load direction to minimise cyclic stress in operation. In practice, casting a single crystal blade is achieved by directional solidification combined with a spiral grain selector. In casting foundries, a prefabricated seed is placed at the bottom
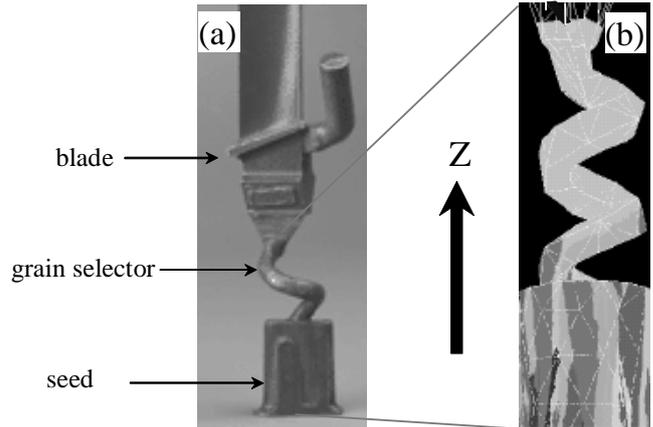

Fig. 7. (a) a single crystal turbine blade with a spiral grain selector; (b) grain selection in the spiral grain selector calculated using CalcoSoft™ solidification software [11]
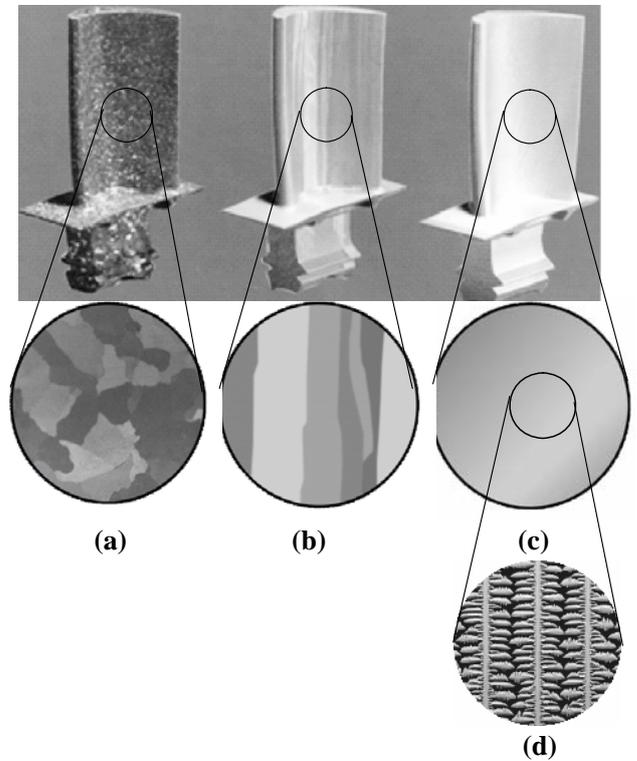

Fig 8. Nickel-base superalloy turbine blades solidified as (a) equiaxed grains, (b) columnar grains, (c) a single crystal, (d) an enlarged view of the single crystal blade showing detailed dendritic structure calculated using CAFD solidification software [12]

of the mould, and is partially melted-back during soak period of the mould after the molten alloy is introduced to the mould (see Fig 7 (a)). The mould is withdrawn from the furnace to grow the blade. As indicated in Fig 7 (b) several grains can grow into the spiral-shaped passageway (called spiral grain selector) and most of them will be eliminated and only one grain can surviveto grow after the grain selector. If solidification in the main body progresses from a single crystal, then the whole blade may solidifies as a single-crystal if a high thermal

gradient and low velocity is maintained during the growth of the blade. For a comparison, turbine blades solidified as equiaxed crystals, columnar crystals and a single crystal are shown in Fig 8. Fig 8 (c) is a nickel-base single crystal turbine blade which was produced by directional solidification and a spiral grain selector. After chemical etching, no grain structure is revealed on the blade surface (no difference in grey level). An enlarged view of the single crystal blade is shown in Fig 8 (d), revealing the detailed dendritic structure at the micrometer level and crystal orientation.

However, in certain circumstances pertaining to mechanical response, it is necessary to impose a specific crystal orientation on the component by using a single-crystal seed of desired orientation. In this case the oriented seeds are placed underneath the spiral grain selector prior to casting.

IV. CONCLUDING REMARKS

The evolution of grain structure and the control of crystal orientation in gas turbine blades have been discussed. The conditions leading to the solidification of columnar grain and single crystal blades have been analysed. To grow the columnar grains in the blades a high thermal gradient and a low solidification velocity are desired in directional solidification, and a grain selector with well controlled directional solidifications are required to produce single crystal blades.

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