NASA Contractor Report 168308

Effects of Cobalt in Nickel-Base Superalloys

John K. Tien and Robert N. Jarett

Columbia University
New York, New York

December 1983

Prepared for

12   1   1 RN/NASA-CR-168308
          DISPLAY 12/2/1
      84N14287*#   ISSUE 5   PAGE 652   CATEGORY 26   RPT#: NASA-CR-168308 NAS
      1.26:168308   CNT#: NAG3-57   83/12/00   26 PAGES   UNCLASSIFIED DOCUMENT
UTTL: Effects of cobalt in nickel-base superalloys   TLSP: Final Report
AUTH: A/TIEN, J. K.;   B/JARRETT, R. N.
CORP: Columbia Univ., New York.   CSS: (Center for Strategic Materials.)
      AVAIL.NTIS   SAP: HC A03/MF A01
      Presented at High Temp. Alloys for Gas Turbines Conf., Liege, 4-6 Oct.
      1982
MAJS: /*COBALT ALLOYS/*HEAT RESISTANT ALLOYS/*MECHANICAL PROPERTIES/*
      MICROSTRUCTURE/*NICKEL ALLOYS/*SUBSTITUTES
MINS: / CARBIDES/ CONCENTRATION (COMPOSITION)/ SOLID SOLUTIONS/ SOLUBILITY/
      VOLUME
ABA: Author
ABS: The role of cobalt in a representative wrought nickel-base superalloy was
      determined. The results show cobalt affecting the solubility of elements
      in the gamma matrix, resulting in enhanced gamma' volume fraction, in the
      stabilization of MC-type carbides, and in the stabilization of sigma
      phase. In the particular alloy studied, these microstructural and
      microchemistry changes are insufficient in extent to impact on tensile
      strength, yield strength, and in the ductilities. Depending on the heat
      treatment, creep and stress rupture resistance can be cobalt sensitive. In
      the coarse grain, fully solutioned and aged condition, all of the alloy's
ENTER:

EFFECTS OF COBALT IN NICKEL-BASE SUPERALLOYS*

John K. Tien and Robert N. Jarrett

Columbia University
Center for Strategic Materials
Henry Krumb School of Mines
New York, New York 10027

The role of cobalt in a representative wrought nickel-base superalloy was recently determined. The results show cobalt affecting the solubility of elements in the γ matrix, resulting in enhanced γ' volume fraction, in the stabilization of MC-type carbides, and in the stabilization of sigma phase. In the particular alloy studied, these microstructural and microchemistry changes are insufficient in extent to impact on tensile strength, yield strength, and in the ductilities. Depending on the heat treatment, creep and stress rupture resistance can be cobalt sensitive. In the coarse grain, fully solutioned and aged condition, all of the alloy's 17% cobalt can be replaced by nickel without deleteriously affecting this resistance. In the fine grain, partially solutioned and aged condition, this resistance is deleteriously affected only when one-half or more of the initial cobalt content is removed. The structure and property results are discussed with respect to existing theories and with respect to other recent and earlier findings on the impact of cobalt, if any, on the performance of nickel-base superalloys.

N84-14287#

1. INTRODUCTION

In 1980, spurred by the 1978-1980 sharp increase in the world price of cobalt, Tien et al. (1) reviewed the role of cobalt in superalloys and concluded that:

a. The superalloy system, including the nickel-base super-alloys, is the single largest consumer of cobalt in the United States. Cobalt as a major alloying element in superalloys accounted for about 30% of the cobalt consumed in the United States in 1979. This percentage increased to over 40% in 1980-1981.

b. Systematic information on the role of cobalt in nickel-base superalloys in developing the appropriate strengthening microstructures and mechanical properties is scanty and not at all comprehensive.

c. Analytical calculations show, however, that the role of cobalt, the nearest chemical and physical neighbor to nickel, may not be pivotal and the present levels of cobalt (10 to 20 percent) in nickel-base superalloys, a priori, are not technically justified.

It was prudently recognized, however, that the last statement is itself based on minimal empirical information and that systematic studies must be undertaken to understand the role of cobalt in nickel-base superalloys. Since 1980, a study in our group has concentrated on understanding the role of cobalt in Udimet 700, which is a representative intermediate γ' volume fraction nickel-base superalloy. Udimet 700, containing about 18% cobalt, has many versatile uses. In the cast form and/or coarse-grained wrought form, it is used in rotating turbine blade applications. In the fine-grained wrought form, it is used as turbine disks. With the appropriate alloy modifications, it is also a powder alloy.

