Temperature Dependence of $\gamma$-$\gamma'$ Lattice Mismatch in Nickel-base Superalloys

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ABSTRACT

High temperature X-ray diffraction techniques were used to determine the $\gamma$-$\gamma'$ lattice mismatch of three different nickel-base superalloys at temperatures between 18 and 1000 °C. The measurements were performed on oriented single-crystal disks which had been aged to produce a semicoherent $\gamma$-$\gamma'$ structure. The thermal expansion of the lattice parameters of the $\gamma$ and $\gamma'$ phases was described by a second-order polynomial expression. The expansion of the $\gamma'$ phase was consistently smaller than that of the $\gamma$ phase, which caused the lattice mismatch to become more negative at higher temperatures. It was also shown that high values of lattice mismatch resulted in increased rates of directional $\gamma'$ coarsening during elevated temperature creep exposure.

1. INTRODUCTION

The mechanical properties of nickel-base superalloys are largely dependent on the precipitation of $\gamma'$, an ordered f.c.c. phase based on Ni$_3$Al. The lattice mismatch between the $\gamma$ matrix and the $\gamma'$ precipitates is one of several factors which can influence the strength and creep resistance of these alloys. The magnitude of the elastic coherency strains between $\gamma$ and $\gamma'$ is determined by the unconstrained lattice mismatch $\delta$ which is given by [1]

$$
\delta = \frac{2(a_{\gamma'} - a_\gamma)}{a_{\gamma'}}
$$

(1)

where $a_{\gamma'}$ and $a_\gamma$ are the lattice parameters of the $\gamma'$ and $\gamma$ phases respectively. The unconstrained lattice parameter of $\gamma'$ can be obtained by electrolytic phase extraction [2] of the $\gamma'$ particles. However, if the lattice parameters are measured in situ, the unconstrained mismatch can only be determined after allowing coherency loss to occur. If the precipitates remain coherent, the elastic coherency strains prevent the lattices of each phase from expanding to the same extent as they would if they were separate phases, and the constrained mismatch $\epsilon$ is then measured. Typically, $\epsilon = \frac{2}{3} \delta$ [1, 3]. Frequently, experimental determinations of $\delta$ are difficult, because its magnitude appears to be unmeasurably small in many superalloys. Furthermore, the misfit measurements can be affected by heat treatment conditions and experimental techniques [4, 5].

Although the influence of mismatch on the mechanical properties of superalloys is acknowledged, considerable uncertainty exists over the detailed mechanisms and the importance of mismatch in comparison with other parameters. Several workers have considered antiphase boundary (APB) strengthening to be the major source for tensile strength in many superalloys [6-8]. However, coherency strain hardening can also provide significant contributions to the tensile strength of many alloys. Decker and Mihalisin [4] and Ansell and coworkers [3, 9] found that the strengthening contribution from $\gamma'$ precipitation correlated well with the magnitude of the $\gamma$-$\gamma'$ mismatch. Grose and Ansell [3] also emphasized the importance of the temperature dependence of lattice mismatch in the elevated temperature tensile properties.

The effects of coherency strain hardening are significant to temperatures of at least 800 °C [3, 4]. However, the influence of lattice mismatch is less clear under conditions where diffusive processes can occur. One important process which occurs in superalloys at these temperatures is $\gamma'$ coarsening.
growth of $\gamma'$ particles can be described by the Lifshitz-Slyozov-Wagner (LSW) theory [10, 11] or by one of several modified treatments [12, 13]. In the original LSW theory the coarsening rate $k$ is given by

$$k = \frac{8\gamma_i V_m^2 C_e D}{9RT}$$

(2)

where $\gamma_i$ is the interfacial energy, $V_m$ is the molar volume of precipitate, $C_e$ is the equilibrium concentration of solutes in the matrix, $D$ is the effective diffusion coefficient, $R$ is the universal gas constant and $T$ is the absolute temperature.

