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The Role of Cobalt on the Creep of Waspaloy

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INTRODUCTION

As part of the NASA Conservation of Strategic Aerospace Materials (COSAM) program[1,2] we have studied the role of cobalt variations on the static properties of Waspaloy. Previously, we reported the effects of cobalt on Udimet 700[3-6]. A comparitive study on Waspaloy is interesting since this alloy has the same alloying elements as Udimet 700, except that Waspaloy has less aluminum and titanium (and hence, less γ' precipitates) and less molybdenum for solid solution strengthening. For these reasons Waspaloy belongs to a lower strength class of alloys.

In the study on Udimet 700, systematic creep and tensile tests were correlated with microstructure and microchemistry results to determine the effects of replacing cobalt with nickel in the alloy which normally contains 18% cobalt. These alloys were given a sub-solvus heat treatment used to retain some primary γ' to pin grain boundaries. This fine grain material is designed for lower temperature, but higher strength applications--such as the gas turbine disk.

The yield and tensile strengths of low cobalt Udimet 700 were found to be slightly lower than the standard alloy. This small decrease in tensile strength was attributed to the slight decrease in strengthening γ' fraction even though the total γ' fraction was found to be independent of alloy cobalt content[3,4,6].

In contrast to the small effect of cobalt on tensile properties, creep and stress rupture strength of the low cobalt alloys fell drastically. Besides increasing the effective γ' fraction, we showed that cobalt partitions to the γ matrix, so it would be expected to decrease the stacking fault energy (SFE) of this matrix. This decrease in the SFE could increase the separation of partial dislocations and strengthen the alloy by reducing cross-slip.

To determine whether SFE or the effective γ' fraction is responsible for the loss in creep resistance, the Udimet 700 alloys were given a second type of heat treatment which included a solution above the γ' solvus. The total γ' fraction and the matrix cobalt content were found to be nearly identical to the alloys after the sub-solvus heat treatment--only the γ' morphology was changed. After this heat treatment all γ' was uniformly distributed, and hence, contributed to the alloy strength. Not unexpectedly, the tensile strength and the yield strength after this second heat treatment were independent of cobalt. But more importantly, with the microstructural variable removed, the creep and stress rupture properties of Udimet 700 also were <u>not</u> affected by cobalt. We conclude that cobalt may lower the stacking fault energy in Udimet 700, but that the SFE effect on properties is found to be minor once this variable is separated from cobalt's effect on the strengthening precipitate content.

Concerning higher strength cast superalloys, Nathal and Maier[7] showed that removing cobalt from conventionally cast

MarM247 lowered the γ' fraction and the creep resistance of this alloy. By removing cobalt from single crystal alloys derived from MarM247, Nathal and Ebert[8] showed the opposite effect of cobalt on γ' fraction and stress rupture. Although there may be some matrix SFE component to the creep behavior in these studies, microstructural constraints have prevented isolating that variable. It does, however, appear that the SFE effects in these alloys are also fairly minor.

At the other end of the strength spectrum, two studies have shown that cobalt greatly improves the stress rupture resistance of both Nimonic 80A[9] and Waspaloy[10]. In both alloys cobalt increases the volume fraction of γ' by decreasing the matrix solubility for aluminum and titanium. Additionally, Heslop[9] showed qualitatively that cobalt lowers the stacking fault energy of the matrix in Nimonic 80A. The cobalt-free matrix after a 1% deformation shows tangled dislocations as evidence of cross-slip in contrast to straight partial dislocations separated by wide stacking faults in the cobalt containing matrix. Maurer[10] alluded to SFE effects by calculating that a 2 volume percent change in γ' fraction would not totally account for the change in stress rupture behavior. Neither author attempted to separate the microstructural effects from the matrix chemistry (SFE) effects of cobalt. In this paper we discuss our efforts to distinguish the effects of cobalt on SFE from the γ' solubility effects.

EXPERIMENTAL PROCEDURE

Cobalt was systematically replaced with nickel in four alloys based on Waspaloy while the alloy contents of all other components were kept constant, see Table I. Heats of 68 kg. (150 lbs.) of each alloy were vacuum induction melted (VIM), vacuum arc remelted (VAR) into a 6 inch (152 mm) ingot, and hot rolled to 3/4 inch (19 mm) diameter bar by Special Metals Corporation, of New Hartford, New York. The γ' solvus determined by differential thermal analysis (DTA) did not vary with cobalt content, so the alloys were given identical heat treatments, Table II, resulting in equivalent microstructures with an average grain size of 10-13 microns.

The alloys with four different cobalt levels were creep and stress rupture tested at 448, 517 and 551 MPa (65, 75 and 80 ksi) and 760°C (1400°F) to determine the phenomenological backstress component to creep at a constant temperature. Tests were also run at 704, 732 and 760°C (1300,1350 and 1400°F) and 551 MPa (80 ksi) to determine the creep activation energy at a constant applied stress. Additionally room temperature tensile tests were used to characterize the effects of cobalt on the low temperature strength of Waspaloy.

Gamma prime phase extractions[6] determined that the fraction of this strengthening phase decreased from 22% to 20% as cobalt was removed. To compensate for this decrease in γ' fraction, two 7 kg heats of cobalt-free material with additional aluminum and titanium, Table II, were VIM cast and rolled to 2.5x0.5 inch (63x13 mm) plate by Special Metals Corporation. Since the γ' solvus in superalloys increases sharply with aluminum and titanium content, the solution temperatures in the heat treatment of these alloys were increased accordingly, Table II.

