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Research Article

The Effect of Surface Columnar Grains on Mechanical Properties in a Nickel-Based Gas Turbine Blade

M.R. Alizadeh[1]*, M. Naseri[2], A.M. Kolagar[3]

[1,2,3]MavadKaran Engineering Company, MAPNA Group, Tehran, Iran

**Corresponding Author: mra.alizadeh64@gmail.com*

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Abstract— The morphology of surface grain of a gas turbine blade has always played a significant role on the mechanical and properties. In this pare, the effect of surface columnar grain on the mechanical properties has been studied on a Nickel-based gas turbine blade. For this purpose, two ceramic moulds were produced by coating ceramic layer. The moulds had different weights due to applying different number of ceramic layers on the moulds; one mould was heavier than the other. Then super alloy IN738LC was poured into the moulds and their surface grains was investigated. The results showed that there was some columnar grain in the blade which was in the heavier ceramic mould, while the other blade which was in the lighter mould, had no columnar grain size. Finally, three mechanical samples were prepared from each blade and their mechanical properties were compared. The test results showed that the mechanical properties of the blade with no-columnar grain were slightly higher than the other blade; in effect, the difference can be insignificant. In fact, the direction of the observed columnar grains was not exactly perpendicular to the airfoil to cause and propagate any cracks when stress is applying. In addition, the critical grains' length was 80 mm that estimated the critical length of the grain which above that can be destructive and should be avoided.

Keywords— Columnar grain, Mechanical properties, Ceramic mould, Investment casing, Nickel-Based super-alloy.

1. Introduction

In general, Nickel-base super alloys is known as an unusual metallic material with different grains on its surface, including equiaxed and columnar and single crystal grains. These materials are widely used in power-generation gas turbines, Creep-resistant turbine blades and typically produced by complex investment casting methods, that are necessary to introduce complex cooling designs and control grain structure. Such components may contain equiaxed grains or columnar grains, or they may be cast as single crystals, completely eliminating all high-angle grain boundaries [1].

In fact, surface grains and their size and their morphology have a significant influence on mechanical properties. The longer the length of grain boundary, the more dislocations are displaced in the slip planes. Therefore, mechanical properties such as yield strength are lower than regions with short grain boundaries [2].

In another study, Deluigi showed that coarse grains can reduce mechanical properties due to greater phase segregation during tensile testing. He also emphasized that the number of dislocation connections also increases with grain size. His experiment was based on computer simulation [3].

The main application of nickel-based superalloys is in the manufacture of turbine blades of aero engines. Nickel base turbine blades structure consist usually equiaxed grains on its surface when the blade is etched. In effect, the grains and their boundaries increase the resistance of the material to creep deformation and could be used at higher temperatures [4].

To compare equiaxed with columnar and single crystal, directionally solidified columnar grain structure has many γ grains, but the boundaries are mostly parallel to the principal stress axis. The performance of such blades is not as good as the single-crystal blades, because in the single crystal there is no grain boundary which can cause to relieve stress and improve its creep and tensile test result. However, the grains with columnar solidification are much better than the blades with equiaxed grain which have the worst creep life. Figure 1 shows the three kind of grains that were discussed [5].

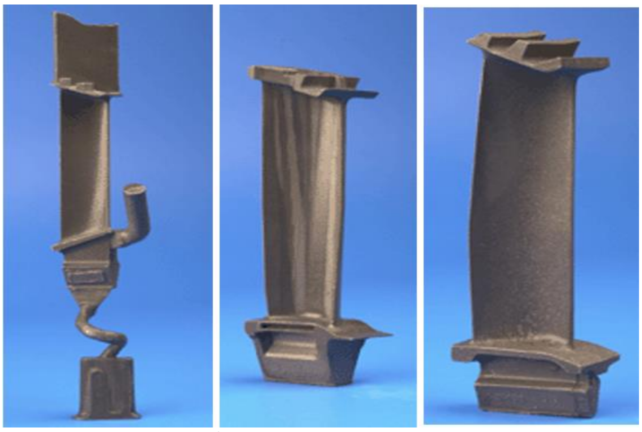

Figure. 1. Three kind of grain structure in a gas turbine blade; a) Single crystal, b) Columnar grains, and c) Equiaxed or polycrystalline [5].