It may be seen that changes in alloy composition could alter the coarsening rate in eqn. (2) by affecting $C_e$, $D$ or $\gamma_i$. Decker [14] and others [5, 15, 16] have argued that $\delta = 0$ would minimize $\gamma_i$ and thus reduce the rate of $\gamma'$ coarsening. However, elasticity theory [17, 18] and recent experimental results [19] lead to the conclusion that $\delta$ should influence neither $\gamma_i$ nor the precipitate-coarsening rate, as long as the particles remain coherent. A review of the results of a number of independent investigations did not reveal any consensus, since the results showed that increasing mismatch could increase [20, 21], decrease [22-26] or have no effect on [27] the $\gamma'$ coarsening rate. It is probable that the compositional modifications used to produce the changes in mismatch in the above investigations could have also affected other parameters, such as $D$ and $C_e$. A further complication in the analysis of these data is that the measurement of $\delta$ was frequently performed at room temperature rather than at the aging temperature. In addition, differences in experimental technique could have contributed to the discrepancies in the literature.

Observations of $\gamma'$ particle coarsening during creep have led to the trend in alloy design to reduce this coarsening and thus to improve creep life. Again, the approach of minimizing $\delta$ is often quoted [14-16, 28]. Although some studies have produced data in support of this approach [29, 30], other studies have indicated that the reverse is true [23, 25, 26, 31]. The correlation between higher values of mismatch and improved creep lives could be the result of both coherency strain hardening and the simultaneous influences on diffusion, coarsening and APB energy caused by the compositional variations. It is also possible that an optimal misfit, which is dependent on composition and testing conditions, would exist as a compromise between the effects of hardening and coarsening.

Lattice mismatch can also influence the directional coarsening of $\gamma'$ which is frequently observed in superalloys that have been given creep exposures. Under an applied stress at elevated temperatures, $\gamma'$ particles can directionally coarsen into rod or plate morphologies. The derivations of Pineau [32], based on isotropic elasticity, are generally accepted as the most satisfactory treatment for the prediction of particle shape under a given set of conditions. This theory considers that lattice mismatch, elastic modulus mismatch and applied stress provide the driving force for directional coarsening. One prediction of Pineau's treatment is that the orientation of $\gamma'$ plates or rods would change with the sign of $\delta$. However, several alloys which have been reported to possess positive values of $\delta$ [33-36], and others with negative values [37-39], all exhibited $\gamma'$ plates normal to the applied stress axis. It appears that some of these discrepancies could be resolved by measurements of lattice mismatch at the testing temperature. In addition, measurements of elastic modulus mismatch appear to be necessary [40]. The rate of directional coarsening can also be expected to be influenced by the magnitude of $\delta$. In a model nickel-base alloy, very rapid stress coarsening kinetics were attributed to a large negative misfit $\delta$ of about $-0.008$ at room temperature [37]. However, another alloy exhibited similar rapid directional coarsening, and its room temperature misfit was less than half the magnitude of that of the model alloy [38].

It can be seen that the role of mismatch in unstressed $\gamma'$ coarsening, stressed $\gamma'$ coarsening and creep mechanisms of superalloys is not very well understood. Again, one factor to consider is the experimental difficulties in measuring $\delta$ values. Secondly, the values of $\delta$ are frequently measured at room temperature rather than at the test temperature. Thus, correlations of elevated temperature properties with $\delta$ values are complicated and are dependent on extrapolations of scarce thermal expansion data. Grose and Ansell [3], who measured the lattice parameters of $\gamma'$
in extracted powders and γ in bulk superalloy specimens, appear to be the only workers to have measured elevated temperature lattice mismatch in superalloys. The present investigation was therefore directed toward the examination of the temperature dependence of the lattice parameters of the γ and γ' phases and the γ–γ' lattice mismatch for several nickel-base superalloys. In addition, the influence of elevated temperature lattice mismatch on the kinetics of directional γ' coarsening were examined. It is hoped that these results may provide information that will assist in improving the understanding of the role of lattice mismatch in the high temperature behavior of superalloys.