EXPERIMENTAL RESULTS AND DISCUSSION

Microstructure

The heat treated microstructures of Waspaloy with varying cobalt levels were examined optically and with SEM. The small effect of cobalt on the γ' fraction in this material is barely noticeable in SEM micrographs, Fig. 1. The carbide morphology does appear to be slightly affected by cobalt as more, and coarser, carbides appear at the grain boundaries in the low cobalt alloys than the standard Waspaloy. The effect of cobalt on the carbides in nickel-base superalloys was demonstrated in earlier papers[3-10] usually with the arguement that cobalt increases the carbon solubility in the matrix. However, recent experimental evidence shows that cobalt can change the transformation temperature of the carbides[5] but that the effect on the carbon solubility (which is extremely low at the operating temperatures) appears to be negligible[11].

Tensile Behavior

The minor microstructural effects of cobalt on γ' fraction and carbides result in little or no change in the room temperature strength or ductility of Waspaloy, Fig. 2 and Table III. The tensile strength and the yield strength are nearly constant at roughly 1400 MPa (200 ksi) and 1000 MPa (145 ksi), respectively. The tensile ductilities of the alloys are essentially unaffected by cobalt, all are in the range of 25 to 30% elongation and 40 to 45% reduction of area. These results are not surprising since in the cases of Udimet 700[3,4], MarM247[7,8], Nimonic 80A[9] and an earlier study on Waspaloy[10] cobalt was found to have little, if any, effect on the tensile behavior of nickel-base superalloys.

<u>Creep and Stress Rupture Behavior</u>

In contrast to the small effect of cobalt on microstructure and properties in tensile tests, the alloys with less cobalt had lower stress rupture and creep resistance than the standard alloy at all applied stresses and temperatures tested. See Fig. 3 for the rupture lives and Fig. 4 for the minimum creep rates as a function of cobalt content. For all alloys the rupture ductilities were scattered in a band from 15 to 30% elongation with no systematic effect of cobalt, Table IV. However, the reduction of area for the cobalt-free alloy (20-35%) was roughly half the reduction (40-65%) for the three cobalt containing alloys.

Cobalt resides mainly in the matrix of Waspaloy (the matrix cobalt content is approximately 15% compared to 5% in the γ') as has been shown previously in this alloy and a range of other superalloys[3,7,12]. Cobalt in the matrix affects the creep behavior of the alloy in two separate ways. First, as mentioned above, cobalt decreases the matrix solubility limit for the γ' formers, aluminum and titanium. In Waspaloy, 13% cobalt produces an increase from 20 to 22% γ'[6]. Using the lever rule applied to a pseudo-binary phase diagram[4,9] for this system the γ' fraction increase translates to a decrease in (Al+Ti) solubility of 0.35 atomic percent.

The second effect of cobalt in the matrix is its solid solution strengthening. Unlike other alloying elements in superalloys, the cobalt mismatch with nickel is less than 1%. Therefore, as a misfitting element its role is negligible. Its effect on the coherency strains of γ/γ' mismatch have been shown to be small[6]. However, Beeston, et al.[13], Heslop[9], and Law, et al.[14] have shown that cobalt substantially lowers stacking fault energy in binary nickel-cobalt alloys, in Ni-Cr-Co ternaries, and in the matrix of a complex nickel-base superalloy, MERL 76, respectively. From these results we conclude that the 13% cobalt in Waspaloy lowers the stacking fault energy in the matrix. By using the various linear approximations[13-16] we will show that this cobalt content lowers the SFE of the matrix by about 43%.

To determine which cobalt effect has the dominant role in the creep behavior of Waspaloy, we separated the particle contribution from the matrix (or SFE) contribution using existing semi-empirical equations[15,16]. A preliminary analysis of the creep data using the standard creep equation (1) was done to determine the stress exponent, n, and the apparent activation energy, Q_A, for each of the cobalt contents, see Table V.

$$\dot{\varepsilon} = A^{\circ} \sigma^{n} e^{(-Q_A/RT)} \tag{1}$$

$\dot{\varepsilon}$ is the minimum creep rate, σ is the applied stress, A° is a structure dependent constant and T is the absolute temperature. Both the stress exponent and the apparent creep activation energy increase (from 7.0 to 7.9 and from 64 to 74 kcal/mole, respectively) with increasing cobalt content in Waspaloy.

A further analysis of the creep results using the creep equation derived to separate the particle contribution from the alloy matrix contribution of complex particle strengthed alloys.

$$\dot{\varepsilon} = A'(1-k)^4 \left[\frac{\sigma - \sigma_p}{E(T)}\right]^4 e^{(-Q^o/RT)} \qquad (2)$$

In this equation A' is a new material constant, k is a factor between 0 and 1 relating the matrix solid solution drag stress, σ_s, to the effective stress on a dislocation $\sigma_s = k(\sigma - \sigma_p)$, σ is the applied stress, σ_p is the particle back stress, E is the temperature dependent elastic modulus, Q^o is the true activation energy for creep which is roughly the activation energy for self diffusion in nickel.

Values of k and σ_p for Waspaloy with various cobalt levels are included in Table V. Note the particle component, σ_p, increases from 207 MPa (30.0 ksi) for the cobalt-free alloy to 243 MPa (35.4 ksi) for the standard alloy. This increase is consistent with the small increase in γ' fraction as the cobalt level increases. In Waspaloy, in contrast to Udimet 700[3], Table VI, the matrix contribution, k, also increases markedly with cobalt content from .651 in the cobalt-free alloy to .800 in standard Waspaloy.

Xie et al.[15] presented a variation of the creep equation (2) based on the work of Sherby and co-workers[18-20] concluding that stacking fault energy is the major matrix contribution to the creep strength of particle strengthened systems.

$$\dot{\varepsilon} = A\ (\gamma_{SFE})^4 \left[\frac{\sigma - \sigma_p}{E(T)}\right]^4 e^{(-Q^\circ/RT)} \qquad (3)$$

In this equation A is a new material constant and γ_{SFE} is the stacking fault energy of the matrix relative to pure nickel. The SFE exponent comes directly from Equation (2) by claiming that the matrix drag effect is due entirely to the SFE. This exponent is slightly higher than the values of 2-3.5 reported by Law[14] or Sherby[18-20] for single phase alloys. The other variables have the same meaning as in equation (2). Interpreting the present creep results with this new equation, the SFE of the Waspaloy matrix is found to be reduced by 43% due to cobalt. This value is quite reasonable and consistent with the linear approximation of SFE in Refs. 14 and 15.