Because grain boundaries are sites for damage accumulation at high temperatures, the blades in the early stages of the turbine are typically single crystals, whereas the blades in the later (cooler) stages of the turbine are fabricated from equiaxed alloys [5].

Moreover, the main requirements for materials used in gas turbines are determined by the temperature capabilities of the rotating blades, their creep resistance at high temperature, good resistance to thermal fatigue and to oxidation/corrosion. All of these properties are strongly related to the surface and internal grains. Since the production process of the blades is usually investment casting, therefore, to attain a proper mechanical property, the condition of ceramic shell must be compatible with casting process. Lacaze and his colleague showed that the growth of grains and their morphology of the surface grains are strongly dependent on the thermal gradient and solidification rate. Figure 2 shows their result [6].

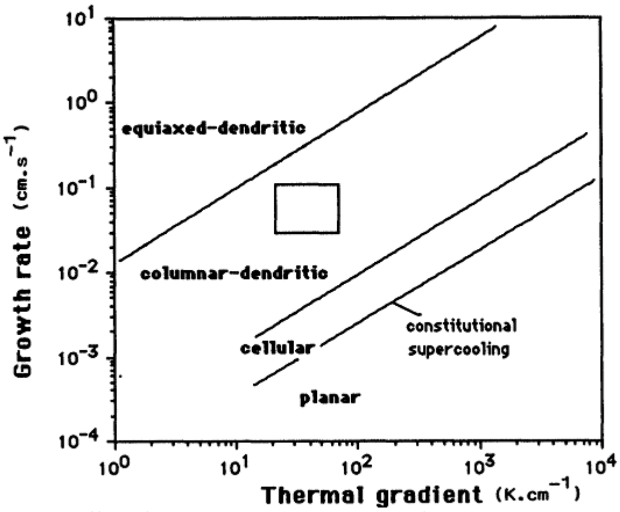

Figure. 2. Effect of thermal gradient (G) and solidification rate (V) on the type of solidification structure. The square represents the domain in which is industrially possible to achieve the D.S process [6].

Zhang and his colleague showed that the shape of the liquid–solid interface in terms of planar, cellular, columnar dendritic, or equiaxed dendritic fronts is governed by the temperature gradient G, solidification rate R, undercooling ΔT, and solute diffusion coefficient DL. According to the solidification theory, the grain morphology and substructure (fineness/size) are strongly affected by the ratios G/R and G ·R (cooling rate), respectively. At the bottom of the melt pool where the solidification rate R ≈ 0, the ratio of G/R is infinite, leading to a planar-dominated grain structure. As the ratio, G/R decreases until G/R < ΔT/DL, the cellular solidification takes place near the planar region. Further decreasing of the G/R ratio leads to the columnar dendritic formation. The equiaxed solidification typically happens near the surface of the melt pool where the temperature gradient is relatively low. Figure 3 shows their result [7].

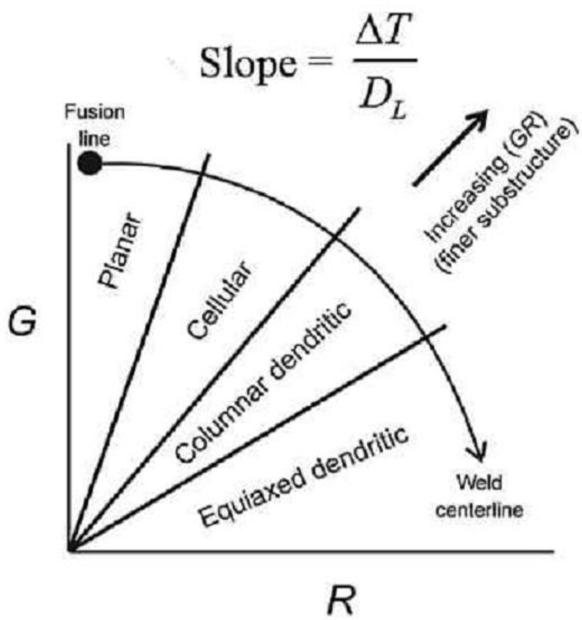

Figure. 3. Schematic of the effects of temperature gradient G and solidification rate R on grain morphology [7].