Our results (2) will be discussed with respect to the findings of other related studies. Particular attention will be given to two other very recent studies (3,4). The study by Nathal and Maier (3) concentrated on Mar-M247, which is representative of the high strength cast alloys for high temperature vane and blade applications and can be used in polycrystalline, directionally solidified and monocrystalline forms. The study of Maurer et al. (4) was on Waspaloy, which is a high sales volume, moderate strength wrought alloy used as turbine disks. The compositions and the γ' fractions of the three alloys are given in Table I. As can be seen, together they span the γ' volume fraction spectrum, and hence, the elevated temperature strength spectrum of today's superalloys.

The common strategy for studying the cobalt effect in nickel-

Table I: Nominal Compositions of Several Nickel-Base Superalloys*

	% γ'		Ni	Co	Cr	Al	Ti	Mo	W	Ta	Hf	B	Zr	C
Waspaloy[4]	20	w/o	58	13.5	19.5	1.3	3.0	4.3				.006	.06	.08
		a/o	56	13.0	21.4	2.7	3.6	2.6				.03	.04	.38
Udimet 700[2]	45	w/o	53	18.5	15.0	4.3	3.5	5.2				.030		.08
		a/o	50	17.4	16.0	8.8	4.1	3.0				.15		.37
Mar-M247[3]	55	w/o	60	10.0	8.2	5.5	1.0	0.6	10.	3.	1.5	.020	.09	.16
		a/o	61	10.1	9.2	12.2	1.2	0.4	3.	1.	0.5	.11	.06	.79

*From the International Nickel Company, Inc. Handbook on "High Temperature, High Strength Nickel-Base Alloys," 1979.

base superalloys is to systematically replace cobalt by nickel. Processing and experimental procedure details for the results discussed below are published elsewhere (2).

2. PARTITIONING AND PHASE EQUILIBRIA

2.1 Partitioning of Cobalt

In Udimet 700, in situ STEM/EDS microchemistry analysis of the γ' and γ phases has shown that cobalt partitions to the matrix (2); see Table II. The concentration of cobalt in the matrix was found to be about 2.5 times that in the γ' precipitate for the coarse grained, fully solutioned alloys and approximately 3 times that in the γ' for the fine grained, partially solutioned alloys. This partitioning ratio did not vary with cobalt content. In the Mar-M247 study by Nathal and Maier (3), the γ' phase was electrolytically extracted from the matrix and its composition determined by emission spectroscopy. The partitioning ratio calculated from the volume fractions showed the matrix cobalt content was about 2 times the γ' content, again regardless of the alloy cobalt content. The partitioning ratio for Waspaloy (4), as determined from SEM/EDS analysis of extracted γ', was found to be roughly 4. These partitioning ratios are consistent with the values cited much earlier by Kriege and Baris (5); see Table II.

Table II. Matrix Partitioning of Cobalt

Alloy		Partitioning Ratios from Kriege and Baris (5)
Udimet 700 (disk)	3.0 (2)	
Udimet 700 (blade)	2.5 (2)	2.8
Mar-M247	2.0 (3)	1.7*
Waspaloy	4. (4)	5.5

* This value is for the alloy Mar-M200, which is the
  sister alloy of Mar-M247.

