The Effect of Cr, Co, Al, Mo, and Ta on a Series of Cast Ni-Base Superalloys on the Stability of an Aluminide Coating During Cyclic Oxidation in Mach 0.3 Burner Rig

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SUMMARY

The influence of varying the content of Co, Cr, Mo, Ta, and Al in a series of cast Ni-base γ/γ' superalloys on the behavior of aluminide coatings was studied in burner rig cyclic oxidation tests at 1100 °C. The alloys had nominally fixed levels of Ti, W, Cb, Zr, C, and B. The alloy compositions were based on a full 2⁵-fractional statistical design supplemented by 10 star point alloys and a center point alloy. This full central composite design of 43 alloys plus two additional alloys with extreme Al levels allowed a complete second degree estimating equation to be derived from the 5-compositional variables. The weight change/time data for the coated samples fitted well to the parilinear oxidation model and enabled a modified oxidation attack parameter, $K_a'$ to be derived to rank the alloys and log $K_a'$ to be used as the dependent variable in the estimating equation to determine the oxidation resistance of the coating as a function of the underlying alloy content. The most protective aluminide coatings are associated with the highest possible base alloy contents of Cr and Al and at a 4 percent La level. The Mo and Co effects interact but at fixed levels of 0, 5 or 10 percent Co a 4 percent Mo level is optimum.

INTRODUCTION

The effect of compositional changes in Ni-base γ/γ' superalloys on the behavior of aluminide coatings has been subject of several investigations (refs. 1 to 9). Also a concise but complete review of this work was published recently by Tomaszewicz and Wallwork (ref. 10). There is agreement that the substrate composition has a major effect on the coating behavior. Many studies (refs. 2 to 4, 7 and 8) suggest that beneath the external B-NiAl layer an inner layer is formed by outward diffusion of nickel and alloying elements from the substrate layer. This inner diffusion zone consists of columnar grains of either B-NiAl or γ-Ni₃Al interdispersed by regions rich in the tungsten, molybdenum, chromium and columbium existing as intermetallic compounds and carbides of these refractory metals. However, the formation of carbides in the base alloy was found by Fleetwood (ref. 4) to be undesirable because they often penetrated the coating, offering an easy path for oxidation.

The exact mechanism of coating degradation remains a point of contention. Early work seemed to suggest that diffusion of aluminum into a substrate alloy was responsible for the degradation. This point of view is supported by the more recent work of Smialek and Lowell (ref. 8). The other point of view is (ref. 5) that in the case of aluminide coatings on nickel-base superalloys, the continuous spalling and reforming of the oxide scale are the main reason for their degradation. It has been established by several investigators that coating degradation is a function of substrate composition (refs. 1,3,4,6,9). It
has been suggested (ref. 6) that the refractory metal phases might act as a diffusion barrier reducing aluminum diffusion into the substrate and the outward diffusion of nickel or alloying elements into the coating, and thus decreasing coating degradation. Except for the work of Talboom and Petrusha (ref. 1) on the single and binary additions to pure nickel on the diffusional stability of NiAl coatings, the work in this area is rather limited.

The study described herein is a part of the Conservation of Strategic Aerospace Materials (COSAM) program. Its objective has been to investigate the effect of Cr, Co, Al, Mo, and Ta contents in a typical Ni-base superalloy on the stability at an aluminide coating during cyclic oxidation in a Mach 0.3 burner rig. The alloys had nominally fixed levels of Ti, W, Cb, Zr, C, and B. The alloy compositions were based on a full 25-fractional statistical design supplemented by 10 star point alloys and a center point alloy. This full central composite design of 43 alloys plus two additional alloys with extreme Al levels was used by Barrett (ref. 11) to derive a complete second degree equation that described the effect of compositional changes on the cyclic oxidation behavior of these alloys.

