PROCESSING AND OPERATING EXPERIENCE OF Ni$_3$Al-BASED INTERMETALLIC ALLOY IC-221M

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ABSTRACT

The cast Ni$_3$Al-based intermetallic alloy IC-221M is the most advanced in its commercial applications. This paper presents progress made for this alloy in the areas of: (1) composition optimization; (2) melting process development; (3) casting process; (4) mechanical properties; (5) welding process, weld repairs, and thermal aging response; and (6) applications. This paper also reviews the operating experience with several of the components. The projection for future growth in the applications of nickel aluminide is also discussed.

INTRODUCTION

Development of intermetallics for structural applications have been talked about in the scientific literature [1-14] for nearly two decades. From the thousands of possible intermetallic compounds [15] that exist based on elements in the periodic table, the aluminides of nickel, iron, titanium, and molydisilicide have shown the most potential for commercial applications. Among the aluminides, a cast Ni$_3$Al-based alloy, developed at the Oak Ridge National Laboratory (ORNL) and known as IC-221M, has reached the most significant stage of commercialization. The purpose of this paper is to provide the processing details, properties, and operating experience for this alloy.

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COMPOSITION

The IC-221M is a cast alloy with composition [15-16] based on controlled additions of boron, chromium, zirconium, and molybdenum to the Ni₃Al base. The nominal composition of IC-221M, given in Table 1, can be produced in the laboratory environment with good control of each element. However, the alloy production under commercial environment resulted in the following described issues which have been dealt with for commercial applications:

1. *Melting procedures not known for such high aluminum content alloy.* This issue stems from two aspects of commercial melting practices. First, only small aluminum additions are typically used in commercial alloys. Such aluminum additions are made to the melt near the end of melting for the purposes of deoxidation. Large additions of aluminum such as in IC-221M were feared to chill the melt and mostly oxidize and go to slag. The oxidation process was expected to cause poor chemistry control. The second concern for melting was based on the assumption that the only way to melt an alloy with such high aluminum content is to load the entire aluminum content at the beginning of the melt. In this scenario, the large melting point difference between aluminum and nickel will cause overheating of the aluminum prior to the start of the nickel melting. The overheated aluminum of very high fluidity will seep through any cracks in the furnace crucible and attack the induction coil. Such an attack of the induction coil will bring molten aluminum in contact with water and result in an explosion. Both of these concerns have been eliminated with the development [17-19] of a melting process known as Exo-Melt™. The key features of this melt practice are described in some detail in a later section.

2. *Recovery of various elements.* The oxidation of aluminum, zirconium, and boron during air melting were considered of concern for their recovery. However, our work with melting of many experimental heats have demonstrated that the use of the Exo-Melt™ process results in essentially 100% recovery of all alloying elements except zirconium, which requires a loading of 120% in the melt stock.

3. *Pick-up of elements other than nominal from the commercial melt stock.* The commercial grade melt stock tends to introduce impurities such as carbon and sulfur. A systematic study of a large number of heats to determine the effect of impurity elements on the weldability has allowed us to set acceptable limits of carbon, sulfur, silicon, and boron. The pick-up of silicon and iron during the foundry practices is described in issue
No. 4 below. Since limited opportunity occurs to remove these impurities during air-induction melting, carbon and sulfur contents can be kept to a minimum by proper selection of the melt stock. The contents of carbon and sulfur may also be controlled by starting with a new furnace lining or using pure nickel wash heat prior to melting the nickel-aluminide alloy.

4. Pick-up of certain elements from the foundry environment. The elements silicon and iron are commonly picked up when melting nickel aluminum in an iron-based alloy foundry. The silicon is picked up from the fact that nickel aluminide tends to react with the sand (SiO₂), especially when extra metal is poured into sand pig molds. If the pig is used in melting revert heats without removing the sand, the aluminum and zirconium contents of nickel aluminide reduces SiO₂ to silicon, which is picked up by the alloy. The silicon pick-up from this source can be reduced by two approaches: (1) to pour the extra metal in ZrO₂ wash-coated pig molds (such a wash eliminates the reaction of molten IC-221M with sand); and (2) if sand is stuck to the pigs, it must be removed by grit blasting prior to melting the revert.

Another source of silicon pick-up is by the attack of molten nickel aluminide on SiO₂ in zirconia crucibles. Silicon pick-up from this source can be minimized by two steps: (1) use Al₂O₃ as a furnace crucible or lining rather than zirconia, and (2) minimize the time that molten IC-221M stays in contact with the crucible. The contact time can be reduced by proper scheduling of melting and casting of heats so that the molten metal does not set in the furnace for long periods waiting for it to be poured.