Most commercial alloys contain between 10 and 20 percent cobalt (1). Hence, the γ cobalt content would usually range between 15 and 25 percent and the γ' would contain up to about 10% cobalt (5). The cobalt in the ordered γ' phase apparently substitutes for nickel (2,5,6), and when present in higher concentrations, it can also displace chromium (2,7). The solubility of cobalt in the γ' increases with temperature (8), and thus, the
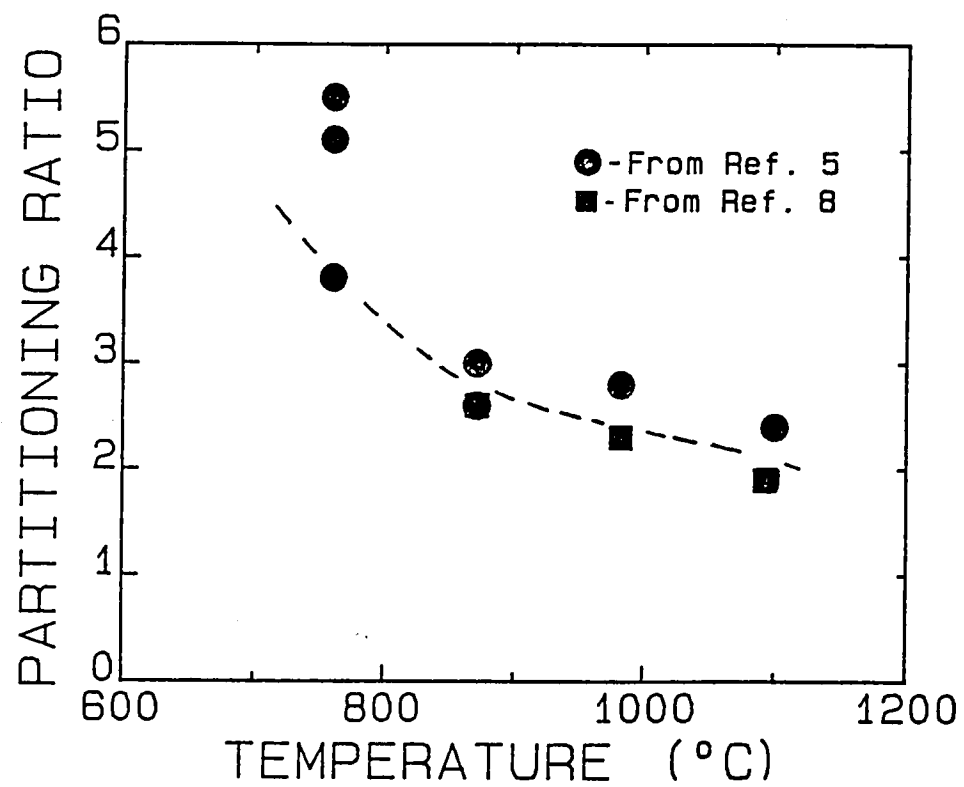
Fig. 1. Partitioning ratios of cobalt (w/o cobalt in γ: w/o cobalt in γ') versus temperature.

partitioning ratio between γ and γ' decreases with temperature. This trend is fairly alloy insensitive, and the γ:γ' cobalt partitioning ratio falls on a single curve as a function of the final aging temperature, Fig. 1.

2.2 The Effect of Cobalt on the Microchemistry of Other Alloying Elements

Maurer et al. (4) found that removing cobalt from Waspaloy decreased the γ' fraction from 18% in the standard alloy to 16 volume percent in the cobalt-free version. A smaller decrease of less than 1 volume percent was observed in Udimet 700 (2). In a 1964 paper (9), Heslop observed roughly a 5% increase in the γ' volume fraction of Nimonic 80A with the addition of 17% cobalt. Nathal and Maier (3) observed an 18% decrease in the complex alloy Mar-M247, as cobalt was completely removed.

We believe that this effect is related to cobalt's reducing the matrix solubility for other alloying elements. In this case cobalt has forced aluminum and titanium out of the γ solution, resulting in more γ'. The ternary Ni-Co-Al diagram, Fig. 2 (10,11), supports this conclusion. For example, adding 30% cobalt to nickel reduces the γ matrix solubility for aluminum from 6% to about 3% at 700°C. Furthermore, Heslop (9) used pseudo-binary phase diagrams of Al+Ti in a Ni-20Cr matrix and a Ni-20Cr-20Co matrix to explain the volume fraction effect in Nimonic 90. In the superposition of the two diagrams, Fig. 3, the Al+Ti solubility at 800°C can be seen to decrease from 1.8 w/o to 1.2 w/o with the addition of 20% cobalt to the matrix.

Indeed, this diagram illustrates that cobalt's effect in increasing volume fraction will be less, due to the lever rule, as the alloy's γ' volume fraction is more. This is consistent with the observed cobalt effect in Nimonic 80A/90, Waspaloy, and Udimet 700.