2. MATERIALS AND PROCEDURES

The compositions of the three nickel-base alloys investigated were determined by wet chemistry and are given in Table 1. The specimens were from the same heats used in previous investigations in which high temperature mechanical properties of Alloy 143 [39, 41] and NASAIR 100 and Alloy E [38, 42, 43] were studied. Alloy 143 is a model alloy which contains a high level of molybdenum. NASAIR 100 and Alloy E are derivatives of MAR-M 247; the main difference between these two alloys is the 5.1 at.% Co in Alloy E. Single crystals of the three alloys were produced by directional solidification. The specimens were solution treated above the γ' solvus and given a simulated coating heat treatment and a subsequent aging treatment, as described in Table 2.

X-ray diffraction using Cu Kα radiation was employed to measure the lattice mismatch between the γ and γ' phases. Single-crystal disks with faces parallel to (001) planes were prepared metallographically for the X-ray experiments. Diffractometer scans of the (004)γ,γ' fundamental reflections and of the (003)γ' superlattice reflection were obtained. The magnitude of lattice mismatch was determined from the difference in lattice parameters calculated from the (004)γ,γ' peaks. The sign of the misfit was confirmed by comparison of the (004)γ,γ' peaks with the (003)γ' superlattice peak. In most cases the magnitude of the lattice mismatch was large enough that the γ and γ' peaks were clearly resolved.

TABLE 1
Compositions of alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Amount (at.%) of the following elements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ni</td>
</tr>
<tr>
<td>143</td>
<td>75.7</td>
</tr>
<tr>
<td>NASAIR 100</td>
<td>70.4</td>
</tr>
<tr>
<td>E</td>
<td>67.4</td>
</tr>
<tr>
<td>14a</td>
<td>73.1</td>
</tr>
</tbody>
</table>

a From Grose and Ansell [3].

TABLE 2
Heat treatments

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Solution treatment</th>
<th>Simulated coating cycle</th>
<th>Subsequent aging treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>143</td>
<td>1277 °C for 4 h + 1288 °C for 2 h + 1299 °C for 2 h + 1313 °C for 100 h</td>
<td>1080 °C for 4 h + 870 °C for 16 h</td>
<td>--</td>
</tr>
<tr>
<td>NASAIR 100</td>
<td>1302 °C for 4 h</td>
<td>982 °C for 5 h + 870 °C for 20 h</td>
<td>1000 °C for 100 h</td>
</tr>
<tr>
<td>E</td>
<td>1302 °C for 4 h</td>
<td>982 °C for 5 h + 870 °C for 20 h</td>
<td>1000 °C at 36 MPa for 587 h</td>
</tr>
</tbody>
</table>
In cases where the \( \gamma \) and \( \gamma' \) peaks overlapped, the X-ray peaks were resolved optically with the aid of a Dupont model 310 curve resolver.

A high temperature attachment was used to record the \((004)_{\gamma', \gamma}\) peaks from 18 to 1000 °C in 50 °C increments. The temperature was measured with a Pt–(Pt–13Rh) thermocouple spot welded directly to the specimen. Although the samples were heated in a nitrogen atmosphere, small leaks in the chamber caused oxidation of the samples. Thus, measurements were limited to temperatures up to 1000 °C and could be obtained during heating only. On occasion, the specimen holder became slightly misaligned during heating. This resulted in a loss of total diffracted intensity and resolution of the \( \gamma \) and \( \gamma' \) peaks. Re-alignment was performed at temperature on these occasions. The maintenance of crystal alignment was considered to be the major factor controlling the precision of the lattice parameter measurements.

In addition, tensile creep specimens were machined by precision grinding from heat-treated single-crystal bars. Constant-load creep tests were performed at 982 °C and 234 MPa on specimens having their longitudinal axes oriented within 10° of [001]. The tests were interrupted after 5 h, and the specimens were cooled to ambient temperature under load.