In addition of surface grain, Murr and his colleagues showed that the internal columnar grains can adversely affect the mechanical properties of nickel-base super alloy. Grain sizes in superalloys are highly dependent on the manufacturing method [8].

In another research, it was stated that in investment casting process, due to segregation of solute elements and the formation of a solute elements enriched layer in front of the advancing solidification, the liquid may be below its equilibrium liquids temperature, forming stray grains. Stray crystals' formation hindered the crystals’ continuous upward growth. The slowdown in the solidification rate also reduced the internal stress generated during the solidification process. Accordingly, the occurrence possibility of defects is reduced, which was conducive to the continuous growth of columnar crystals [9].

In the present research, some scientific and experimental investigation have been done on a nickel-base gas turbine blade. In fact, these investigations are about effect of the type of surface grains on mechanical properties of this blade.

2. Experimental method

In this research, the effect of columnar grains on the mechanical properties of a typical gas turbine blade has been investigated. For this purpose, two ceramic moulds were produced by investment casting process. In the investment casting process, first, two wax clusters were assembled and then coated with different number of ceramic layers to obtain two ceramic moulds with different weights and thicknesses; one mould was heavier than the other. The schematic of the wax cluster was the same and is shown in the Figure. 4.

Then, the ceramic moulds were poured by molten metal. After that the blades were cut off and the etched. All the casting conditions were presented in previous work written by this arterial's authors [10].

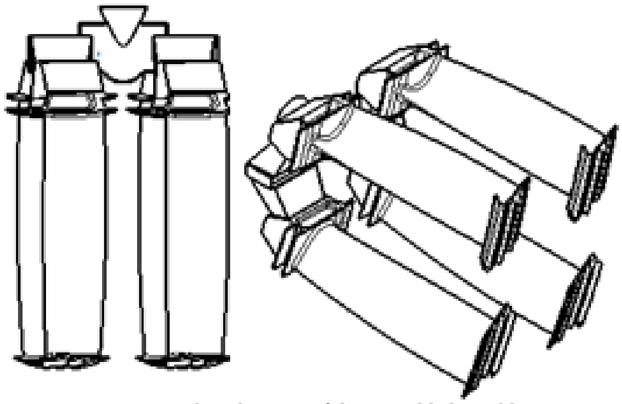

Figure. 4. The schematic of the assembled moulds.

After cutting of the blades from their cluster, one blade from each mould was selected and etched to see its surface grains. The etchant solvent was also the same and its composition included HCL, $FeCl_3$ and water. In the next step of the investigation, the surface grain size of the blade was compared with each other.

Ultimately, three tensile samples were prepared from each blade to compare and evaluate their mechanical properties. The location of the test sample was illustrated in Figure. 5. The dimensions of the test samples are shown in Figure. 6.

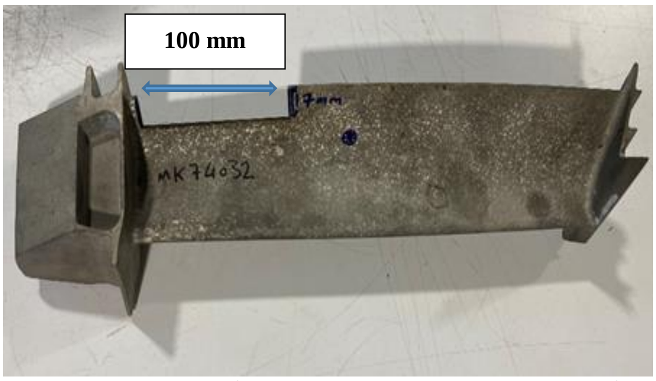

Figure. 5. The location of the test samples on the blade (Dimension of the blade is 350×70×55 mm)

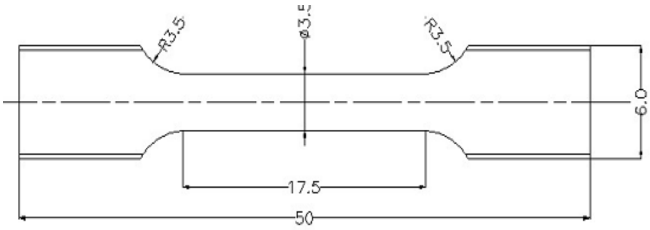

Figure. 6. The dimensions of the samples.

