Life and Temperature prediction for TBC MCrAlY on the IN-939 system

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Background:

Alloy IN-939 with MCrAlY was selected for development lifetime and service temperature prediction models. The basis for this modeling method is measuring β-phase depletion in the MCrAlY coating on both the outer (oxide side) and inner (alloy side) depletion of the MCrAlY coating.

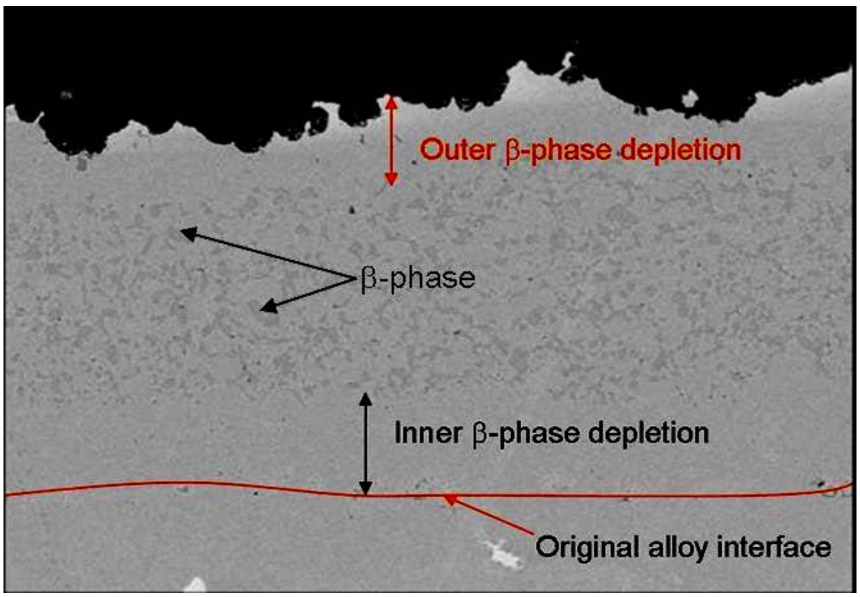

Figure 1 - β-phase Depletion Zones formed in alloy systems

Outer β-phase depletion:

The outer β-phase depletion (OBD) is controlled by the formation of aluminum oxide, Al_2O_3, by a parabolic growth law.

$$X_O = k_O * \sqrt{t} \qquad (1)$$

Where X_O is outer β-phase depletion distance below the oxide layer, k_O is the β-phase depletion rate constant and t is exposure time. The rate constant k_O follows an Arrhenius type relationship, **equation 2**.

$$k_O = A_O * \exp\left(-\frac{Q_O}{RT}\right) \quad (2)$$

$$\ln(k_O) = \ln(A_O) - \frac{Q}{R}\frac{1}{T} \qquad (3)$$

$$X_O = A_O * \exp\left(-\frac{Q_O}{RT}\right) * \sqrt{t} \qquad (4)$$

Where T is exposure temperature, R is the ideal gas constant, A_O is a pre-exponential constant and Q_O is the activation energy for OBD. Both A_O and Q_O are determined from a plot of the natural log of **equation 2** by taking $\ln(k_O)$ versus 1/T, **equation 3**. The slope of this plot is $-\frac{Q}{R}$ with a y-intercept of $\ln(A_O)$. Solving for A_O and Q_O from **equation 3** and substituting into **equation 4** gives OBD distance as a function of exposure time and temperature.

Inner β-phase depletion:

The inner β-phase depletion (IBD) is controlled by aluminum diffusing from the aluminum rich MCrAlY coating in to the aluminum lean nickel-base superalloy. This diffusion processes can be modeled by **equation 5**.

$$\frac{C_\beta - C_\alpha}{C_o - C_\alpha} - 1 = erf\left(\frac{x_i}{2\sqrt{Dt}}\right) \quad (5)$$

$$Z = \left(\frac{x_i}{2\sqrt{Dt}}\right) \quad (6)$$

Where C_o is the original concentration of the MCrAlY coating, C_α is the alloy concentration and C_β is the equilibrium concentration of the β-phase and the surrounding matrix. Also, X_i is the diffusion distance, D is the diffusion coefficient and t is diffusion time. Solving **equation 6** for X_i and correlating it with **equation 1**, which also can be applied to IBD, k_i is then shown to be $2Z\sqrt{D}$. Solving k_i for D and substituting into **equation 7** and resolving for K_i^2 gives **equation 8** where $4Z^2D_0$ can be taken as a pre-exponential constant A_i. Like with the OBD, Q_i and A_i are found by take the natural log of **equation 8** and plotting 2*ln(k) versus 1/T.