The aluminide coating was applied by the RT-21a process. Cyclic oxidation tests were performed in a Mach 0.3 burner rig for 150 and 300 1-hour cycles with a sample temperature of 1100 °C. Weight change of the specimens was determined by removing them periodically from the burner rig and weighing. After testing, the specimens were subjected to metallographic and x-ray diffraction analyses.

MATERIALS AND EXPERIMENTAL PROCEDURES

Preparation of the Specimens

The basic levels of the five compositional variables are schematically designated as 0, 1, 2, 3, and 4 where the 2 values are the center point of the design. Table I shows the actual weight percent (wt %) corresponding to the five levels. The basic composition of the prototype alloy was: Ni-balance, Ti-1.0 wt %, W-2.0 wt %, Cb-1.0 wt %, Zr-0.10 wt %, B-0.01 wt %, C-0.12 wt %. The five levels chosen for the five alloying elements represent their range in commercial alloys. Thus, the center point alloy designated as (22222) would be the basic composition with the five varied levels Al-4.75 wt %, Cr-12.0 wt %, Co-10.0 wt %, Mo-2.0 wt %, and Ta-4 wt %. Similarly the alloy coded (00113) has the basic composition with Al-3.25 wt %, Cr-6.0 wt %, Co-5.0 wt %, Mo-1.0 wt %, and Ta-6.0 wt %.

The master heats of the alloys were prepared by vacuum induction melting by Howmet Turbine Components Corporation of Dover, New Jersey as 3 in. diameter ingots, each weighing approximately 40 lb.

The master heat ingots were then used to make individual investment frame castings (vacuum induction melted) by Duradyne Technologies, Inc. of Mentor, Ohio. Included on each frame were 12 round coating bars: 12 tensile/stress
rupture bars, 12 round burner rig bars, and 16 rectangular oxidation leaves. The burner rig bars were 3/8 in. diameter and 4 in. long. Table II lists the actual compositions of each alloy. In all cases the actual compositions were within 10 percent of the target compositions. The aluminide coating was applied to all specimens by the RT-21 process.

**BURNER RIG TESTING**

The Mach 0.3 burner rig used in these tests has been described in reference 12. Eight specimens were placed in a carousel holder which was rotated at 400 rpm in front of the burner nozzle. The centers of the specimens were evenly spaced on a 4.2 cm (approx. 1-3/8 in.) diameter circle. In this cyclic oxidation test, the specimens were heated for 1 hr and then cooled with a stream of compressed air for 3 min. The burner rig was fired at a fuel-to-air ratio of about 0.05 using jet A fuel and combustion air preheated to 260 °C (500 °F). Test temperature was 1100±20 °C (2012 °F) as determined with a calibrated (for emissivity and window absorption) disappearing filament optical pyrometer when focusing on the center of the hot zone of the specimens facing the nozzle of the burner.

The back side (facing away from the nozzle) of the specimens was hotter than the front face by 20 °C. Only the central part of the specimens was exposed to the flame. All alloys were tested for 150 1-hr cycles. Fifteen of the alloys were also tested for 300 1-hr cycles. The weight of each specimen was monitored periodically by removing it from the holder and weighing. Orientation of each specimen with regard to the nozzle was maintained. Thermo-gravimetric data were recorded as total weight change (ΔW) versus the number of cycles. Weight change per unit area (ΔW/A) was not used because the longitudinal distribution of temperature on the specimens was not uniform. The most heavily oxidized region was the central part of the specimens with an area of about 4 cm². Two specimens of each alloy were tested at the same time and the average value of ΔW was used in the analysis. After testing, XRD patterns were taken from the cylindrical surface of the specimens (one specimen per alloy) in order to identify the phases present on the oxidized surface. The same specimens were plasma sprayed with copper for edge preservation and cross sectioned through the center of the hot zone for metallographic examination to ascertain the oxidation damage and accompanying microstructural changes.