3. RESULTS

3.1. Lattice parameter measurements

The specimens were given various aging treatments prior to the X-ray measurements so that the \( \gamma' \) particles would be semicoherent with the \( \gamma \) matrix. For Alloy 143 the simulated coating cycle was sufficient for the production of semicoherent \( \gamma' \) and, for NASAIR 100, an additional aging treatment of 100 h at 1000 °C was used to produce the loss of coherency. However, Alloy E possessed a significantly smaller lattice mismatch and did not readily lose coherency. Aging treatments of up to 975 h did not produce a semicoherent \( \gamma' \) structure in this latter alloy.

However, it was previously shown [39, 41, 42] that the \( \gamma' \) particles can lose coherency if subjected to a stress-annealing treatment. The stress anneal results in directional coarsening such that a lamellar \( \gamma-\gamma' \) structure is formed. This lamellar structure can be developed with a creep strain of less than 1%. Therefore, creep rupture specimens of Alloy E were tested at 1000 °C and 148 MPa and interrupted after 60 h, which was sufficient to produce semicoherent \( \gamma' \). However, the small gauge diameter of the creep specimen did not permit easy attainment of accurate lattice parameter measurements. The shoulders of a rupture specimen, which was tested at 1000 °C and 148 MPa and failed at 587 h, provided both a suitable specimen size and a \( \gamma' \) structure similar to that in the interrupted creep specimen. The applied stress in the shoulder area of the specimen was approximately 36 MPa.

The differences in the constrained and the unconstrained lattice mismatch can be seen in Table 3. For all three alloys the magnitude of the lattice mismatch increased after strict coherency was lost. The lattice parameters of \( \gamma' \) which had been electrolytically extracted

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Coherent interface</th>
<th>Semicoherent interface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Extracted ( a_{\gamma'}(\AA) )</td>
<td>In situ ( a_{\gamma'}(\AA) )</td>
</tr>
<tr>
<td>143</td>
<td>-</td>
<td>3.5870</td>
</tr>
<tr>
<td>NASAIR 100</td>
<td>3.5839</td>
<td>3.5849</td>
</tr>
<tr>
<td>E</td>
<td>3.5835</td>
<td>3.5842</td>
</tr>
</tbody>
</table>

\(^a\) 95% confidence intervals based on six or more measurements.

\(^b\) Below detection limit.
are also listed in Table 3. These values should be representative of the unconstrained lattice parameters; yet they did not vary appreciably from the coherent in situ measurements.

Room temperature X-ray diffractometer scans of the (004), γ, γ' peaks of the alloys are presented in Fig. 1. Both Alloy 143 (Fig. 1(a)) and NASAIR 100 (Fig. 1(b)) had sufficiently large lattice mismatch values that the γ and γ' peaks could be clearly resolved. However, the lower magnitude of the lattice mismatch of Alloy E (Fig. 1(c)) resulted in overlap of the γ and γ' peaks such that the γ peak could barely be resolved.

Lattice parameter measurements are presented as a function of temperature in Fig. 2. All the alloys exhibited similar increases in the lattice parameter as the temperature increased. However, the γ phase in Alloy 143 exhibited some anomalous behavior between 650 and 800 °C, as shown in Fig. 2(a), and this will be discussed in more detail.

Fig. 1. Diffractometer scans of (004), γ, γ' peaks of the single-crystal alloys at room temperature: (a) Alloy 143; (b) NASAIR 100; (c) Alloy E.

Fig. 2. Temperature dependence of the γ and γ' lattice parameters: (a) Alloy 143; (b) NASAIR 100; (c) Alloy E.
The lattice parameter data were fitted to a second-order polynomial with the temperature data in centered form [44]:

\[ a = B_0 + B_1 (T - \bar{T}) + B_2 (T - \bar{T})^2 \]  

(3)

where \( a \) is the lattice parameter, \( T \) (°C) is the temperature, \( B_0, B_1 \) and \( B_2 \) are constants and \( \bar{T} \) is the mean of the temperature values in the range studied. The inclusion of a third-order term was also examined but, in all but one case, the coefficients for the third-order term were statistically insignificant. The values of the coefficients for the present alloys and for Alloy 14 studied by Grose and Ansell [3] are presented in Table 4. For comparison purposes, the mean linear thermal expansion coefficients for the various alloys are also presented in the table. The full lines drawn through the data points in Fig. 2 represent the curve fit with eqn. (3).