The creep activation energies determined in this study provide further evidence that SFE is playing the dominant role in cobalt's effect on the creep resistance of Waspaloy. The apparent creep activation energy in Waspaloy increases with cobalt content (see Table V). The true creep activation energy, Q°, can be calculated from the apparent value, Q_A, by including the temperature effect on the elastic modulus in equation (1). In a range of particle strengthened nickel-base alloys previous researchers[16,21-23] have shown that the true creep activation energy is alloy independent and nearly equal to the self diffusion activation energy for nickel.

$$Q^{o} = QA + \frac{nRT^2}{E(T)}\left[\frac{dE}{dT}\right] \tag{4}$$

For Waspaloy at 760°C, the elastic modulus is 168 GPa[24] and (dE/dT) is roughly −85 MPa/K, giving Q^{o} the value of 66 kcal/mole. We have not experimentally determined the values of E(T) and dE/dT for cobalt modified Waspaloy. However, the elastic moduli would not be expected to differ much from the standard alloy, as the case with Nimonic 80A and 90[24]. Indeed, the difference between the elastic moduli for any two nickel-base superalloys would not be sufficient to explain the these differences in the creep activation energies with cobalt. This indicates that cobalt's effect on the creep activation energy cannot be explained by a simple modulus effect in equation (1).

A more thorough analysis of the activation energies in particle strengthened alloys using equations (2) or (3) includes temperature effects on the particle and drag back stresses[23,16] in addition to the modulus effect. The true activation energy, Q^{o} takes the form,

$$Q^{o} = Q_A + \frac{n^{o}RT^2}{E}\left[\frac{dE}{dT}\right] + \frac{n^{o}RT^2}{\sigma_p}\left[\frac{d\sigma}{dT}p\right] + \frac{n^{o}RT^2}{(1-k)}\left[\frac{dk}{dT}\right] \tag{5a}$$

or, alternatively, in terms of the stacking fault energy,

$$Q^{o} = Q_A + \frac{n^{o}RT^2}{E}\left[\frac{dE}{dT}\right] + \frac{n^{o}RT^2}{\sigma_p}\left[\frac{d\sigma}{dT}p\right] - \frac{n^{o}RT^2}{\gamma_{SFE}}\left[\frac{d\gamma}{dT}\right] \tag{5b}$$

The variables are defined as in equation (3) where n^0 was given the value of 4. In this form the particle back stress has the same temperature dependence as the elastic modulus[22] and, as such, should not be greatly affected by cobalt. However, the stacking fault energy term would be expected to show a cobalt effect.

Ericsson[25] and Tisone[26] have shown that the SFE of Co-Ni alloys increases with temperature, so the last term in equation (5b) becomes more negative with increasing cobalt. Thus, although the true activation energy does not change with cobalt, the apparent activation energy in cobalt containing Waspaloy would be expected to be higher than in the cobalt-free alloy. We can calculate the temperature dependence of the SFE assuming this effect accounts for the 10 kcal/mole difference in the activation energies between the standard and cobalt-free Waspaloy. Using 240 erg/cm² as the SFE of nickel[13], $d\gamma/dT$ at 760°C is found to be .056 erg/cm²-°C. This is within a factor of two of the value $.03 \pm .02$ erg/cm²-°C determined by Ericsson[25] using the node area method in the binary Co-Ni alloys.

From the results of the analyses of both the matrix drag back stress and the creep activation energy we conclude that the effect of cobalt on the creep of Waspaloy is due the reduction of the matrix stacking fault energy. Although cobalt does cause some microstructural changes in the γ' and carbides of Waspaloy, these effects are decidedly small when compared to the SFE effect.

Modified Waspaloy

The next phase of this project was to attempt to remedy the loss of creep resistance in Waspaloy due to the removal of cobalt. This can be accomplished by raising the matrix drag stress (by adding solid solution strengtheners), or by raising the particle resisting stress (by increasing the γ 'fraction), or a combination of both. In the earlier study on Udimet 700[3], microstructural effects were the origin of a loss of creep strength. Modifying the heat treatment and thermomechanical processing to compensate for the γ' solvus effects of cobalt restored the creep resistance without any chemistry alterations.

The effect of cobalt on Waspaloy is not microstructural so thermal treatment options do not apply. Therefore, we either 1) replace cobalt with an equivalent amount of another HCP metal to lower the stacking fault energy, or 2) increase the solid solution strengthening by adding refractory elements, or 3) increase the γ' fraction by adding γ' formers.

The approach we decided to use was increasing the γ'formers, aluminum and titanium. Since these elements are potent strengtheners, minor changes in chemistry can result in substantial gains in strength. We ruled out increasing the chromium or molybdenum contents to lower the SFE because the alloy matrix in nearly saturated with these elements and such an addition could lead to phase instabilities with a marginal effect on the solid solution strength. Also, we eliminated adding an alternative HCP metal to replace the cobalt since introducing, say, 10% of a new element to the alloy is the equivalent of designing an entirely new alloy, which is not the intent of this study.

The alloy D1-1948-1 was modified with an addition of 0.42 atomic % (Al+Ti) to compensate for the 2% γ' volume fraction decrease due to removing cobalt. This alloy showed essentially no improvement in the 551 MPa/732°C (80 ksi/1350°F) stress rupure life over the cobalt-free Waspaloy with the standard γ' content[17]. However, the alloy with 1.23 atomic % (Al+Ti) added did show the expected increase in the rupture life so we concentrated on this alloy in our study. (As a reference, the aluminum and titanium contents of this alloy are 0.10 w/o and 0.15 w/o above the specification maximum.)

