Investment Casting of NiAl Single-Crystal Alloys

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INTRODUCTION

NiAl alloys have several advantages over superalloys (e.g., melting point, density, thermal conductivity, and oxidation resistance) that make them very attractive for turbine airfoil applications. While a significant amount of work has been devoted to developing NiAl alloys and optimizing their properties, less attention has been paid to the production-scale processing of these alloys. Investment casting has been recognized as a viable approach for producing NiAl single-crystal castings. However, considerable technical difficulties, due to the unique physical properties of these alloys, need to be overcome before production quantities of NiAl castings are a reality. Recent work at PCC Airfoils and General Electric (G.E.) Aircraft Engines has brought closer an understanding of the effects of those physical properties on castability, microstructure evolution, and defects formation during investment casting.

REASONS FOR USING NICKEL ALUMINIDES

NiAl alloys are being considered as a replacement material for single-crystal superalloys in some turbine airfoils. Compared to superalloys, NiAl materials have four major advantages:

1. The melting point of NiAl alloys (1,610–1,676°C) is about 250°C higher than that of single-crystal superalloys. This provides the opportunity for a significant increase in the turbine inlet temperature.

2. The density of NiAl alloys (5.9–6.3 g/cm³) is about two-thirds that of a typical superalloy (8.6 g/cm³). This is particularly attractive because in a high-pressure turbine blade application, this could result in up to a 40% reduction in the turbine rotor (disk and blades) weight compared to superalloy counterparts.

3. The thermal conductivity of NiAl alloys [35–76 W/(m·K)] is three to seven times that of typical superalloys; thus, the temperature distribution in a turbine airfoil during operation would be more uniform. This could redue the hot-spot temperature by up to 50°C, significantly increasing thermal fatigue life.

4. NiAl alloys have excellent oxidation resistance. This offers the possibility of eliminating the coatings that are applied to single-crystal superalloy castings.

PROCESSING DIFFICULTIES

Some physical properties (e.g., high melting point and thermal conductivity) that are considered advantages of NiAl alloys also cause significant difficulties during solidification processing of single-crystal NiAl castings. Other factors contributing to these difficulties are very low room-temperature ductility and a relatively high ductile-to-brittle transition temperature (DBTT).

Because of their high melting points, the processing temperatures during investment casting of NiAl alloys are well above the maximum temperature capability of currently used silica-based mold materials. Thus, the most difficult task for investment casting of NiAl alloys is developing a mold material that not only has adequate high-temperature strength but also is chemically inert to avoid any severe metal-mold reactions.

During investment casting, the high thermal conductivity of NiAl alloys results in a lower temperature gradient and larger mushy zone size than that found in superalloy castings. This results in an increased potential for the formation of grain-related defects (e.g., equiaxed grains) and microporosity. The processing flexibility for avoiding casting defects is limited by the high-temperature capability of the mold material, so only a small amount of superheat can be generated during the investment casting of NiAl single-crystal castings.

The very low room-temperature ductility and the high DBTT of NiAl alloys contribute to cracking during the cooling stage of the casting process. The tendency of the casting to crack is proportional to the magnitude of residual stress, which increases with increasing casting temperature gradient.

PROGRESS

For the past two years, PCC Airfoils and G.E. Aircraft Engines have studied the potential to make single-crystal NiAl turbine blades using investment casting. The approach combined finite-element thermal analyses and experimental casting results. Solidification conditions of cylindrical bars and slabs were simulated for two NiAl alloys and one single-crystal superalloy (René N5). The results of the simulations and experimental castings were used to establish the effects of NiAl's high melting point and...
high thermal conductivity on microstructure evolution and defect formation.

The secondary dendrite arm spacing (SDAS) as a function of local solidification time (LST) for NiAl alloys and superalloy René N5 is shown in Figure 1. It can be seen that the higher the alloy liquidus temperature (1,678°C for NiAl alloy A, 1,662°C for NiAl alloy B, and 1,430°C for superalloy René N5), the higher the measured SDAS. This is because a higher solidification temperature results in faster diffusion and a higher dendrite coarsening rate. Consequently, NiAl alloys have higher SDAS values than those of René N5. Similar results were also obtained for primary dendrite arm spacing.

Thermal conductivity had important effects on casting solidification conditions and defect formation. For the two particular alloys studied, the thermal conductivity of alloy A was four times higher than that of superalloy René N5, while alloy B had three times higher thermal conductivity. Figure 2 shows that when NiAl alloy A and René N5 had an identical withdrawal cycle, the main difference in the solidification conditions was the mushy zone location. It can be seen that the mushy zone of NiAl alloy A is always located above that of René N5. This is because the higher thermal conductivity of NiAl alloy A results in a faster cooling rate than for René N5 and, hence, pulls the mushy zone inside the furnace hot zone (i.e., above the baffle location).

Another important difference in the solidification conditions is mushy zone size. A small mushy zone size is desired, because this means that solidification is occurring over a narrow space and there is less opportunity for defect formation. Figure 2 shows that NiAl alloy A has a larger mushy zone and, hence, a lower temperature gradient than René N5. Table 1 shows the calculated temperature gradient of the NiAl alloys and René N5 slabs. It can be seen that in general, the higher the alloy thermal conductivity, the lower the casting temperature gradient during solidification.

Due to the low temperature gradient and fast cooling rate during solidification resulting from the high thermal conductivity, the major grain defects found in the NiAl castings were equiaxed grains (Figure 3). The tendency to form equiaxed grains decreases with the increase of G/R (where G is temperature gradient in °C/cm and R is solidification rate in cm/s) at the liquidus temperature.

<table>
<thead>
<tr>
<th>Slab Position</th>
<th>N5 Alloys A and B and René N5 Slabs*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient at Liquidus Temp. (°C/cm)</td>
<td>Gradient at Solidus Temp. (°C/cm)</td>
</tr>
<tr>
<td>Top</td>
<td>60.1 50.5 38.3</td>
</tr>
<tr>
<td>Middle</td>
<td>59.9 52.7 43.3</td>
</tr>
<tr>
<td>Bottom</td>
<td>44.0 53.6 43.3</td>
</tr>
<tr>
<td>Relative Thermal Conductivity</td>
<td>1 3 4 1 3 4</td>
</tr>
</tbody>
</table>

* For an identical withdrawal cycle.