Effect of Microstructure on The Ambient Tensile Deformation Behavior of Nickel Base Superalloy Supercast 247A

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Abstract— Supercast 247 A is a aeronautical grade advanced nickel base cast superalloy, taken up for development by M/s MIDHANI, Hyderabad, India keeping in view its high temperature strength capabilities, which is one of the principal requirements for aero-engine hot end applications, such as turbine blades and vanes, whose performance ultimately decides the efficiency of the aero-engine. The alloy has been developed successfully in the form of remelt-stock by M/s Midhani under the Airworthiness coverage of RCMA (Materials), CEMILAC, Hyderabad, India. Further to the certification of this alloy, a study has been taken up to correlate the heat treatment effects on the mechanical strength behavior of this alloy. The present paper is, one among such studies. The objective of this paper is to study the effect of microstructure on the tensile deformation behavior of the Supercast 247A alloy at ambient temperature. The study includes among others Microstructural characterization, evaluation of ambient tensile properties in different heat treated conditions.

Keywords—Aging treatment, Microstructure, Nickel base superalloy, Supercast 247, Tensile properties.

I. INTRODUCTION

The thrust and fuel economy displayed by the modern aircraft strongly depend upon and limited by the high temperature strength of the material used for its hot sections¹. Though the aircraft comprises many individual mechanical devices, its power plant and in particular the engine, generally governs the performance, efficiency, reliability and cost of operation². The traditional goals for aero engines powering fighter aircrafts are higher power to weight ratio and improved reliability. The key for achieving an increase in thrust lies in capabilities of materials and components to sustain higher hot end temperatures¹-³. The ever increasing demand for the high temperature strength materials for hot end components has resulted in the development of superalloys with useful strength up to the highest fraction of their melting point (0.9Tₘ) with substantial resistance to mechanical degradation over extended periods of time⁴. In order to provide indigenous capabilities in this critical technological front, an advanced nickel base cast super alloy SUPERCAST 247 A in the form of remelt stock (similar to CM 247 LC of western origin) has been developed.

Supercast 247A constitutes large number of alloying elements, such as Cr, Co, Mo, W, Al, Ti, Ta, Hf, C, B, Zr and nickel as base [⁵]. The material also has 8 trace elements and 9 low boiling elements, which are needed to be controlled at ppm levels, if not, the strength of the superalloy gets adversely affected to a significant extent⁶,⁷. The Supercast 247 A alloy attains its strength from gamma prime (γ') precipitates, an ordered intermetallic compound Ni₃ (Al, Ti)⁷-¹⁰. Solid solution and carbide strengthening are the other mechanisms that contribute further to the strength of this alloy¹⁰-¹². This alloy is mainly intended for the manufacture of critical aero engine components viz., aero foils and integral wheel castings of small aero engines due to its excellent castability, which enables to cast the components of wall thicknesses as low as 600 µm.

II. EXPERIMENTAL PROCEDURE

As a part of indigenization activity, under self reliance program Supercast 247A, near equivalent to CM 247 LC is developed by M/s MIDHANI in remelt Stock form with R&D inputs from DMRL, Hyderabad. This alloy has been taken up for thorough evaluation of all required mechanical properties and certified for its Airworthiness by RCMA (Materials), Hyderabad in the form of 80mmφ bars. The nominal composition of the alloy is given in Table I. Selected the test bars of 12mmφ were given three different heat treatments apart from as cast condition viz., direct aging, solutioning+aging, solutioning+double aging ⁵,¹³. The details of the heat treatment schedules are given in Table II. Characterization for microstructure studies was carried out by both Zeiss light optical microscopy fitted with a Hitachi digital camera and Edax Quanta 400 Scanning Electron Microscope (SEM). Fracture surfaces of tensile tested specimens were examined to identify the fracture modes and morphologies using the Phenom table top scanning electron microscope. The Vickers micro hardness was measured by the Buehler Vickers’s Micro hardness testing machine under a load of 100 grams and Tensile tests at room temperature were conducted on Instron 5500R universal testing machine at a crosshead speed of 1 mm min⁻¹ (i.e., at an initial strain rate of ~5*10⁻⁴ s⁻¹) using rounded specimens of gauge length 25 mm and width 3.88 mm. The axial strain was monitored with the help of an extensometer of 25 mm gauge length span.
III. RESULTS AND DISCUSSION