The \( \gamma-\gamma' \) lattice mismatch for the alloys are plotted as a function of temperature in Figs. 3(a)–3(c). The data points in Fig. 3 represent the \( \delta \) values calculated from the actual lattice parameter measurements, whereas the full lines represent the \( \delta \) values calculated from the fitted lattice parameters using eqn. (3). The polynomial expressions for the \( \gamma \) and \( \gamma' \) lattice parameters can also be used to describe the temperature dependence of \( \delta \):

\[ \delta = C_0 + C_1 (T - \bar{T}) + C_2 (T - \bar{T})^2 \]  

(4)

(Table 5). The polynomial expressions of eqns. (3) and (4) were found to be sufficiently accurate for a general description of the lattice parameters and lattice mismatch. However, the polynomials did predict a slight peak in the \( \delta \) values near 300 °C for all the alloys. This peak was considered to be unreasonable and was disregarded when drawing the curves between 18 and 400 °C in Fig. 3. Equation (4) is still considered to be a reasonable description of lattice mismatch at temperatures above about 400 °C. Although the three alloys of the present study possessed different magnitudes of \( \delta \), the temperature dependences were quite similar; the mismatch remained relatively constant up to about 600 °C and then gradually increased in magnitude (became more negative) as the temperature was increased further. As the temperature was increased from 18 °C to 1000 °C, the \( \delta \) values of Alloy 143 changed from \(-0.78\%\) to \(-0.82\%\), those of NASAIR 100 changed from \(-0.37\%\) to \(-0.45\%\) and those of Alloy E from \(-0.18\%\) to \(-0.22\%\).

Figure 3(d) is a summary plot of the temperature dependence of the \( \delta \) values for the alloys in the present study and for Alloy 14 from Grose and Ansell [3]. The similarities between the three alloys of the present study are again evident. However, it should also be noted that the data of Alloy 14 exhibited a significantly stronger temperature dependence than did the alloys of the present study. As noted previously, Alloy 143 exhibited anomalous behavior in the form of a peak between 650 and 800 °C in the \( \delta \) versus tem-

### Table 4

<table>
<thead>
<tr>
<th>Alloy</th>
<th>( \bar{T} ) (°C)</th>
<th>Coefficients from eqn. (3)</th>
<th>Mean linear coefficient( a \times 10^6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \delta )</td>
<td>( B_0 )</td>
<td>( B_1 \times 10^5 )</td>
</tr>
<tr>
<td>143</td>
<td>( \gamma' )</td>
<td>477.3</td>
<td>3.60568 ± 0.00049(^b)</td>
</tr>
<tr>
<td>143</td>
<td>( \gamma )</td>
<td>477.3</td>
<td>3.63360 ± 0.00047</td>
</tr>
<tr>
<td>NASAIR 100</td>
<td>( \gamma' )</td>
<td>500.9</td>
<td>3.60529 ± 0.00040</td>
</tr>
<tr>
<td>NASAIR 100</td>
<td>( \gamma )</td>
<td>500.9</td>
<td>3.61934 ± 0.00040</td>
</tr>
<tr>
<td>E</td>
<td>( \gamma' )</td>
<td>500.9</td>
<td>3.60482 ± 0.00017</td>
</tr>
<tr>
<td>E</td>
<td>( \gamma )</td>
<td>500.9</td>
<td>3.61100 ± 0.00015</td>
</tr>
<tr>
<td>14(c)</td>
<td>( \gamma' )</td>
<td>454.2</td>
<td>3.59249 ± 0.00083</td>
</tr>
<tr>
<td>14(c)</td>
<td>( \gamma )</td>
<td>454.2</td>
<td>3.59727 ± 0.00064</td>
</tr>
</tbody>
</table>