The iron pick-up can occur in at least two different ways. First, being in an iron foundry, there is always a chance of a small piece of iron or steel from other heats getting into the nickel-aluminide melt stock. Pick-up from this source can be minimized by careful controls in the foundry practice. The second source for the pick-up of iron is the steel liner that is typically used for setting a new furnace lining. The best method to reduce such a pick-up is to run a wash heat of nickel after setting the new lining and prior to melting IC-221M. The pick-up of iron over 1 wt % has the tendency to precipitate the beta phase, which lowers the high-temperature strength of IC-221M.

5. Melting of foundry revert stock. The foundry revert stock consists of several items: (1) pigs cast from metal left over after casting all planned molds, (2) runners and risers removed from the castings, and (3) any defective castings that are beyond weld repairing. Any of these three revert stocks have a potential of adding
impurities to the alloy. The potential of silicon from the pigs has already been described above. The runners and risers can also add silicon if all of the sand stuck to the castings is not completely removed. The remelting of the castings can also add iron impurities if some of the steel beads become trapped in the defective area. Proper removal of any sand from the runners and risers and trapped steel beads can minimize the pick-up of silicon or iron from the foundry revert stock.

6. Oxidation of molten metal. The zirconium in the IC-221M is the first element to oxidize followed by aluminum, if molten metal is exposed to air for long periods of time. Such oxidation can be minimized using an argon cover during air-induction melting. Similarly, the oxidation of molten metal flowing through the sand molds can be minimized by flushing the molds with argon prior to casting.

MELTING PROCESS

The most significant progress towards commercialization of IC-221M has occurred through the development of the Exo-Melt™ process for melting of IC-221M using the currently available melt technology at most foundries. The process is based on the fact that the formation of aluminides from their alloying elements is exothermic [17-19] and uses a furnace-loading sequence to effectively use the heat of formation in the melting process. The most significant benefits of the Exo-Melt™ process for melting IC-221M include:

1. It permits the commercial melting of IC-221M and uses the currently available foundry equipment.
2. It produces reproducible alloy chemistries.
3. For virgin heats, it save 50% energy and 50% time as opposed to the conventional process, which industry was not willing to try for reasons listed above.
4. The energy and time savings and extended crucible life result in 50% lower cost than the conventional process.
5. One ORNL licensee has melted over 22,700 kg of the IC-221M alloy in 1996, and two licensees have melted over 22,700 kg so far in 1997.
6. The use of the Exo-Melt™ process has helped accelerate the commercialization process.
CASTING PROCESSES

The IC-221M produced by the Exo-Melt™ process can be cast into complex shapes by the static sand mold casting process. It can be cast into tubes and pipe by the centrifugal process. The components of nickel aluminide can be produced by welding the centrifugal and static castings. The alloy can also be investment cast into ceramic molds. Examples of sand casting of IC-221M are shown in Fig. 1. These castings vary significantly in section thickness from 6.35 mm for the heat-treating fixture to 203 mm for the forging die. The casting complexity also increases from a simple shape such as pallet tip to very complex heat-treating fixtures. Not only can the complex shapes be cast, but they can also be produced with good dimensional control as demonstrated in Table 2.

PROPERTIES

The physical and mechanical properties and corrosion data on nickel aluminide alloys were compared with commercial alloys in a recent paper [20]. The characteristic physical and mechanical properties [21] of the IC-221M alloy are listed for a range of temperatures in Table 3.

WELDING

The continuing effort at ORNL has demonstrated that the cast IC-221M can be successfully welded for either the repair of castings or fabrication of components. The gas tungsten arc is the best welding process, and IC-221LA and IC-221W are the two recommended filler wires. The composition for IC-221LA in weight percent is 4.5 Al-16.0 Cr-1.2 Mo-1.5 Zr-0.003 B-76.8 Ni, and the composition for IC-221W in weight percent is 8.0 Al-7.7 Cr-1.4 Mo-3.0 Zr-0.003 B-79.9 Ni. The welding process development has progressed to a point of being able to successfully weld large-diameter centrifugal-cast pipe to sand-cast trunnions. The welding success of such large components has resulted from optimized weld design, a tight control of base metal chemistry, and the use of stainless steel backing ring to minimize root pass cracking.

The weldment properties reported elsewhere [22] show that tensile properties are similar to base metal with somewhat lower ductility and creep rupture strengths, 70% of the base metal.
NICKEL-ALUMINIDE APPLICATIONS

The applications of nickel aluminide continue to grow. They range from heat-treating fixtures for carburizing and oxidizing environments, rolls for steel-hardening furnaces, dies for hot-forging applications, tube hangers for high-temperature processing furnaces, and components for calcination furnaces. A new application is developing in the area of radiant burner tubes for furnace heating.