**RESULTS AND ANALYSIS**

**Metallography**

Metallographic examination of the specimens in the as-coated condition revealed that the coating consisted of two layers (fig. 1). The outer layer, about 40 µm thick, is a large grained NiAl (γ) with Cr, Mo, and Co in solid solution. The inner layer contained MC, M₂₃C₆ or M₆C carbides and sigma phase in a columnar matrix of NiAl + Ni₃Al (ref. 3). The substrate was composed of Ni solid solution (γ) with very fine precipitates of Ni₃Al (γ'). During cyclic oxidation all the alloys showed an initial weight gain (tables III and IV) but after about 40 cycles some alloys began to lose weight faster than others. Figure 2(a) illustrates typical changes that took place during cyclic oxidation testing of the alloys. Here, in the case of Alloy 16, after 150 cycles, the
The columnar zone has disappeared and its original location is marked by the presence of carbide and sigma phase grains. NiAl formed large grains separated from the substrate by a layer of Ni₃Al. The Ni₃Al precipitates in the substrate became coarser and the 40 µm thick zone of the substrate near the original substrate-coating interface was depleted of Ni₃Al. The same alloy (fig. 2(b)) when subjected to 300 1-hr oxidation cycles underwent similar but more extensive changes. The amount of NiAl was significantly reduced and Ni₃Al precipitates in the substrate grew in size. XRD analyses of the oxide scales (in situ) revealed the presence of Al₂O₃, NiAl(B), Ni₃Al(γ'), Ni₃ss(γ) and on several occasions an aluminate spinel structure was detected. The Ni₃ss was formed on the surface of the coatings as result of aluminum loss from Ni₃Al, which, in turn was also the product of aluminum loss from NiAl. No simple relationships can be drawn regarding the stability of the aluminide coating as a function of alloy composition based on the examination of thermogravimetric data, metallographic and XRD analyses and therefore it is necessary to make use of a statistical approach.

REGRESSION ANALYSIS

The oxidized coated bars were separated into two groups for purposes of analysis. In the first group the samples were tested for 150 hr and in the second for 300 hr. The weight change time data for the 150 hr run for each alloy is listed in table IV. These values are the average of two samples for each alloy.

Initially, for the 150 hr data set the entire test interval of weight change/time data was fitted for each alloy to a paralinear model equation (11)

\[ \Delta w = k_1^{1/2} t^{1/2} - k_2 t + \sigma \]  \hspace{1cm} (1)

Where \( k_1 \) is the parabolic scaling constant, \( k_2 \) is a linear spalling constant and \( \sigma \) is the standard deviation of the \( \Delta w \) estimate. The rejection level was set at 0.90 (i.e., if either coefficient is not significant at this level it is dropped and the regression equation is recomputed).

Note here that this is not a specific weight change equation since the weight was not divided by a surface area. This lead to a modified attack parameter defined as

\[ K'_a = (k_1^{1/2} + 10 \cdot k_2) \]  \hspace{1cm} (2)

These equations have been discussed previously in references 12 and 14 to 16. The derived coefficients, \( k_1^{1/2} \) and \( k_2 \), the coefficient of determination, \( R^2 \) and \( \sigma \) values for equation (1) are listed in table V for each alloy. The \( K'_a \) estimates from equation (2) are also listed.

The data fitted for each alloy represents the average of two samples (designated a and b) run together as replicates on the eight-sample carousel. In general the weight changes tended to follow in tandem i.e. the individual sample curves had similar shapes, with time with one sample either lagging or leading. These average curves tended to be classically paralinear in nature.
(i.e., they start out parabolic in nature, reach a gradual maximum and drop at nearly a linear rate). This was true for all the alloys tested except for alloy G-42. Note that its $k_2$ coefficient was such as to make the weight change curve more positive. When in the $K_a'$ calculation the absolute value of $k_2$ is used it makes no difference in this calculation even though the weight change curve is quite different (i.e., not paralinear).