\(^a\) Between 18 and 800 °C.  
\(^b\) 95% confidence intervals.  
\(^c\) From Grose and Ansell [3].
Table 5
Temperature dependence of lattice mismatch: coefficients from eqn. (4)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$C_0 \times 10^3$</th>
<th>$C_1 \times 10^7$</th>
<th>$C_2 \times 10^9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>143</td>
<td>-7.714</td>
<td>-3.886</td>
<td>-1.043</td>
</tr>
<tr>
<td>NASAIR 100</td>
<td>-3.891</td>
<td>-4.649</td>
<td>-1.662</td>
</tr>
<tr>
<td>E</td>
<td>-1.711</td>
<td>-5.222</td>
<td>-0.985</td>
</tr>
<tr>
<td>14$^a$</td>
<td>-1.330</td>
<td>-18.85</td>
<td>-2.003</td>
</tr>
</tbody>
</table>

$a$ From Grose and Ansell [3].

Fig. 4. Temperature dependence of the lattice mismatch for Alloy 143 showing anomalous behavior between 650 and 800 °C: ©, trial 1; ☐, trial 2; △, trial 3.

Temperature plot shown in Fig. 3(d). This peak was reproducible over three different runs on different samples, as illustrated in Fig. 4, although its position and height varied slightly between the three runs. This behavior was associated with an extra X-ray peak in the diffractometer scans in this temperature regime. Subsequent analysis identified the phase associated with this extra peak as Ni$_3$Mo, which has a body-centered tetragonal (b.c.t.) (D0$_{22}$) structure and lattice constants $a$ of about 3.59 Å and $c$ of about 7.33 Å. Evidence for the existence of this phase at room temperature was also seen in the electron diffraction patterns, although not in the (004)_{\gamma',\gamma} diffractometer scans. However, a very low intensity (011)$_{b.c.t.}$ peak was observed in a [012]-oriented sample at room temperature.

3.2. Directional coarsening behavior

The influence of lattice mismatch on the kinetics of directional $\gamma'$ coarsening was also
investigated. In order to provide the full driving force for directional coarsening, the alloys were tested with the initial structure consisting of fully coherent γ' particles. For NASAIR 100 and Alloy E, the standard heat treatment consisting of a solution treatment and simulated coating cycle was adequate for this purpose. However, the high lattice mismatch of Alloy 143 required a smaller γ' size to ensure complete absence of misfit dislocations; this was accomplished by oil quenching from the solution treatment temperature [41].

Longitudinal sections of samples tested at 982 °C and 234 MPa for 5 h are presented in Fig. 5. These microstructures showed that directional coarsening of γ' had developed to various degrees in the three alloys. Alloy 143, with the largest magnitude of δ, exhibited the quickest rate of directional coarsening and NASAIR 100, which possessed an intermediate value of δ, exhibited slower γ' coarsening. For Alloy E, with the lowest value of δ, the directional coarsening was almost negligible after this time period.

4. DISCUSSION

4.1. Lattice parameter measurements

The measurement of the lattice parameters was strongly affected by the nature of the γ-γ' interface. Significant increases in the magnitude of δ were achieved after the aging treatments were performed, because the γ' particles had become semicoherent. The presence of a hexagonal network of misfit dislocations at the γ-γ' interfaces relieves much of the elastic coherency strains. Thus the lattice parameter measurements obtained after the aging treatment would be closer to the unconstrained values. However, some constraints would still be present at lower temperatures as a result of differences between the thermal contraction of the two phases and the precipitation of fine γ' during cooling from the aging temperature.