The additional γ'(estimated to be about 5 percent) raised the 448 MPA/760°C (65 ksi/1400°F rupture life of the cobalt-free alloys from 3.48 to 18.85 hours, reducing the minimum creep rate from 6.3×10^{-6} to 0.25×10^{-6} per sec, see Table III. Note that the creep rates of this alloy at 760°C are nearly identical to the standard alloy. The trade-off for this additional strength is a drop in ductility (from 15-30% for the standard alloy to 11-14% for this low cobalt alloy with more γ'). The combination of equivalent minimum creep rates and reduce ductility results in shorter rupture lives for this modified alloy compared to the standard cobalt-containing Waspaloy.

These results indicate that although cobalt is certainly necessary for the high temperature creep strength of Waspaloy, some conservation of this strategic element may be achieved by increasing the γ' content of a low cobalt version of the alloy. However, to achieve the creep resistance in a cobalt-free alloy a decrease in the rupture ductility results. A possible compromise alloy with, say, half the cobalt content and maximal aluminum and titanium contents may be an effective alternative alloy with adequate creep and stress rupture resistance.

CONCLUDING REMARKS

Waspaloy and Udimet 700 belong to the the same family of wrought nickel-base alloys containing Cr, Co, Mo, Al and Ti as the major alloying elements. Waspaloy is at the low end of the strength scale with roughly 20% γ' and Udimet 700 at the high end with 45%. In this study and the previous work on Udimet 700[3,4] we have systematically replaced the cobalt with nickel to isolate cobalt's effect on properties and microstructure.

In these alloy systems we have identified the primary effects of cobalt. Because it partitions to the γ matrix, cobalt predominently affects this phase. Cobalt lowers the matrix stacking fault energy and decreases the aluminum and titanium solubilities. Since cobalt and aluminum do not form Co_3Al, substituting cobalt for nickel lowers the γ' solvus in superalloys. Cobalt also lowers the terminal matrix aluminum solubility so a cross-over of the cobalt containing and cobalt-free solvus lines results. Indeed, Waspaloy is at this cross-over composition while Udimet 700 is above[3] and Nimonic 90 is below[9] the aluminum content of the cross-over.

As a consequence of this solvus effect, the carbide solvus and the processing temperatures of high γ' fraction alloys like Udimet 700 decrease with decreasing cobalt content. However, after the proper processing modifications cobalt effects on microstructure can be essentially eliminated.

In Waspaloy, as in Udimet 700, cobalt does not affect the tensile or yield strengths. This result is quite reasonable since the strengthening methods for short times or at low temperatures in these alloys are determined by γ' fraction, anti-phase boundary energy, coherency strains, and, of course, microstructure[27-29].

Cobalt's effect on microstructure is, again, minimal. Its effects on mismatch or on coherency strains are also very small-- essentially below the resolvable limit[6]. Cobalt can increase the γ' fraction by decreasing the solubility for (Al+Ti). In Waspaloy, the γ' prime fraction increased from 20 to 22% which would not have a measurable effect on properties. In Udimet 700, a smaller volume increase of less than 1% resulted. The effect of cobalt on APB would be expected to be very small since the γ' cobalt content is much smaller (roughly one-third) the matrix content. Should cobalt have any effect it would be expected to lower the APB since it tends to de-stabilize the γ'.

Under elevated temperature creep and stress rupture conditions the matrix (and, hence, cobalt) would be expected to play a larger role than in short time tensile tests. During creep deformation, matrix dislocations by-pass the γ' precipitates by thermally activated cross-slip[30,31] and climb mechanisms[32] as well as cutting the particle[23,33,34]. In Waspaloy cobalt plays an important role in creep by lowering the stacking fault energy of the matrix and apparently inhibiting the cross-slip and climb processes. However, in Udimet 700, with nearly an identical matrix as Waspaloy, cobalt has no effect on creep.

Resolving the difference in behavior of cobalt between low volume fraction Waspaloy and high volume fraction Udimet 700 is key to understanding not only the role of cobalt in superalloys, but more generally, understanding the role of SFE in particle strengthened systems. The major differences between the two alloy systems are the γ' volume fraction and particle size. In Waspaloy the 20% volume fraction of γ' is precipitated mostly as very small spheroids 40-60nm in diameter and a small fraction of larger particles 150-200nm in diameter. In contrast, the γ' in Udimet 700 precipitates as alligned cubes 300-500nm on a side and a small fraction of round very fine particles about 60-100nm in diameter.

Due to the difference in volume fraction the mechanical behavior of Waspaloy would be dominated by the matrix while the behavior of Udimet 700 would be dominated by the γ'. Kear, et al. (Refs. 31,33,34) present a model of the γ' cutting behavior of dislocations in the high γ' fraction alloy Mar M200. They explain that the cutting mechanism is provided by a pair of $\frac{a}{2}\langle\bar{1}01\rangle(111)$ dislocations. The first forms an anti-phase boundary (APB) in the γ' and the second removes that APB leaving behind a perfect crystal. The lowest energy configuration of these dislocations is as a co-planar pair. The separation of these co-planar pairs is far greater than the stacking fault width between the partials of the individual dislocations. Thus cross-slip or climb of the pairs would be fairly insensitive to changes in stacking fault energy (which determines the separations of the partials but not the distance between the dislocation pairs).

This pairing and cutting has been observed in Udimet 700 but is not seen in Waspaloy[23,35]. For this reason the effect of cobalt on the stacking fault energy of the matrix does not affect the creep behavior of Udimet 700 while it has a considerable effect on the creep of Waspaloy. In Waspaloy, the results of the present study indicate that raising the SFE by removing cobalt may significantly increase creep rates by reducing the barriers to cross-slip by reducing the partial dislocation separation.