One additional solubility argument may help to explain the reduced effect of cobalt on volume fraction in the molybdenum containing alloys, Udimet 700 and Waspaloy. From Ni-Al-X ternary phase diagrams--where X is either chromium (12), titanium (12), molybdenum (13), or cobalt (10,11)--the third element is seen to always reduce the solubility of γ for aluminum. We maintain that the combined effects of many alloying elements would result in a greater reduction of the solubility for aluminum than cobalt alone. It is perhaps for this reason that the aluminum solubility at 800°C in the Ni-Co-Al ternary decreases 2.0% for a 20% cobalt addition (11), whereas the (Al+Ti) solubility decreases by only 0.8% for the same 20% cobalt addition to the Ni-Cr-Co-(Al+Ti) pseudo-binary diagram (9).
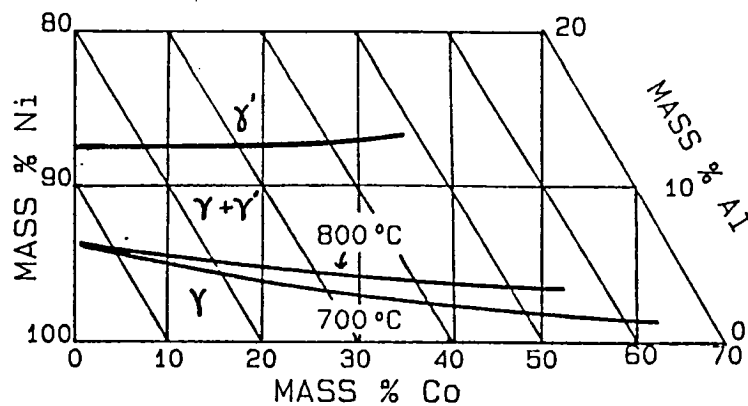
(a)
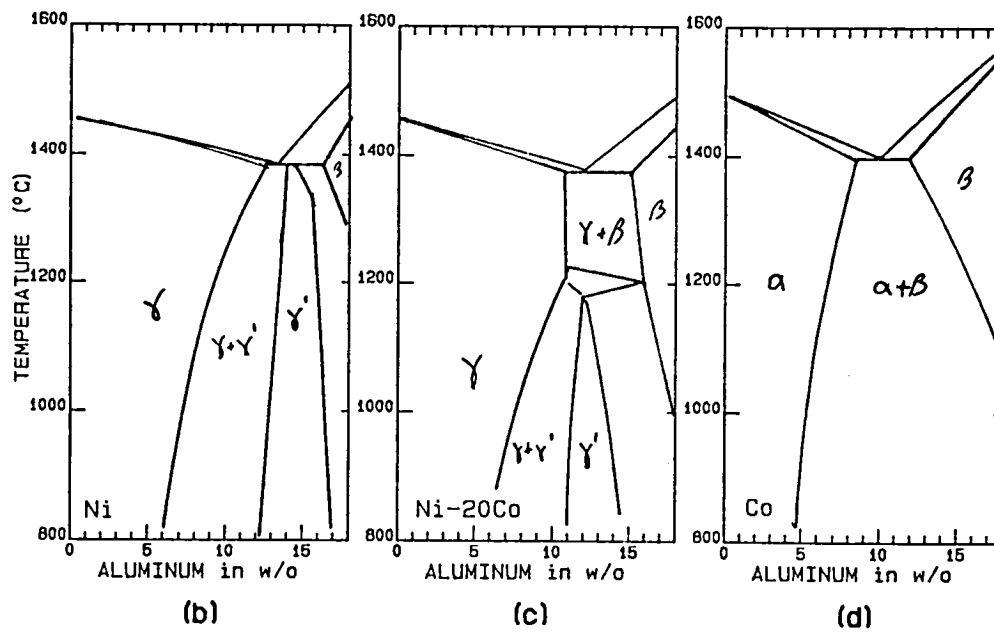
(b)

(c)

(d)