$$D = D_0 \exp\left(-\frac{Q_i}{RT}\right) \quad (7)$$

$$k_i^2 = 4Z^2 D_0 \exp\left(-\frac{Q_i}{RT}\right) \quad (8)$$

$$X_i = \sqrt{A_i} * \exp\left(-\frac{Q_i}{2RT}\right) * \sqrt{t} \quad (9)$$

Inner β-phase depletion distance as a function of exposure time and temperature can be found combining **equations 1 and 8** and solving for X_i which gives **equation 9**.

Total β-phase depletion:

Total β-phase depletion, **equation 10,** is then the summation of inner and outer β-phase depletion rate constantans applied in the parabolic growth law, **equation 1**.

$$X_{Total} = (k_O + k_i) * \sqrt{t} \quad (10)$$

Temperature correlations:

One can correlate from the β-phase depletion models a method for evaluating accurate service temperatures in field components. To do this **equations 4 and 9** need to be solved for exposure temperature, T, as a function of exposure time, t, and β-phase depletion, X. Both outer and inner β-phase depletion equations will be solved separately **equations 11 and 12**, respectively, for exposure temperature.

$$T = \frac{-Q_O}{R \cdot \ln\left(\frac{X_O}{A_O \cdot \sqrt{t}}\right)} \qquad \text{OBD (11)}$$

$$T = \frac{-Q_i}{2R \cdot \ln\left(\frac{X_i}{A_i \cdot \sqrt{t}}\right)} \qquad \text{IBD (12)}$$

Experimental:

As in previous work β-phase depletion distance measurement data was collected from micrographs of lab aged specimens, both inner and outer β-phase depletion measurements where taken in micrographs at various ageing times and temperatures. Samples where sectioned from rod segments of IN-939 coated with MCrAlY that where cyclically heated to T_1, T_2 and T_3, $T_1<T_2<T_3$ under 24 hour cycles for various exposure time.

Results:

Outer β-phase depletion:

Outer β-phase depletion measurements for various exposure times are shown in **figure 2** for exposure temperatures T_1, T_2 and T_3, $T_1<T_2<T_3$. Evaluation of the kinetic parameters, k_β, A_β, and Q_β,are show in **figure 3 and 4** and tabulated in **table1**.

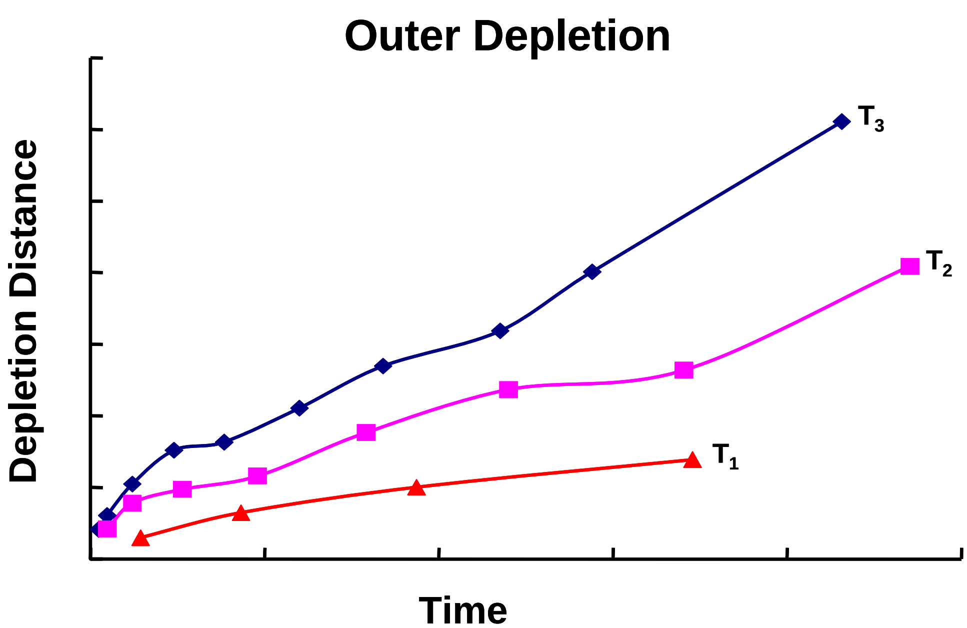

Figure 2 - Raw Depletion Data for IN-939 Outer Deletion distance vs. exposure time