A. Microstructural Properties

Table I

<table>
<thead>
<tr>
<th>Element</th>
<th>Ni</th>
<th>C</th>
<th>Cr</th>
<th>Co</th>
<th>Mo</th>
<th>Ta</th>
<th>Ti</th>
<th>W</th>
<th>Al</th>
<th>Hf</th>
<th>B</th>
<th>Zr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt (%)</td>
<td>Balance</td>
<td>0.074</td>
<td>8.2</td>
<td>9.30</td>
<td>0.505</td>
<td>3.185</td>
<td>0.81</td>
<td>9.5</td>
<td>5.6</td>
<td>1.51</td>
<td>0.015</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Carbides are observed, in particular with dense and lean areas in the as-cast condition. Variation in carbide particle size observed in above heat treated conditions and are looking more regular. The micrographs are given in (Fig. 1). However, as seen from the samples in etched conditions (Fig. 2) it is observed that the carbides aligned around the grain boundaries with discontinuous network, occasionally in intra-granular sites. In Solutioning + aging the particles are very fine and discontinuous where as in Solutioning + double aging they are coarser and discontinuous.

Cast structures with colonies of γ/γ′ eutectic, carbides and γ′ have been observed in etched condition (Fig. 2). No appreciable change in aging condition observed. However, considerable reduction in vol. fraction of γ/γ′ eutectic observed in Solutioning + aging condition. γ′ observed to be very fine. Where as in Solutioning + double aging condition, γ′ observed to be slightly coarser compared to sample observed with heat treatment in Solutioning + aging condition.

Gamma prime (γ′) particle distribution and size variation with respect to heat treatment has been studied by SEM. An uneven distribution of γ′ w.r.t size has been observed with γ′/γ′ eutectic colonies and carbides in as cast condition. The average size of γ′ calculated as 630 nm (Fig. 3).

With aging at 870°C (1143 K) for 20 hrs., an increase in size of the γ′ observed. No change in γ/γ′ eutectic observed. Discontinuous carbides were observed along the grain boundaries. The average γ′ calculated as 822 nm.

Altogether a different structure with very fine and uniform γ′ precipitate throughout the matrix with fine carbide network, which is discontinuous with reduced vol. fraction of γ/γ′ eutectic phase in inter dendritic regions observed in solutioning + aging condition. The average γ′ size calculated as 270 nm (Fig. 3).

Well developed Bi-model γ′ (cuboidal + fine spherical) observed in solutioning + double aging condition. However the size of the gamma prime particles observed to be coarser.
The structure is uniform throughout the matrix. Discontinuous carbide network along the grain boundaries with slightly coarser particle size compared to that observed at (solutioning + aging) condition is observed. There is no difference in vol. fraction of γ'/γ' eutectic. The average γ' size calculated as 1011 nm (Fig. 3).

Different sizes of γ' in different heat treatment conditions mentioned above can be attributed to the following reasons: As cast γ' which forms during the solidification is expected to be coarser and uneven in size due to the temperature at which it forms that is due to the wider solidification range approximately 1380°C – 1340°C. Further heat treatment at 870°C (direct aging) to the cast structure has no effect on the γ'/γ' eutectic as it is very stable at lower temperature and starts going into solution only above the temperature of the order of 1230°C. However a slight growth observed in the size of the γ' and carbide precipitates are due to soaking at 870°C for long duration (20 hrs) which resulted in the growth. Where as in the case of (solution + aged) all the primary γ' as well as most of the γ'/γ' eutectic has been taken into solution at the temperature 1260°C. Which is very close to γ' solves (1270-1275°C) advantage is taken to precipitate ordered γ' by nucleation and growth kinetics by aging at 870°C for 20hrs. As the temperature is not sufficient enough for the precipitate to grow, uniform spherical precipitate retained. Due to the introduction of aging at high temperature 1080°C (double aging) a step in between solutioning and aging at 870°C the γ' as well as carbides which have precipitated at this temperature are expected to grow during the soaking periods at 1080°C aging and 870°C aging treatments, apart from the finer γ' precipitates which forms at 870°C which has resulted in a bimodal γ' structure (cuboidal and spherical).