Fig. 2. The Ni-Co-Al ternary phase diagram. Fig. 2a shows a composite of isothermal sections at 700°C and 800°C from Davies et al.[11] Fig. 2b is the Ni-Al binary, Fig. 2c is the 80Ni-20Co compositional section, and Fig. 2d is the Co-Al binary.[10]
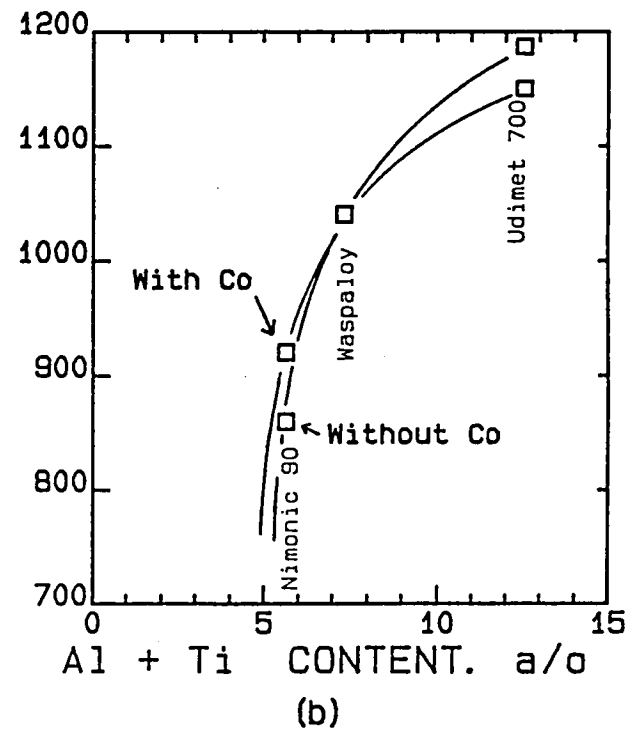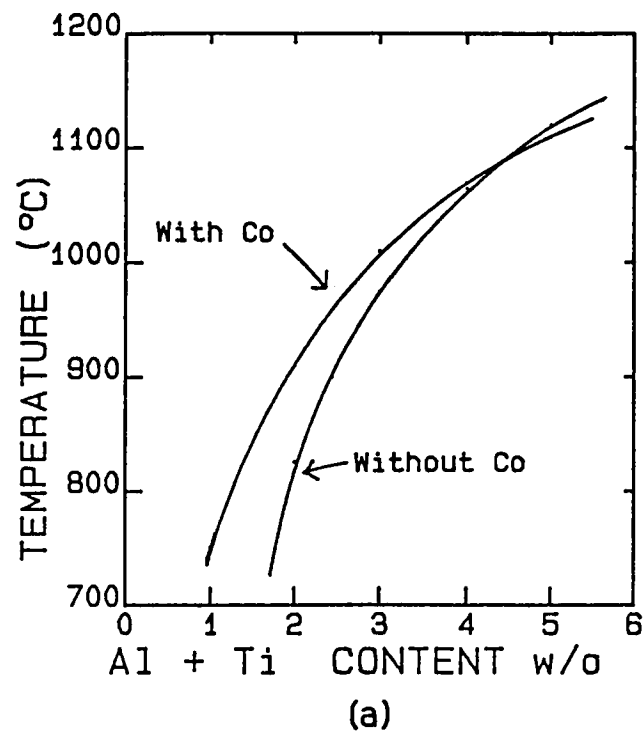
Fig. 3.   Pseudo-binary phase diagrams. Fig. 3a: Heslop's[9] pseudo-binary of the Ni-20Cr and
Ni-20Cr-20Co matrices. Fig. 3b: Composite from γ' solvus results.[2,4,9] In both
diagrams note that cobalt decreases the solubility of (Al+Ti) and in the higher γ'
volume fraction alloys cobalt decreases the γ' solvus temperature.

8.

The combined effect of additional components on the solubil-
ity of aluminum and the γ' fraction may also explain stress rupture
results of Peter et al. (14). In this study on the effect of
molybdenum on Nimonic 80A and Nimonic 90, they found that adding
4.5% molybdenum to both systems reduces the effect of cobalt on
the 750°C 100-hour or 1000-hour rupture stress by approximately
one-third.

2.3 Gamma Prime Solvus Effect

The γ' solvus in Udimet 700 increases by 35°C (2) when co-
balt is removed, Fig. 4a. Similarly, Nathal and Maier (3) found
the solvus in Mar-M247 increases by 30°C, Fig. 4b. In Waspaloy,
with a smaller γ' volume fraction, Maurer et al. (4) observed
that the solvus temperature is unaffected by cobalt. The γ'
solvus in Nimonic 90, with yet a smaller γ' fraction, is found
to decrease by 60°C when cobalt is completely removed (9).

This seemingly complicated solvus effect can also be explained
by the ternary Ni-Co-Al phase diagram, Fig. 2 (10). Since cobalt
and aluminum do not form a Co_3Al intermetallic, cobalt destabilizes
the Ni_3Al γ' when it substitutes for nickel, lowering the solution
temperature. Recalling that cobalt lowers the matrix solubility
for aluminum, a cross-over of the cobalt containing solvus and the
cobalt-free solvus must exist. Heslop's pseudo-binaries, Fig. 3,
illustrate this cross-over (9). Mar-M247 and Udimet 700 are in
the region with a large γ' fraction where cobalt decreases the
solvus temperature; Waspaloy is in the intermediate, cross-over
region; and Nimonic 90 is in the low volume fraction region where
cobalt raises the solvus temperature.