Since the alloy chemistry determines the matrix stacking fault energy, few alternatives are available to lower this energy without making considerable changes in the alloy. Such changes may far outweigh the subtle effect on SFE. The alternative method we used to correct this decreased creep resistance is to increase the number of obstacles (i.e., the γ' fraction). A cobalt-free alloy with the creep resistance of standard Waspaloy was produced by adding 0.25 weight percent (Al+Ti) above the specification maximum. The trade-off of reduced ductility for the increased strength resulted. Optimizing Waspaloy with an intermediate cobalt level and the aluminum and titanium contents at the specification maximum may be a reasonable means of reducing cobalt consumption in this alloy.

The effects of cobalt on creep deformation in wrought nickel-base superalloys can be summarized as follows:

1) Cobalt decreases the matrix solubility for aluminum and

titanium which slightly increases the γ' volume fraction in low volume fraction alloys. This effect is usually too small to affect the properties of the alloys (as seen in Waspaloy and Udimet 700).

2) Cobalt lowers the matrix stacking fault energy of all nickel-base alloys.

3) SFE effects of cobalt have been shown to control the creep resistance of Waspaloy and the results fit a semi-empirical equation which includes the SFE term in the resisting stress model for creep in particle strengthened systems.

4) The same SFE effect in the high γ' fraction alloy, Udimet 700, has no effect on creep.

5) We attribute this difference between the two alloys to the dislocation pairing in the high volume fraction alloys overshadowing the effects of SFE on partial dislocation separation.

6) The loss of creep resistance in low cobalt, high strength alloys is not generally an intrinsic effect and can be corrected with proper thermomechanical processing or heat treatment. In the low γ' fraction alloys such as Waspaloy, the effect of cobalt on creep is intrinsic to the matrix chemistry so compositional changes are a necessity to restore properties.

7) We have demonstrated that the creep resistance of a low cobalt version of Waspaloy can be restored to the level of the standard alloy with minor additions of (Al+Ti) to increase the γ' fraction.

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Table I. Alloy Compositions (in weight percent)

Heat No.	Ni	Co	Cr	Mo	Al	Ti	C	B	Zr
D5-1947	bal.	<0.1	19.6	4.07	1.30	3.03	.039	.005	0.07
D5-1948	bal.	4.6	19.5	4.08	1.29	3.02	.042	.005	0.07
D5-1949	bal.	9.0	19.4	4.12	1.32	2.99	.041	.004	0.07
D5-1950	bal.	13.4	19.5	4.19	1.33	3.05	.040	.005	0.07
D1-1948-1	bal.	0.0	19.3	4.00	1.50	3.15	.035	.005	0.07
D1-1948-2	bal.	0.0	19.3	4.00	1.70	3.40	.035	.005	0.07

For all alloys Fe<.13, Mn, Si, Cu <.10, S<.004 and P<.01.

Table II. Heat Treatment Schedules.

Heats D5-1947, 1948, 1949 and 1950

1010°C (1850°F) / 4 Hours / Oil Quench
843°C (1550°F) / 4 Hours / Air Cool
760°C (1400°F) /16 Hours / Air Cool

Heat D1-1948-1

1029°C (1885°F) / 4 Hours / Oil Quench
843°C (1550°F) / 4 Hours / Air Cool
760°C (1400°F) /16 Hours / Air Cool

Heat D1-1948-2

1052°C (1925°F) / 4 Hours / Oil Quench
843°C (1550°F) / 4 Hours / Air Cool
760°C (1400°F) /16 Hours / Air Cool

Table III. Room Temperature Tensile Properties of Waspaloy

Heat Number	0.2% Yield Strength (in MPa)	Ultimate Strength (in MPa)	Elongation (in %)	Reduction of Area (in %)
D5-1947 (0 % Co)	999	1375	30.4	43.9
D5-1948 (4.6% Co)	1010 1012	1380 1390	28.9 28.8	42.9 39.8
D5-1949 (9.0% Co)	1026 1048	1410 1420	29.7 29.5	46.3 42.8
D5-1950 (13.4% Co)	1026 1021	1425 1420	29.2 29.6	43.1 41.6
D1-1948 (Al + Ti)	879 923	1325 1368	26.2 26.3	29.2 31.5

Table IV. Creep and Stress Rupture Properties of Waspaloy

Alloy Heat Number	Temperature (in °C)	Applied Stress (in MPa)	Rupture Life (hours)	Minimum Creep Rate (per sec)	Elongation (in %)	Reduction of Area (in %)
D5-1947	760	448	3.48	$6.3x10^{-6}$	22.5	32.3
(0% Co)		517	1.55	$1.7x10^{-5}$	22.9	37.2
		551	1.49	$1.0x10^{-5}$	16.5	26.2
	732	551	4.03	$4.4x10^{-6}$	18.0	27.6
		551	4.61	$6.3x10^{-6}$	23.4	20.7
	704	551	19.56	$6.0x10^{-7}$	16.0	21.3
D5-1948	760	448	8.81	$2.3x10^{-6}$	21.7	56.1
(4.6% Co)		517	1.97	$7.4x10^{-6}$	11.2	34.9
		551	2.29	$1.0x10^{-5}$	24.3	62.8
	732	551	6.	$2.2x10^{-6}$		54.4
	704	551	65.30	$1.5x10^{-7}$	15.7	46.7
D5-1949	760	448	14.15	$9.1x10^{-7}$	37.6	58.7
(9.0% Co)		517	5.77	$3.0x10^{-6}$	28.4	48.8
		551	2.04	$7.5x10^{-6}$	30.9	50.3
	732	551	12.80	$1.1x10^{-6}$	29.9	44.7
	704	551	109.5	$6.3x10^{-8}$	16.4	39.6
D5-1950	760	448	30.01	$3.5x10^{-7}$	25.3	65.8
(13.4% Co)		517	11.53	$7.9x10^{-7}$	15.4	54.7
		551	8.99	$1.8x10^{-6}$	24.6	59.7
	732	551	32.0	$1.7x10^{-7}$	17.2	39.1
	704	551	225.4	$1.8x10^{-8}$	29.1	54.3
D1-1948	760	448	18.85	$2.5x10^{-7}$	14.0	18.1
		517	4.35	$8.3x10^{-7}$	11.0	14.6