3. Results and discussion

After etching the blades, the results showed there was some surface columnar grains in the blade which was in the heavier ceramic mould, while the other blade which was in the lighter mould did not have any surface columnar grains.

The reason for the formation of columnar grains is more probably related to the change of the thermal gradient which itself related to the regions of the mould with more thicknesses. In other words, the molten metal near the root of the blade is solidified later than the other regions of the blade. In addition, the thick layer of ceramic in the mould which coated with more number of layer led to the formation of columnar grains near the root of the blade which is hot section in casting. But, the blade that was in the lighter ceramic mould illustrated only equiaxed grains when it was etched due to the thinner thickness of the moulds in these regions. These results are completely in match with Zhang and Errichello and their colleagues' work in which with a low thermal gradient more columnar grains were appeared [2,7]. Figure. 7 and 8, are depicted the equiaxed and columnar grains, respectively.

Then, three mechanical sample from each blade were made and their tensile properties were tested compared with each other. The results of tensile tests in ambient temperature showed that in the mechanical samples which had columnar grains, the average mechanical properties were a little lower than the blade which did not have any columnar grains. These results are shown in table 2. This difference in Yield Stress (YS) and Ultimate Tensile Strength (UTS) was very negligible and lower than 2 percent, and for the elongation was lower than 5 percent. The stress rupture results have shown in table 3 that shows there is no significant difference in the time of rupture in equiaxed and columnar grains.

Thus, it can be concluded that, the surface grains can play an important role in mechanical and properties, but, in fact, the intense and amount of the columnar grains in this work was minor and negligible. In other words, the intense and amount of the columnar grains was not that destructive to affect the properties negatively. In essence, the direction of the observed columnar grains was not exactly perpendicular to the airfoil to cause and propagate of any cracks when stress is applying. In addition, the critical grains' length was 80 mm that the size above this amount can be destructive.

Table 2. The result of tensile properties in ambient temperature.

Type of Surface Grain	Yield Stress (YS) MPa	Ultimate Tensile Strength (UTS) MPa	Elongation %	Hardness (HRC, 150kgf)
Not-Columnar	780	962	8.4	40
Columnar	766	950	8	40

Table 3. The result stress rupture (at temperature 982°C and Stress 152 MPa).

Type of Surface Grain	Time to Rupture (hr)	Elongation %	Reduction of Area %
Not-Columnar	40	10.2	14.4
Columnar	36	14.5	16.7

Figure. 7. The blade without surface columnar grains which shows only equiaxed grains on its airfoil.

Figure. 8. The blade with surface columnar grains that is not exactly perpendicular to the airfoil and their length are about 80mm.

4. Conclusion

In summary, the results showed that the pattern, morphology and size of surface grains can influence the mechanical properties. The main reason for observing the columnar grains was the difference in thermal gradient and solidification rate in different section of the blade, and these two parameters are the most important parameters to prevent columnar grain from formation. In effect, whenever the grain shape deviates from the equiaxed grains, the mechanical properties can be affected. In fact, columnar grains can be destructive when their intensity and amount were increased.

However, the intensity and quantity of these columnar grains that was observed in this research were very negligible. The mechanical properties also proved that the differences in YS and UTS were very lower than 2 percent, and for the elongation was lower than 5 percent, and the stress ruptures also did not have a significant difference. All in all, the presence of columnar surface grains can reduce tensile properties, but it did not affect the results because the intensity of the columnar grains was minor. In other words, the intense, amount and the direction of the columnar grains were not that destructive to affect the properties negatively. In essence, their directions were not exactly perpendicular to the stress direction to cause and propagate any cracks when stress is applying. The critical length of the columnar grain was 80 mm. In other words, if the size of the grain is more than this amount, it may also cause to more reduction in the properties.

Data Availability

None.

Conflict of Interest

All authors are requested to disclose any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations that could inappropriately influence, or be perceived to influence, their work. Otherwise, Authors declare that they do not have any conflict of interest.

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Author’s Contribution

Author 1- Designed the experimental procedure and discussed its concepts and wrote the first draft of the manuscript.
Author 2- Designed the experimental procedure and discussed its concepts and edited the manuscript.
Author 3- Evaluated the results and Edited the manuscript.

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