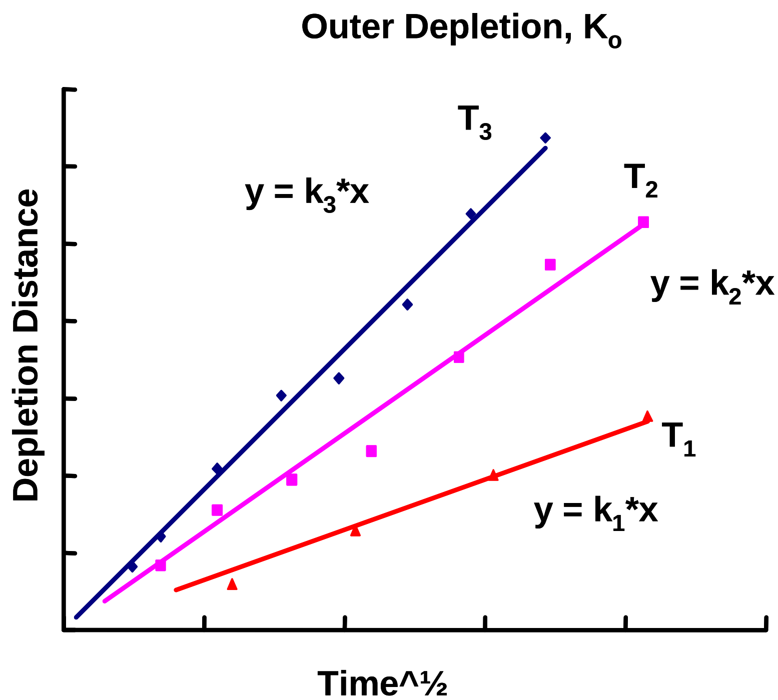

Figure 3 - Deletion distance vs. √Time to find k_β

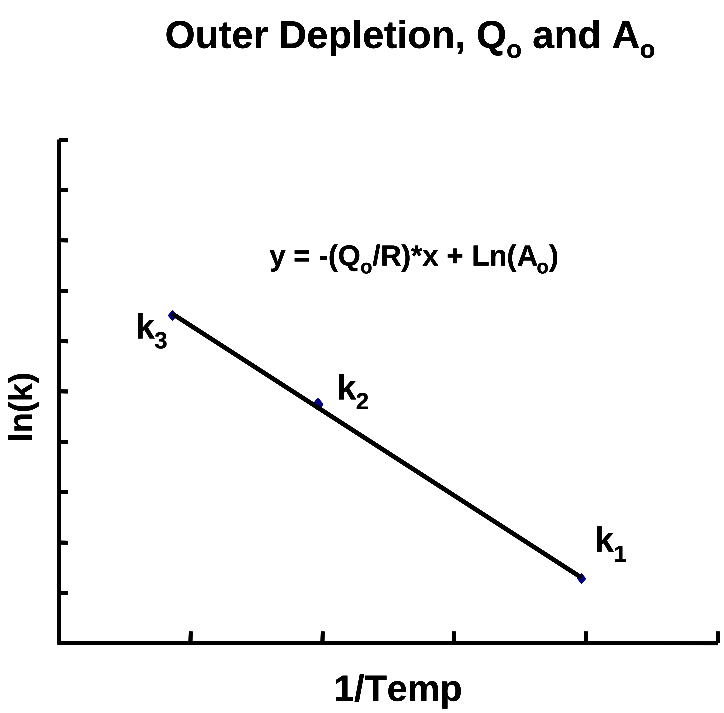

Figure 4 - ln(k) vs. 1/Temprature, to find A_β and Q_β

Applying the pre-exponential constant A_β and the activation energy Q_β in to **equation 4** generates the modeling equation for outer β-phase depletion.

Inner β-phase depletion:

Inner β-phase depletion measurements (mm) for various exposure times are shown in **figure 5** for exposure temperatures T_1, T_2 and T_3, $T_1 < T_2 < T_3$. Evaluation of the kinetic parameters, $2Z\sqrt{D}$, A_i, and Q_i, are show in **figure 6 and 7** and tabulated in **table 2**.