It is possible that the shift in lattice parameters and lattice mismatch after aging

Fig. 5. Scanning electron micrographs of longitudinal sections of alloys creep tested at 982 °C and 234 MPa for 5 h: (a) Alloy 143; (b) NASAIR 100; (c) Alloy E. The stress axis is vertical in all the micrographs.
resulted at least partly because the \( \gamma \) and \( \gamma' \) phases approach their equilibrium concentrations. However, the ratio of the constrained to the unconstrained mismatch values in Table 3 was approximately \( \frac{2}{3} \), which is in agreement with theoretical predictions [1, 3]. Accordingly, the loss of strict coherency is considered to be the major cause for the change in the measured lattice mismatch. The significance of obtaining a semicoherent \( \gamma-\gamma' \) structure is particularly evident from the data of Alloy E. It was previously reported that the mismatch of Alloy E was below the resolution limit of the X-ray technique [43]. However, after loss of coherency was achieved in the present work, a \( \delta \) value of \(-0.18\%\) was obtained.

Since there is no generally accepted relation for the description of thermal expansion data, a simple polynomial model was chosen. Second-order polynomial expressions, such as that in eqn. (3), were found to be sufficiently accurate for a general description of the lattice parameter data and the determination of \( \delta \) values, especially between 400 and 1000 °C. The second-order polynomials provided significantly better descriptions than the simpler model of a mean linear thermal expansion coefficient.

The coefficients from eqn. (3) and the mean linear thermal expansion coefficients are in reasonable agreement with those of Grose and Ansell [3]. Because of the few alloys studied in this investigation, little can be said about the influence of composition on thermal expansion. Alloy 143 did have the lowest expansion coefficients for both the \( \gamma \) and the \( \gamma' \) phases, which is consistent with the higher refractory metal level in this alloy [3, 45]. Comparison of the coefficients of NASAIR 100 and Alloy E reveals that cobalt apparently increases the thermal expansion of \( \gamma \) and \( \gamma' \), although further work would be necessary to confirm this result. In all the alloys studied in this investigation, as well as those studied by Grose and Ansell, the expansion coefficients of the \( \gamma' \) phase were lower than those of the \( \gamma \) phase. This is consistent with the long-range-ordered structure of \( \gamma' \) [3, 46]. The difference in expansion coefficients thus contributes to the temperature dependence of \( \delta \), which tends toward increasingly negative values as the temperature is increased. In addition to the effects of long-range order, another possible contribution to the temperature dependence of \( \delta \) is the changing compositions of the two phases. As the temperature is increased, the \( \gamma' \) phase starts to dissolve in the \( \gamma \) matrix. As evidenced by \( \gamma' \) volume fraction measurements, this dissolution appears to become significant at temperatures near 1000 °C for NASAIR 100 [42].

As mentioned previously, the \( \delta \) values of the alloys studied by Grose and Ansell exhibited a stronger temperature dependence than that found in the present work. Again, it is difficult to compare the alloys of these two investigations, since the compositions are not closely related. Inspection of the various thermal expansion coefficients of the different alloys did not reveal any clear reasons for the observed differences. However, one possibility could involve the volume fraction of \( \gamma' \), which is equal to about 60% in the present alloys and to approximately 25% in the alloys of Grose and Ansell. The lower \( \gamma' \) volume fractions also correspond to a solvus temperature which is approximately 200 °C lower than those of the present alloys. Because of the lower solvus temperatures, the temperature range at which the \( \gamma' \) volume fraction and the compositions of the \( \gamma \) and \( \gamma' \) phases can significantly change could be shifted to lower temperatures. Thus, there is the possibility that the higher temperature dependence of \( \delta \) in the alloys of Grose and Ansell is at least partially attributed to the compositional variations that result in lower \( \gamma' \) volume fractions and solvus temperatures. In the light of these differences between the alloys investigated thus far, additional measurements on other alloys would be useful for the prediction of high temperature mismatch from low temperature measurements.