Table V. Creep Parameters for Cobalt Modified Waspaloy Heat

Number	Cobalt Content	n	Q_{App} (kcal/mole)	σ_p (MPa)	k	σ_s* (MPa)	Relative# γ_{SFE}
D5-1947	0.0	7.0	64.1	207	.651	202	1.00
D5-1948	4.6	7.6	68.7	235	.693	195	0.86
D5-1949	9.0	8.3	73.1	249	.739	198	0.75
D5-1950	13.4	7.9	74.1	243	.800	219	0.57
D1-1948-2	0.0	8.4	--	251	.810	215	0.54

* The value for σ_s is based on an applied stress of 517 MPa.
\# The SFE value calculated from equation 3.

Table VI. Creep Parameters for Cobalt Modified Udimet 700

Heat Number	Cobalt Content	n	Q_{App} (kcal/mole)	σ_p (MPa)	k	σ_s* (MPa)	Relative# γ_{SFE}
D5-1884	0.0	12.3	--	427	.744	195	1.00
D5-1886	8.6	12.5	--	430	.754	195	0.96
D5-1933	17.0	12.1	--	423	.739	198	1.02

* The value for σ_s is based on an applied stress of 689 MPa.
\# The SFE value calculated from equation 3.

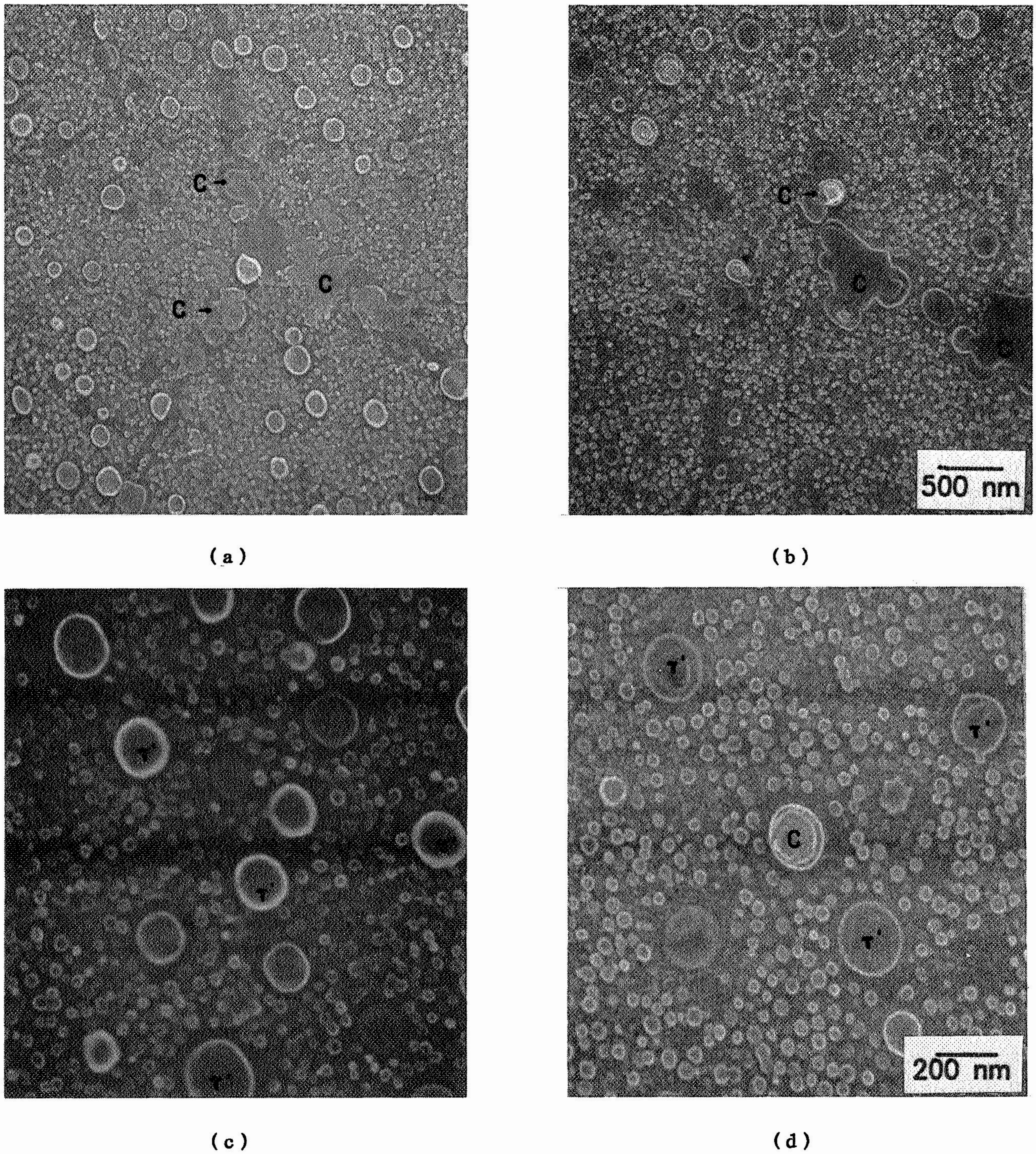

Figure 1. SEM micrographs of Waspaloy with 13% cobalt (a and c) and 0% cobalt (b and d).