B. Mechanical Properties

Tensile tests at room temperature carried out on the test samples machined from the test bars heat treated as per the given conditions (Table I) and from the as cast bar. As seen from the test results it is observed that the sample tested from (solutioning + aging) condition has resulted in higher yield strength and tensile strength and the sample tested for heat treatment (solutioning + double aging) condition slightly inferior in properties to that of solutioning + aging condition. The sample tested in as cast condition has given the lowest yield strength and tensile strength and sample from (as cast + aging) has resulted in a slight hike in yield strength and tensile strength compared to as cast sample. Table III shows the properties obtained on the samples tested in different conditions. The corresponding γ' particle size measured in the particular condition is also shown in the table III. Further, the tensile properties are well in compliance with the formula derived from precipitation strengthened Ni-base superalloys, which says:  

$$\tau = \frac{Gb}{\lambda},$$  

Where τ is the stress to shear the particle, λ is the inter particle spacing, G is the shear modulus and b is the burger vector. Graphical representation of tensile properties in different heat treatment conditions is given in Fig. 3(a) and (b). Micro-hardness on the samples assessed in as cast and heat treated conditions (Table I) in Vickers scales and recorded. The hardness measured across the diameter of the sample and the average hardness recorded. As seen from the
TABLE II.
MECHANICAL PROPERTIES OF SUPERCAST 247A IN AS-CAST AND THREE DIFFERENT HEAT TREATMENT CONDITIONS

<table>
<thead>
<tr>
<th>Tensile Specimen Condition</th>
<th>Gamma prime particle size (nm) (avg.)</th>
<th>0.2% YS (MPa)</th>
<th>UTS (MPa)</th>
<th>% Elongation</th>
<th>% R.A</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>As cast</td>
<td>630</td>
<td>743</td>
<td>900</td>
<td>8.35</td>
<td>15.39</td>
<td>505, 49.2</td>
</tr>
<tr>
<td>As cast + aging</td>
<td>822</td>
<td>748</td>
<td>897</td>
<td>15.0</td>
<td>17.45</td>
<td>402, 41.0</td>
</tr>
<tr>
<td>Solutioning + aging</td>
<td>270</td>
<td>881</td>
<td>911</td>
<td>5.6</td>
<td>13.71</td>
<td>461, 46.7</td>
</tr>
<tr>
<td>Solutioning + double aging</td>
<td>1011</td>
<td>795</td>
<td>892</td>
<td>13.9</td>
<td>16.98</td>
<td>405, 41.2</td>
</tr>
</tbody>
</table>

readings it is observed that the sample in (solutioning + aging) has maximum hardness. Values obtained are in compliance with the tensile strengths obtained in different conditions and are given in Table IV. Comparison of hardness in different conditions and comparison of tensile strength (UTS) with hardness (HRC) are shown in Fig. 3 and Fig. 4.

Fig. 3 (a) Comparison between Yield Strength (Y.S) and Ultimate Tensile Strength (U.T.S) (b) Comparison between Elongation (%) and Reduction in area

Fig. 4 (a) Graphical representation of the hardness values (b) Comparison between hardness (HRC) and tensile strength (UTS)

IV. CONCLUSIONS

1. A general Microstructural examination by optical and scanning electron microscopy of Nickel base cast superalloy Supercast 247 A, in different heat treated conditions has helped in understanding the physical metallurgy and tensile deformation behavior of the above advanced superalloy with an extremely narrow range of composition limits.

2. It is observed that the gamma prime morphology and size distribution of the material is changed with varying heat treatment conditions. Also size variation in grain boundary carbides observed. Finer gamma prime
precipitate obtained with aging at 870°C (1143 K) for 20 hrs. After solutioning at 1260°C (1533 K) for 2 hrs. has resulted in highest tensile strength compared to other conditions. This is attributed to the reduced inter particle spacing of the gamma prime precipitate due to its finer particle size, compared to other heat treatment conditions. This is also confirmed when compared the tensile strength of material tested under condition IV where the particle size is 1.0 µm which ultimately resulted in increased inter particle spacing.

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