The anomalous behavior of Alloy 143 in the temperature range 650–800 °C appears to be related to the precipitation of Ni\(_3\)Mo. This phase has been reported to precipitate between 770 and 800 °C in this alloy system [47]. It appears that some Ni\(_3\)Mo precipitated during cooling from the aging treatment temperature and thus was present at room temperature. The Ni\(_3\)Mo phase could not be detected in the (004) diffractometer scans below 650 °C because of the proximity of the \( \gamma \) and \( \gamma' \) peaks with the very low intensity
Ni$_3$Mo peak. However, differences in thermal expansion, plus the precipitation of additional Ni$_3$Mo, permitted the detection of this phase in the (004) diffractometer scans between 650 and 800 °C. The formation of the additional Ni$_3$Mo depleted the γ matrix of molybdenum, which caused a decrease in the γ lattice parameter, thus resulting in a decrease in the magnitude of δ in this temperature range. As the temperature was increased further, the Ni$_3$Mo phase started to dissolve, and the δ measurements returned to more typical values. The slight variations in the position and magnitude of the peak in δ values between the various trials, shown in Fig. 4, can be explained by the differences in quench rate from the aging temperature, as well as by the differences in the time spent at temperature during the high temperature diffraction experiments.

4.2. Directional coarsening behavior

The present results clearly show that higher magnitudes of lattice mismatch result in faster rates of directional coarsening. This result is consistent with the work of Pineau [32], who considered that lattice mismatch was one of the driving forces which influence directional coarsening. These results are also consistent with previous work on Alloy 143, whereby specimens with initially semicoherent γ' structures exhibited slower directional coarsening than did specimens with initially coherent γ' particles [39, 41]. In this case the driving force provided by the lattice mismatch was reduced by the presence of misfit dislocations.

However, the rate of directional coarsening may not have a major influence on the creep behavior of these alloys. Directional coarsening is still relatively rapid at elevated temperatures, even for Alloy E or CMSX-2 [35], which have low magnitudes of δ. For example, continuous finely spaced γ' lamellae are still developed during the first 50–100 h for these alloys, when tested at temperatures near 1000 °C and for applied stresses that produce creep rupture lives greater than about 500 h. Thus, the fully formed lamellae would still be present for over 80% of the creep life of the specimen.

On the basis of previous studies [41, 43], it appears that the major influence of lattice mismatch on the creep behavior of these alloys is not through the rate of directional coarsening. Rather, the influence of δ appears to be in the determination of the strength of the γ-γ' interface. Higher values of δ would result in a finer misfit dislocation spacing at the interface, thus providing a stronger barrier to dislocation flow.

Another prediction based on Pineau's analysis is that the orientation of the directional coarsening would depend on the sign of δ. However, several alloys [33–36] have been reported to have slightly positive values of δ at room temperature and yet still to form γ' plates normal to the applied stress. In agreement with the suggestions of other investigators [36, 40, 47], the temperature dependence of δ appears to explain these discrepancies. Values of δ which are slightly positive at room temperature could become negative at elevated temperatures and thus result in the observed γ' plate orientations.

5. CONCLUSIONS

(1) The lattice mismatch for the three alloys remained relatively constant up to approximately 600 °C and then gradually became more negative with further increases in temperature. This was the result of lower expansion coefficients for the γ' phase in comparison with those of the γ phase. This behavior is consistent with the long-range-ordered structure of γ' and the possible effects of the changing phase compositions due to γ' dissolution at the highest temperatures.

(2) Higher magnitudes of lattice mismatch resulted in increased rates of directional γ' coarsening during creep at 982 °C. This was associated with an increased driving force from the elastic coherency strains.

(3) X-ray measurements on a semicoherent γ-γ' structure appeared to provide a good approximation of the unconstrained γ and γ' lattice parameters. The elastic coherency strains in a coherent γ-γ' structure resulted in significantly smaller magnitudes of measured lattice mismatch.

(4) The anomalous decrease in the magnitude of the lattice mismatch exhibited by Alloy 143 between 650 and 800 °C was associated with the precipitation of Ni$_3$Mo in this temperature range.
REFERENCES

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