FUTURE PROJECTIONS

The calendar year 1996 has been an excellent year for commercialization of nickel aluminides. Over 22,700 kg of the IC-221M alloy were melted and cast into a variety of components. The performance of 1996 has extended into 1997. This is evidenced by the extension of a single foundry licensed in 1996 to three licensees at the time of this writing. The current application development activity suggests that the production of IC-221M is expected to double in 1997 and has the potential to grow to five times during 1998.

CONCLUSIONS

The cast nickel-aluminide alloy IC-221M is well on its way to commercialization. This paper has presented the compositions, melting, casting processes, properties, welding, applications, and future projections.

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REFERENCES


FIGURE CAPTION

1. Examples of sand casting of IC-221M alloy.
Table 1. Comparison of nominal chemical analysis of IC-221M with the range observed for heats made using virgin and revert stock in a pilot commercial melt run of 94 heats carried out at Alloy Engineering & Casting Company

<table>
<thead>
<tr>
<th>Element</th>
<th>Nominal (wt %)</th>
<th>Virgin heats (wt %)</th>
<th>Revert heats (wt %)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>Al</td>
<td>8.0</td>
<td>7.5 - 8.2</td>
<td>7.86</td>
</tr>
<tr>
<td>Cr</td>
<td>7.7</td>
<td>7.63 - 8.11</td>
<td>7.81</td>
</tr>
<tr>
<td>Mo</td>
<td>1.43</td>
<td>1.38 - 1.50</td>
<td>1.45</td>
</tr>
<tr>
<td>Zr</td>
<td>1.70</td>
<td>1.73 - 2.02</td>
<td>1.93</td>
</tr>
<tr>
<td>B</td>
<td>0.0080</td>
<td>0.004 - 0.008</td>
<td>0.0054</td>
</tr>
<tr>
<td>C</td>
<td>--</td>
<td>0.012 - 0.032</td>
<td>0.022</td>
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<tr>
<td>Si</td>
<td>--</td>
<td>0.021 - 0.055</td>
<td>0.036</td>
</tr>
<tr>
<td>Fe</td>
<td>--</td>
<td>0.03 - 0.15</td>
<td>0.077</td>
</tr>
<tr>
<td>Ni</td>
<td>81.1</td>
<td>b</td>
<td>80.81</td>
</tr>
</tbody>
</table>

*a50% virgin and 50% revert.
bBalance.
Table 2. Variability of casting dimensions for a pilot commercial run of 63 sets of IC-221M castings

<table>
<thead>
<tr>
<th>Component</th>
<th>Average ± standard deviation (length)</th>
<th>Average ± standard deviation (width)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tray</td>
<td>672.7 ± 0.7</td>
<td>672.5 ± 1.2</td>
</tr>
<tr>
<td>Lower fixture</td>
<td>657.7 ± 1.8</td>
<td>657.4 ± 1.9</td>
</tr>
<tr>
<td>Upper fixture</td>
<td>632.8 ± 2.2</td>
<td>632.3 ± 2.0</td>
</tr>
<tr>
<td>Property</td>
<td>Temperature (°C)</td>
<td>Room</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>------------------</td>
<td>------</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td></td>
<td>7.86</td>
</tr>
<tr>
<td>Hardness (R_c)</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Microhardness (dph)</td>
<td></td>
<td>260</td>
</tr>
<tr>
<td>Modulus (GPA)</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Mean Coeff. of thermal expansion (10⁻⁶/°C)</td>
<td></td>
<td>12.77</td>
</tr>
<tr>
<td>Thermal conductivity (w/m K)</td>
<td></td>
<td>11.9</td>
</tr>
<tr>
<td>0.2% Tensile yield strength (MPa)</td>
<td></td>
<td>555</td>
</tr>
<tr>
<td>Ultimate tensile strength (MPa)</td>
<td></td>
<td>770</td>
</tr>
<tr>
<td>Total tensile elongation (%)</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>10² h Rupture strength (MPa)</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>10³ h Rupture strength (MPa)</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>10⁴ h Rupture strength (MPa)</td>
<td></td>
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<tr>
<td>Charpy impact toughness (J)</td>
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<td>40</td>
</tr>
<tr>
<td>Fatigue 10⁵ cycle life (MPa)</td>
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</tr>
<tr>
<td>Fatigue 10⁶ cycle life (MPa)</td>
<td></td>
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</tr>
</tbody>
</table>

*Room temperature to 100°C.
*Room temperature to specified temperature.
*Data at 650°C for investment-cast test bars.