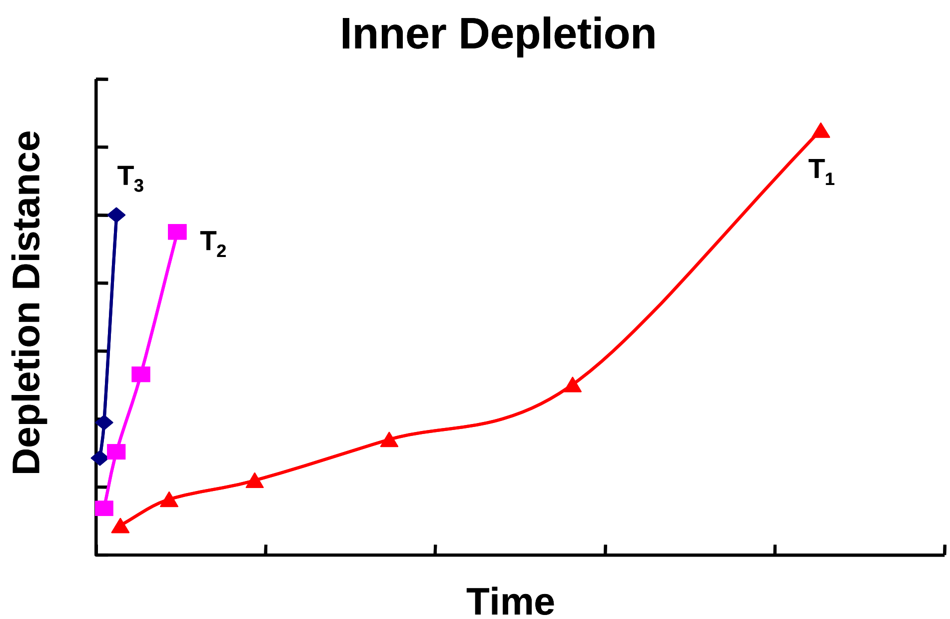

Figure 5 - Raw Depletion Data for IN-939 Inner Deletion distance vs. exposure time

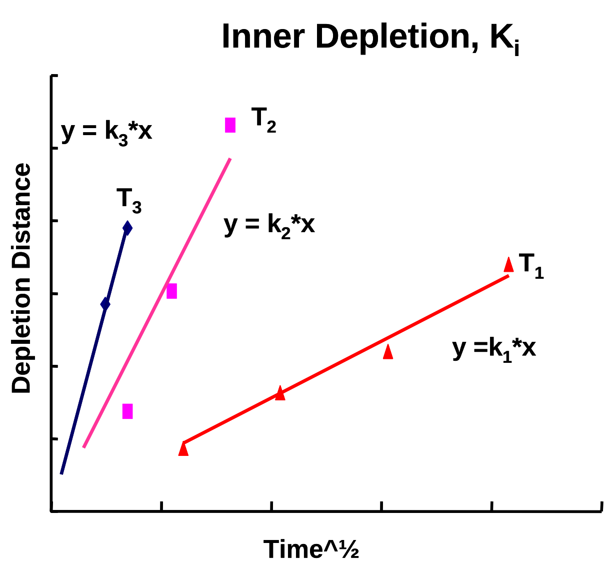

Figure 6 - Deletion distance vs. √Time to find 2Z√D

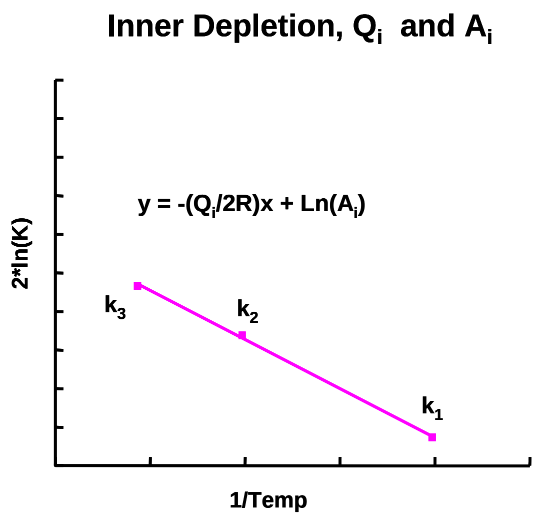

Figure 7 - 2 ln(k) vs. 1/Temprature, to find A_i and Q_i

Applying the pre-exponential constant A_i and the activation energy Q_i in to **equation 9** generates the modeling equation for inner β-phase depletion

By comparing the raw data to the model equation evaluated at the same points comparison charts where made, **figures 8 and 9**, one for outer and one for inner depletion distances.