In most cases the fit was excellent with $R^2$ values well over 90 percent. In six cases the fit was fair to good with values between 80 to 90 percent. However, two alloys, G-41 and G-31, had fits that were relatively poor with $R^2$ values of 38.8 and 49.5 percent respectively. Figures 3 and 4 show the individual sample weight change values for G-41 and G-31 along with the paralinear curve fit vector line along with the ±1-σ error lines for the average of the two samples as given in table III. Compared with these are figures 5 and 6 for individual samples G-6 and G-24 which represent fits in the mid 80 percent $R^2$ value range and those with fits of >90 percent, respectively. Figure 7 shows the samples G-42A and G-42B along with the derived average vector line. Here as discussed above the $k_2$ component makes the curve more positive.

The poor fit in figure 3 is due primarily to the divergence of the individual sample curves. In this case it is difficult to decide which sample is truly representative of the alloy. Figure 4 on the other hand shows the samples behaving similarly but with a high degree of scatter. Figures 5 and 6 are more typical of the general body of data with the samples moving together and the scatter decreasing.

The $K_a'$ values range from a minimum value of 0.1763 for alloy G-41 to a maximum value of 10.706 for alloy G-1. This represents virtually no attack at the lowest $K_a'$ value to catastrophic oxidation for the G-1 alloy. For reasons above, however, the low $K_a'$ value for G-41 is questionable due to the individual sample divergence.

Where possible, thickness change measurements were made on the test samples at the completion of the 150 hr test. These values are also listed in table V. They represent the total diameter change in microns. In earlier studies the attack parameter has correlated well with thickness change measurements. This nearly linear relationship is shown in figure 8. Because in many ways a $K_a'$ type parameter is a better measurement of corrosion attack than thickness change (refs. 13 and 14), the thickness change measurement is used more as a confirmation of the $K_a'$ type analytical approach.

Derived $K_a'$ values were fitted as a function of alloy chemistry according to the following second degree multiple linear regression estimating equation using the log $K_a$ transformation (ref. 15) where the elemental symbols stand for weight percent of each alloy constituent:
\[ \log K_a' = A_0 + b_1 Al + b_2 Cr + b_3 Co + b_4 Mo + b_5 Ta \\
+ b_6 Al^2 + b_7 Cr^2 + b_8 Co^2 + b_9 Mo^2 + b_{10} Ta^2 \\
+ b_{11} Al \cdot Cr + b_{12} Al \cdot Co + b_{13} Al \cdot Mo + b_{14} Al \cdot Ta \\
+ b_{15} Cr \cdot Co + b_{16} Cr \cdot Mo + b_{17} Cr \cdot Ta \\
+ b_{18} Co \cdot Mo + b_{19} Co \cdot Ta + b_{20} Mo \cdot Ta \pm \sigma \] (3)

A version of equation (3) was also used which included linear terms for the slight degree of variability for supposedly fixed elements Ti, Nb, W, Zr, and C but these terms were, as expected, not significant.

Equation (3), was analyzed by means of the statistical software package MINITAB, release 81.1 on an IBM 370 main frame computer. In addition all the compositional variables were first "centered" by subtracting the mean of the weight percent of each compositional variable from each individual compositional value for each sample. This tends to minimize the correlation between linear and higher order terms sometimes leading to bias in estimating the coefficients (17).

The forward selection method was used with a rejection F-value of 2.88 or a probability 90 percent. This gave the following regression equation

\[ \log K_a = 0.27160 - 2.0005W - 0.04169Cr - 0.02112OCo - 0.006981a^2 + 0.2709 \\
\] (4)

with an \( R^2 \) of 38.8 percent. However, alloy G-41 gave a very high standardized residual of -4.25 \( \sigma \) units indicating a probable outlier. Because of the problems with this sample discussed above its \( K_a \) was discarded and the entire regression equation recomputed. This gave the following estimating equation:

\[ \log K_a' = 0.17654 - 0.026523Co - 0.04314Cr + 0.03873Ta^2 - 0.08464Al \\
- 0.07264Mo - 0.04884Al^2 + 0.01062Mo \cdot Co \pm 0.1647 \] (5)