This γ' solvus effect of cobalt results in microstructural
changes in Udimet 700 during aging. For example, after the blad-
ing heat treatment, the fraction of fine, cubic γ' is larger and
the fraction of residual ultrafine γ' formed is much smaller in
the cobalt-free alloy than in a cobalt-containing alloy, Fig. 5.
After solutioning, both alloys were aged at 1079°C for 4 hours,
which produced cubic γ' roughly .3 μm to a side. At this aging
temperature, which is above the cross-over in the pseudo-binary
phase diagram, more γ' precipitates in the cobalt-free alloy. In
the remaining aging steps, less ultrafine γ' forms in this alloy
since the corresponding pseudo-binary boundary has a steeper tem-
perature dependence than the solvus boundary of the alloy contain-
ing cobalt.

In Udimet 700, although the aluminum and titanium solubil-
ities in the matrix at low temperatures are reduced by cobalt, at
temperatures above the cross-over (ca. 1000°C) the solubilities
are increased by cobalt. For this reason the values of the alum-
inum and titanium contents in the matrix determined by STEM/EDS

in Reference (2) show a trend of increasing solubility with cobalt content. STEM/EDS analysis of thin foils includes ultrafine γ' particles in the determination of the matrix composition.

Cobalt also affects the solidus temperature in these alloys. For example, as cobalt is completely removed from Udimet 700 (2), the solidus is observed to increase by approximately $10^{\circ}C$. Accordingly, the temperature range of solutioning decreases as cobalt is removed from Udimet 700. A similar trend was found for the higher γ' fraction Mar-M247 (3). This effect can potentially result in heat treatment problems when cobalt is removed from alloys which already have narrow solutioning ranges.

2.4 Phase Stability

Udimet 700 containing 17% cobalt exposed to $815^{\circ}C$ for 1000 hours resulted in the formation of ~1.5% feathery sigma phase (2). Alloys with 12.8% cobalt and 8.6% cobalt contained only about 1% sigma and a trace of sigma, respectively. No sigma phase formed in alloys with yet lower cobalt contents. This is not surprising since cobalt was previously determined to be a major constituent in the sigma phase in Udimet 700 (2,15) and in other superalloys (7,16).

Again the ternary and quaternary phase diagrams can describe the behavior seen in superalloys. Cobalt lowers the solubility of chromium and molybdenum in a nickel solid solution (17). The sigma phase that forms is based on a Co-Cr intermetallic.

PHACOMP (16,18), the semi-empirical method of forecasting sigma instabilities based on electron vacancy numbers, also predicts that cobalt will promote sigma instabilities. The electron vacancy number for cobalt is 1.71 compared to 0.66 for nickel. Thus, when cobalt replaces nickel in an alloy, the electron vacancy number is increased and the alloy is expected to be less stable with respect to sigma phase formation.

In a 1968 paper on Mar-M421, Lund et al. (12) observed sigma phase in cobalt-free 713C and in another experimental cobalt-free alloy. They also observed no sigma formation in three experimental alloys that contained cobalt to varying levels. On that basis they concluded that cobalt stabilized the alloys with respect to sigma instability. However, we maintain that such a conclusion cannot be made, since unfortunately the cobalt-free alloys also had more of the alloying elements tungsten, molybdenum, and columbium as well as aluminum and titanium. These elements promote sigma formation (19).