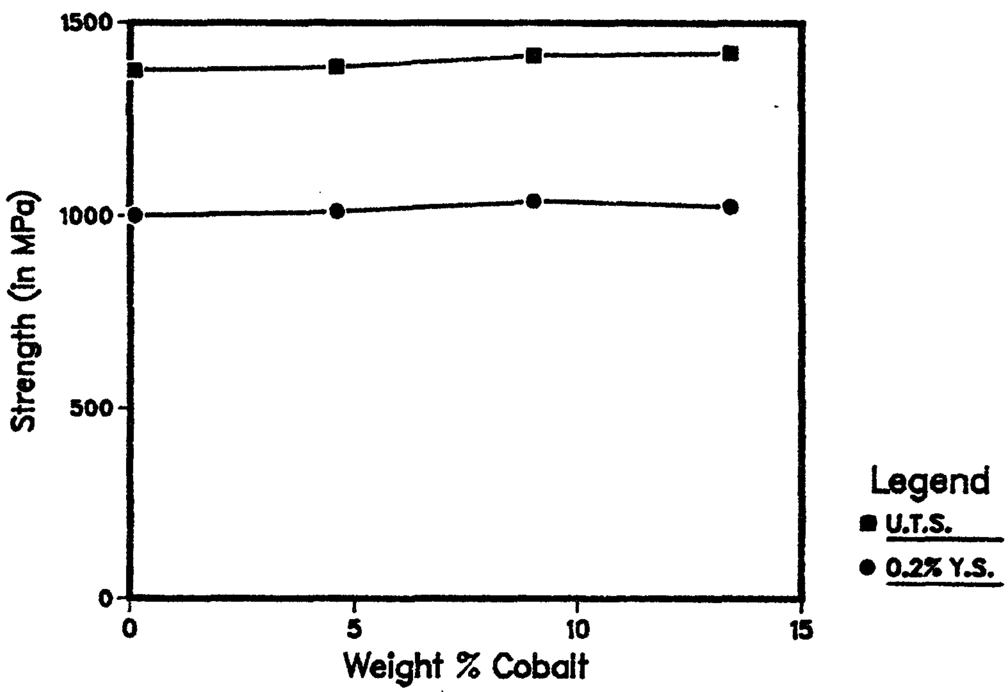

Figure 2. Tensile strength of Waspaloy as a function of cobalt.

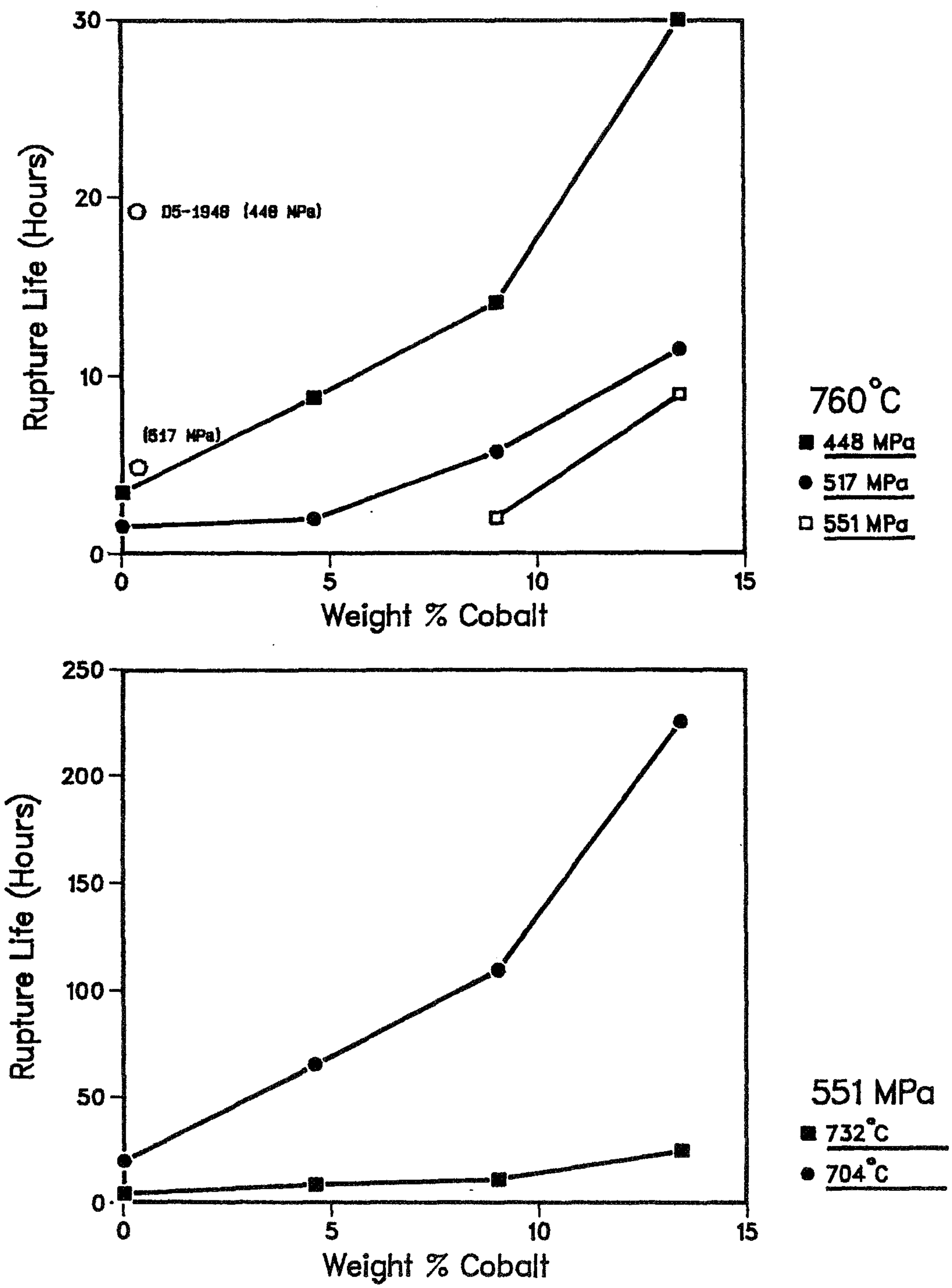

Figure 3. Stress rupture lives of Waspaloy as a function of cobalt.