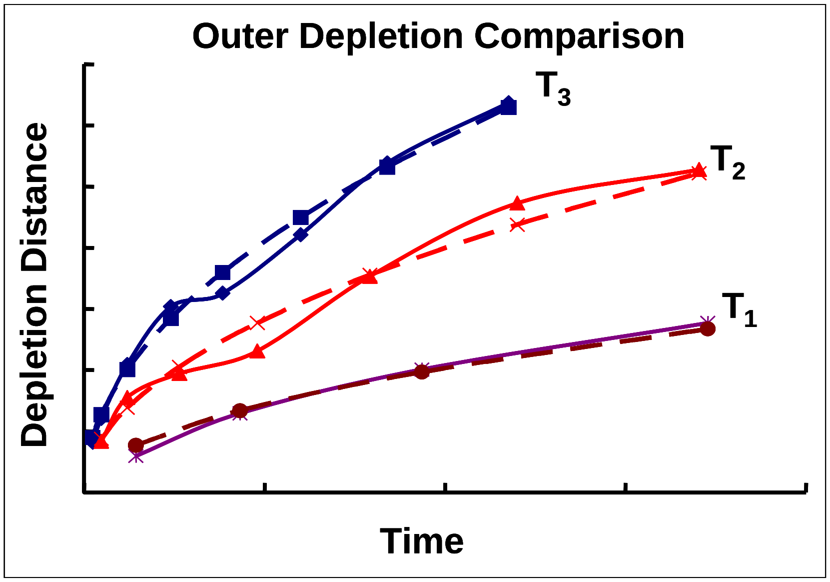

Figure 8 - Outer β-phase depletion distance comparison between measured and calculated data

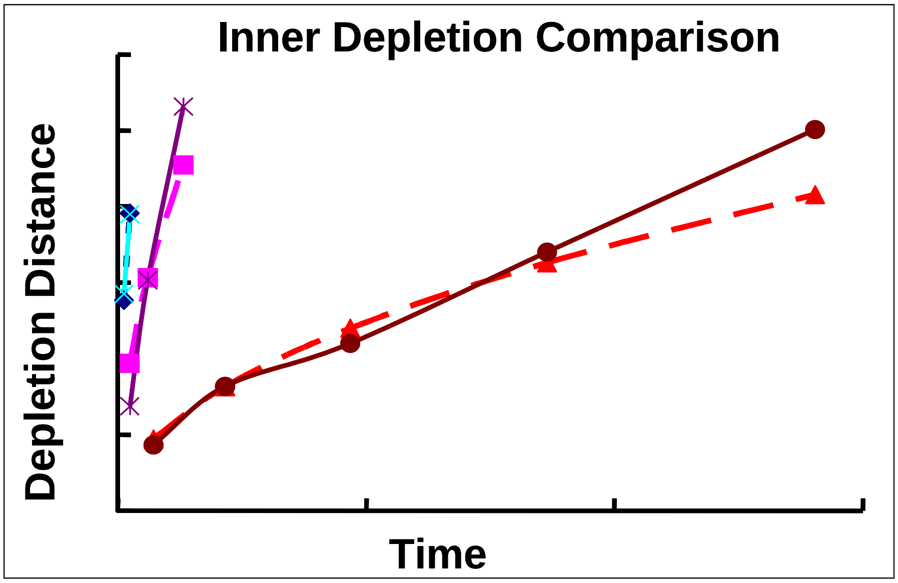

Figure 9 - Inner β-phase depletion distance comparison between measured and calculated data

Discussion:

The procedure use to model and calculate the kinetic parameters of the β-phase depletions is a very common method of calculating such values from experimental data. Thus, the usefulness of the project is then in the final values of the kinetic parameters A and Q for the MCrAlY/IN-939 system not in the mathematical method used to develop them.

Plotting the modeled expressions for inner and outer β-phase depletion, X_o and X_i, against the experimental data shows a good fit, verifying the accuracy of the model. Using the temperature correlation equations with the IN-939 alloy system, the operation temperatures of the rotation components can be determined from the inner or outer β-phase depletion and the known operation time.