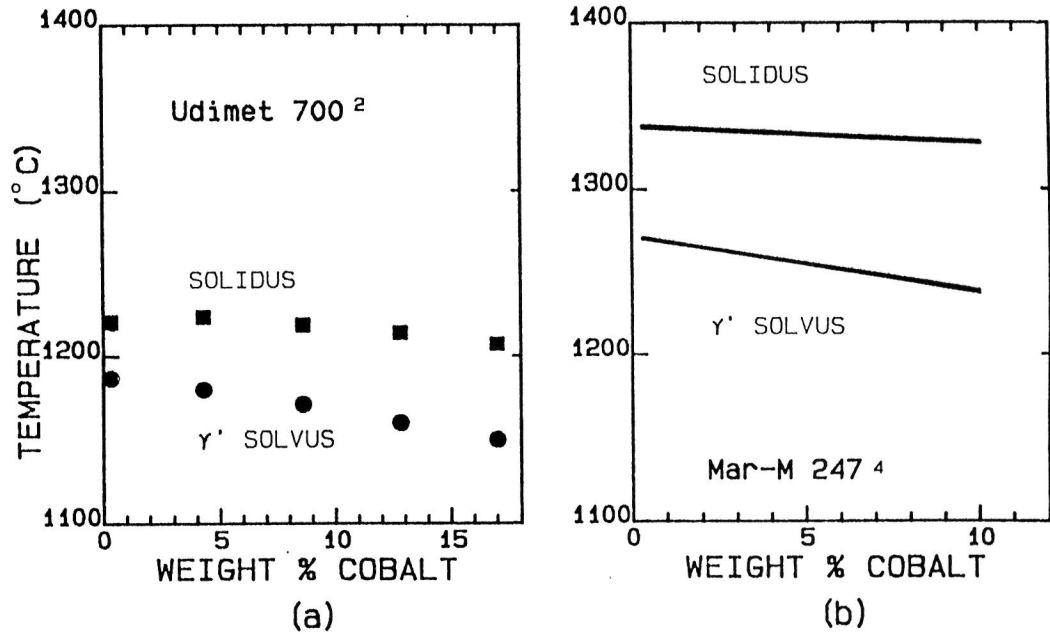The effect of cobalt on the coarsening of γ' in Udimet 700

Fig. 4. γ' solvus and solidus temperatures versus cobalt content for (a) Udimet 700[2] and (b) Mar-M247.[3]
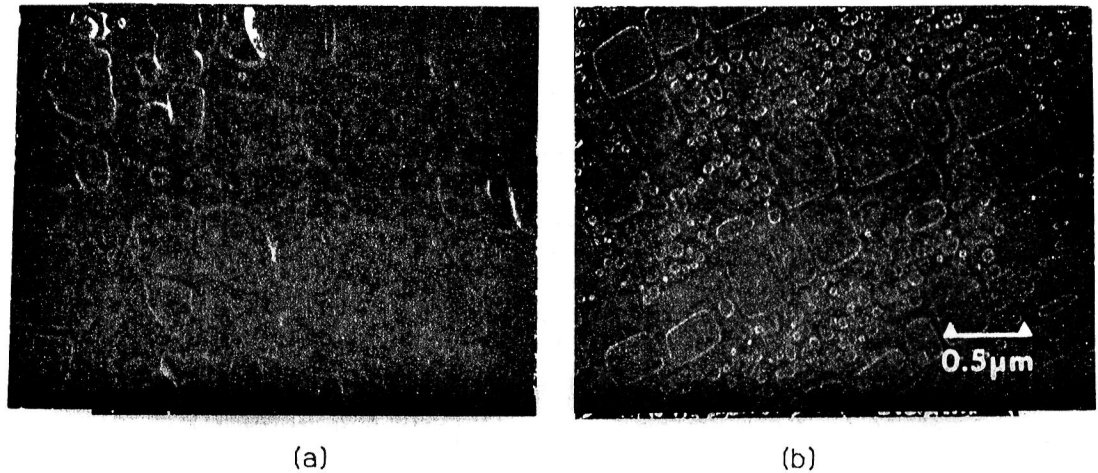

Fig. 5. SEM micrograph of blade heat treated Udimet 700, showing more cubic γ' and less ultrafine γ' in the cobalt-free alloy (a) than the 17 w/o cobalt-containing alloy (b).

(2,20) was shown to be negligible for the disk (fine-grained) material at 815°C and also for fully solutioned material with homogeneously nucleated γ' particles coarsened at 982°C. The γ' in the cobalt-free blade heat treated material aged at 982°C developed a rod-like appearance as the particles coalesced. This behavior was not observed in the cobalt-containing alloys. The effect of such shape changes in properties has not been examined. The insensitivity of γ' coarsening kinetics to cobalt content is believed to be due to the small effect which cobalt has on γ' misfit in the Udimet 700-type alloy (2).