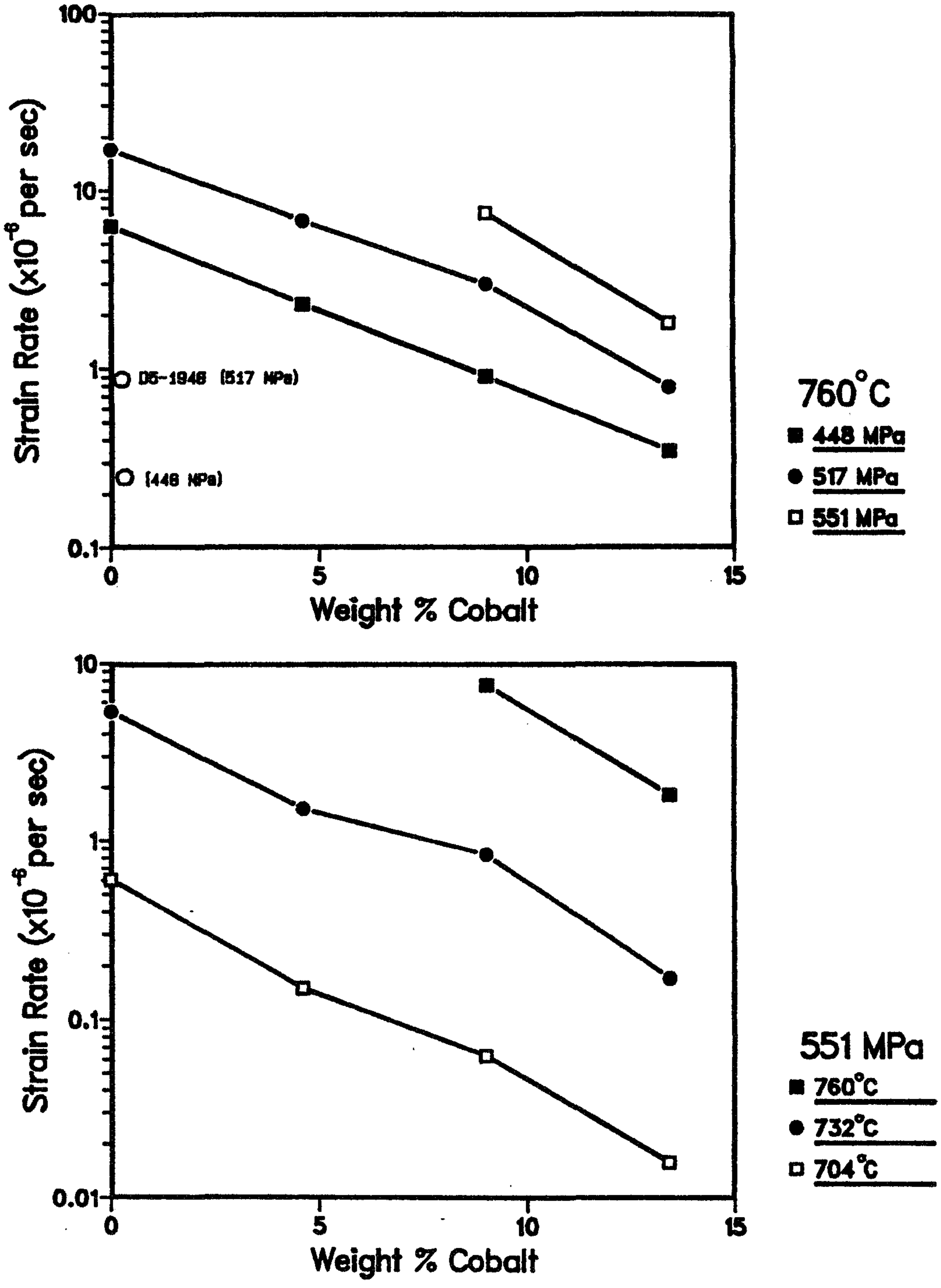

Figure 4. Minimum creep rates as a function of cobalt content. Note that the cobalt free alloy with additional (Al+Ti) shows the same creep rate as the alloy with the standard cobalt, aluminum and titanium contents.

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16. Abstract

Cobalt was systematically replaced with nickel in Waspaloy (which normally contains 13% Co) to determine the effects of cobalt on the creep behavior of this alloy. Effects of cobalt were found to be minimal on tensile strengths and microstructure. The creep resistance and the stress rupture resistance determined in the range from 704° to 760° C (1300° to 1400° C) were found to decrease as cobalt was removed from the standard alloy at all stresses and temperatures. Roughly a ten-fold drop in rupture life and a corresponding increase in minimum creep rate were found under all test conditions. Both the apparent creep activation energy and the matrix contribution to creep resistance were found to increase with cobalt. These creep effects are attributed to cobalt lowering the stacking fault energy of the alloy matrix. The creep resistance loss due to the removal of cobalt is shown to be restored by slightly increasing the γ' volume fraction. Results are compared to a previous study on Udimet 700 - a higher strength, higher γ' volume fraction alloy with similar phase chemistry - in which cobalt did not affect creep resistance. An explanation for this difference in behavior based on interparticle spacing and cross-slip is presented.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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