The \( R^2 \) increased to 74.0 percent. For this data set of 43, only three values were flagged as possible outliers but they are close to being within an acceptable \( \pm 2 \sigma \). Figure 9 shows a plot of the predicted versus observed \( K_a' \) values in terms of \( \log \) values. Figure 10 shows the standardized residuals versus the \( \log K_a' \) estimated values. The randomized nature of the data are another indication of the validity of equation (5). Figure 11 plots the converted antilogs of the values estimated by equation (5) versus the observed \( K_a' \) values listed in table VI. The diagonal line shows the perfect fit line along with the computed average deviation values.

Based on the derived \( K_a' \) estimates for the standard 43 alloy design the minimum predicted value is for alloy G-37. However, special alloy G-45 with an Al level higher than the designed alloys has the lowest overall predicted oxidation attack.

It is possible to use the derived regression equation and predict the lowest attack rate over the range of alloy compositions. This was done for
three typical Cr levels which should be as high as possible for maximum protection as indicated by the regression coefficients. The results are shown in table VII for three typical Co levels of 0, 5, and 10 percent and for Cr levels of 8, 12, and 16 percent. A detailed analysis of equation (5) at these 9 combinations of Cr and Co levels shows the Al level should be as high as possible here 6.25 percent. The Ta level is optimum due to the Ta² term at its mean value near 4 wt %. The ideal Mo values are partly dependent on the Co composition. At Co levels of 0, 5, and 10 wt % Co, a Mo level of 4 wt % gives the minimum $K_a$ values.

An additional series of runs were made on selected samples for a total of 300 hr. This data is listed in table IV with the values again listed for the average of two samples tested during the same run. In general this longer time data would be expected to fall within the error bars of the vector extended from 150 to 300 hr unless breakaway had occurred (16). Breakaway is a sharp downward break in the $\Delta W$/time curve associated with a less protective oxide becoming rate controlling. If breakaway takes place, the weight change values should drop well below the error bars of the predicted curve. Of the twenty-eight-300 hr runs, ten fell below the 1σ band at 300 hr, 15 were above, and 3 were within. Of the 10 that fell below the error band, the question is whether the low estimates are due to scatter, breakaway or a combination of both. If it is breakaway then the original $K_a$ value is probably too low. X-ray diffraction results of the two sets of samples show no difference with time, NiO might have shown up in the spall, however. Figure 11 is typical of breakaway in a paralinear oxidation process when spalling becomes excessive.

In summary the above results suggest that for this series of Ni-base $\gamma/\gamma'$ superalloys that the best cyclic oxidation burner rig resistance conferred by an aluminide coating is associated with the highest levels of Cr and Al. Ta is optimum at 4 wt %. The Mo content is related to the Co level. At typical Co compositions of 0 to 10 percent Co a 4 wt % Mo level is optimal. It was suggested (ref. 6) that certain elements including Ta, Cr, and Mo tend to inhibit the diffusion of Ni into the NiAl or more likely the back diffusion of Al from the NiAl into the alloy. This enables the NiAl coating to confer a high degree of cyclic oxidation resistance with the low scaling rates associated with $Al_2O_3$ formation along with low oxide spalling rates.

CONCLUDING REMARKS

B-NiAl coatings on a series of Ni-base $\gamma/\gamma'$ superalloys with 45 systematic variations in the substrate alloy of Cr, Co, Al, Mo, and Ta were tested in cyclic oxidation at 1100 °C in a Mach 0.3 burner rig. In tests of 150 to 300 hr the best of the alloys exhibited the same type of paralinear oxidation behavior as plain B-NiAl with both low scaling and spalling rates associated with $Al_2O_3$ formation. An oxidation attack parameter derived from the sample weight change/time data was used to determine the effect of the 5 alloy elements by regression analysis. The results indicate the Cr and Al should be as high as possible. The Ta level is optimum at a midrange of 4 percent. The Co and Mo interact but if typical Co levels of 0 to 10 percent are fixed the highest Mo level tested of 4 percent is the most beneficial.
REFERENCES


TABLE I. - ALLOY CODE LEVELS CONVERTED TO TARGET COMPOSITIONS FOR PROTOTYPE ALLOY

[Ni-balance, Ti-1.0 wt %, W-2.0 wt %, Cb-1.0 wt %, Zr-0.10 wt %, B-0.01 wt %, C-0.12 wt %. (G-1 to G-43)].

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TABLE II. - INGOT CHEMISTRY FOR PROTOTYPE Ni-BASE TEST ALLOYS WITH VARYING Al, Cr, Co, Mo and Ta LEVELS

and Ni LEVELS

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Fixed elements: Ti range 0.92 to 1.09 wt %
W range 1.88 to 2.16 wt %
Cb range 0.90 to 1.06 wt %
Zr range 0.05 to 0.11 wt %
C range 0.08 to 0.12 wt %
B all 0.01 wt %

Lost in remelting for test samples.
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TABLE III. - THERMOGRAVIMETRIC DATA FOR ALUMINIZED COATED NI-BASE γ/γ′ ALLOYS TESTED AT 1100 °C IN A MACH 0.3 BURNER RIG FOR 150 ONE-HOUR CYCLES

[Average of twin samples tested in same run.]

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TABLE IV. - THERMOGRAVIMETRIC DATA FOR ALUMINIZED COATED Ni-BASE γ/γ' ALLOYS TESTED AT 1100 °C IN A MACH 0.3 BURNER RIG FOR 300 ONE-HOUR CYCLES

[Average of twin samples tested in same run.]

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<th>ΔW, mgs (Number of cycles)</th>
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*Extrapolate 150 hr vector to 300 hr.*

A $\Delta W$ is above error band.
B $\Delta W$ is below error band.
E $\Delta W$ is within error band.
- Not tested.
TABLE VI. - OBSERVED AND DERIVED $K_a$, $K_a'$ VALUES FOR ALUMINIDE COATED SERIES OF Ni-BASE $\gamma/\gamma'$ SUPERALLOYS TESTED IN A MACH 0.3 BURNER RIG AT 1100 °C FOR 150 HR.

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<td>3.0425</td>
<td>2.4522</td>
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<td>1.3403</td>
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<td>-----</td>
</tr>
<tr>
<td>37</td>
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<td>.7929</td>
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<td>3.0366</td>
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<td>39</td>
<td>2 2 4 2 2 2</td>
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<td>.8109</td>
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TABLE VI. - Concluded

<table>
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<th>Sample</th>
<th>Alloy Factor Levels</th>
<th>Observed Ka</th>
<th>Estimated(^a) Ka</th>
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<tr>
<td></td>
<td>Al</td>
<td>Cr</td>
<td>Co</td>
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<td>2</td>
<td>2</td>
</tr>
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<td>2</td>
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<tr>
<td>45</td>
<td>5</td>
<td>2</td>
<td>2</td>
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\(^a\)Derived from equation (5) with \( \log K_a \) as the dependent variable and converted from \( \log K_a \) estimates.

\(^b\)Outlier-discarded.
TABLE VII. - OPTIMUM LEVELS OF Al, Mo AND Ta FOR MINIMUM $K_a$ ESTIMATES AT SELECTED LEVELS OF Cr AND Co COMPUTED FROM THE REGRESSION EQUATION

<table>
<thead>
<tr>
<th>Cr</th>
<th>Co</th>
<th>Al</th>
<th>Mo</th>
<th>Ta</th>
<th>$\log K_a$</th>
<th>$K_a$-est.</th>
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<td>8</td>
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<td></td>
<td></td>
<td></td>
<td>-0.3674</td>
<td>0.4291</td>
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</tbody>
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FIGURE 1. - TYPICAL MICROSTRUCTURE OF ALLOYS COATED WITH ALUMINIDE BY RT-21 PROCESS.
FIGURE 2. - TYPICAL MICROSTRUCTURE OF ALUMINIDE COATED ALLOY 16 AFTER 150 AND 300 1-HOUR OXIDATION CYCLES AT 1100 °C IN A MACH 0.3 BURNER RIG.
FIGURE 3. - INDIVIDUAL REPLICATE COATED TEST BAR DATA FOR ALLOY 6-41 AND REGRESSION CURVE FIT OF THE AVERAGE WEIGHT CHANGE DATA WITH TIME. UPPER AND LOWER CURVES INDICATE ±1 σ LIMITS. \( R^2 = 38.8\% \).

FIGURE 4. - INDIVIDUAL REPLICATE COATED TEST BAR DATA FOR ALLOY 6-31 AND REGRESSION CURVE FIT OF THE AVERAGE WEIGHT CHANGE DATA WITH TIME. UPPER AND LOWER CURVES INDICATE ±1 σ LIMITS. \( R^2 = 49.5\% \).
Figure 5: Individual replicate coated test bar data for Alloy G-6 and regression curve fit of the average weight change data with time. Upper and lower curves indicate $\pm 0$ limits. $R^2 = 82.6\%$.

Figure 6: Individual replicate coated test bar data for Alloy G-24 and regression curve fit of the average weight change data with time. Upper and lower curves indicate $\pm 0$ limits. $R^2 = 99\%$. 
FIGURE 7. - INDIVIDUAL REPLICATE COATED TEST BAR DATA FOR ALLOY G-42 AND REGRESSION CURVE FIT OF THE AVERAGE WEIGHT CHANGE DATA WITH TIME. UPPER AND LOWER CURVES INDICATE ±1 σ LIMITS. $R^2 = 99.8\%$.

FIGURE 8. - RELATIONSHIP OF KA' VALUES DERIVED FROM WEIGHT CHANGE KINETIC DATA FOR 150 HOUR TESTS AND MEASURED THICKNESS CHANGE. REGRESSION FIT: 

\[
\log(KA') = -2.2650 + 1.1728 \log(\Delta T) + 0.2644.
\]

$R^2 = 38.4\%$. 
FIGURE 9. - DERIVED $K'A'$ VALUES FROM REGRESSION FIT OF EQUATION (3) VERSUS OBSERVED $K'A'$ VALUES. DIAGONAL SOLID LINE DEFINES PERFECT FIT. UPPER AND LOWER DASHED LINES REPRESENT $\pm$1-AVERAGE DEVIATION.

FIGURE 10. - RESIDUALS PLOTTED AGAINST FITTED VALUES OF $K'A'$ FOR REGRESSION ANALYSIS FOR EQUATION (3).
Figure 11. - Comparison 150 hour test data for alloy 6-10 and its regression fit extrapolation to 300 hours with its ±1σ deviation curves compared with actual 300 hour data for the same alloy showing apparent breakaway.
The influence of varying the content of Co, Cr, Mo, Ta, and Al in a series of cast Ni-base superalloys on the behavior of aluminide coatings was studied in burner rig cyclic oxidation tests at 1100 °C. The alloys had nominally fixed levels of Ti, W, Cb, Zr, C, and B. The alloy compositions were based on a full 25-fractional statistical design supplemented by 10 star point alloys and a center point alloy. This full central composite design of 43 alloys plus two additional alloys with extreme Al levels allowed a complete second degree estimating equation to be derived from the 5-compositional variables. The weight change/time data for the coated samples fitted well to the paralinear oxidation model and enabled a modified oxidation attack parameter, $K_A$, to be derived to rank the alloys and $\log K_A$ to be used as the dependent variable in the estimating equation to determine the oxidation resistance of the coating as a function of the underlying alloy content. The most protective aluminide coatings are associated with the highest possible base alloy contents of Cr and Al and at a 4 percent Ta level. The Mo and Co effects interact but at fixed levels of 0, 5 or 10 percent Co a 4 percent Mo level is optimum.