2.5 Carbides

Although cobalt is not a constituent in either the MC-type or in the $M_{23}C_6$-type carbide in Udimet 700 (2,15), it plays a major role in the relative stabilities of these carbides. Titanium-rich MC forms as the primary carbide in Udimet 700, and during alloy aging additional chromium-rich $M_{23}C_6$ carbides precipitate at the grain boundaries. In cobalt-free Udimet 700, predominantly primary $M_{23}C_6$ forms in the lower solution temperature (disk-type) heat treatment. No additional grain boundary carbides form even after a 1000 hour exposure at 815°C (2). These primary $M_{23}C_6$ carbides can be dissolved in the full-solutioning blade-type heat treatment, with grain boundary carbides precipitated during aging. The resulting cobalt-free Udimet 700 microstructure is very similar to the standard alloy except that there are fewer MC-type carbides and more of the stable $M_{23}C_6$-type carbides.

Maurer (4) also found that removing cobalt destabilizes MC in Waspaloy so that more grain boundary $M_{23}C_6$ forms during aging. Likewise, Nathal and Maier (3) observed more grain boundary carbides in lower cobalt and cobalt-free Mar-M247.

In $M_{23}C_6$ carbon combines with roughly four times as many metal atoms as in MC carbides. Accordingly, a fourfold increase in the volume fraction of carbides can result if $M_{23}C_6$ becomes the predominant primary and secondary carbide. In cobalt-free Udimet 700 containing only 0.07 w/o carbon such excesses in carbides are seen as stringers. Although these carbide stringers did not hinder the hot workability of lower cobalt and cobalt-free Udimet 700 (2), an excess of primary carbides can result in decreased workability in superalloys with generically higher carbon content. Interestingly, Heslop (6) showed that removing cobalt from Nimonic 115-type alloys (which normally contain .15 w/o carbon) reduced their hot ductility in the workability-simulating hot twist tests.

2.6 Solid Solution Effects of Cobalt

As discussed above, cobalt in solid solution reduces the solubility of the other alloying additions. In the γ matrix, cobalt

is expected to contribute little to direct strengthening since its atomic misfit is only 1% in nickel. Not surprisingly, in Udimet 700 (2), Waspaloy (4), and Mar-M247 (3), the effect of cobalt on yield strength is minimal (see below).

In creep deformation where the effect of stacking fault energy on thermally activated recovery by climb or cross-slip is important (21), cobalt in the matrix may play a significant role (22). In Ni-Co binary alloys, Beeston et al. (23) showed that the adding of 30% cobalt resulted in the lowering of the stacking fault energy (γ_{SFE}) by about 50%. Whether cobalt would decrease the SFE of a complex superalloy matrix to the same extent is uncertain at this time (22-24).

3. MECHANICAL BEHAVIOR

3.1 Tensile Behavior

The average room temperature tensile and yield strengths of Udimet 700 and Waspaloy (based on duplicate tests) are presented in Fig. 6 as a function of cobalt content (2,4). Examples of elevated temperature tensile properties of Waspaloy and Mar-M247 are compared in Fig. 7 (3,4) for discussion purposes. In all cases the strength dependence on cobalt is extremely slight. No more than a 10% decrease in the strengths is observed when cobalt was removed completely from Waspaloy and from the disk heat treated Udimet 700 (2,4). Blade heat treated Udimet 700 basically showed an invariance of yield strength with cobalt content (2). In the Mar-M247 case, the strengths show a slight but discernible peak at one-half the standard cobalt level.

Ham and Brown's equation (25), which recognizes both the bowing between and the cutting of coherent γ' precipitates, apparently can satisfactorily explain the yield strength results for all three alloys where,

$$\Delta\tau_y = (\Gamma_{APB}/2b)[(4\Gamma_{APB}r_0f/\pi\phi)^{\frac{1}{2}}-f] \qquad (1)$$

$\Delta\tau_y$ is the difference in yield strength between $\gamma+\gamma'$ and the γ phase, Γ_{APB} is the APB energy, b is Burger's vector, r_0 is the average γ' size, f is the volume (or weight) fraction of γ', and ϕ is the strain energy of the mobile dislocations bowing between and/or cutting through the coherent γ' precipitates. In the case of disk heat treated Udimet 700, a quantitative analysis was performed (2). The conclusion was that the slight drop in strength as cobalt is removed can be attributed to the observed decrease in the volume fraction of the fine, strengthening γ' precipitates. Conversely, the invariance in strength with cobalt after the fully solutioning, blade-type heat treatment is consistent with the ob-
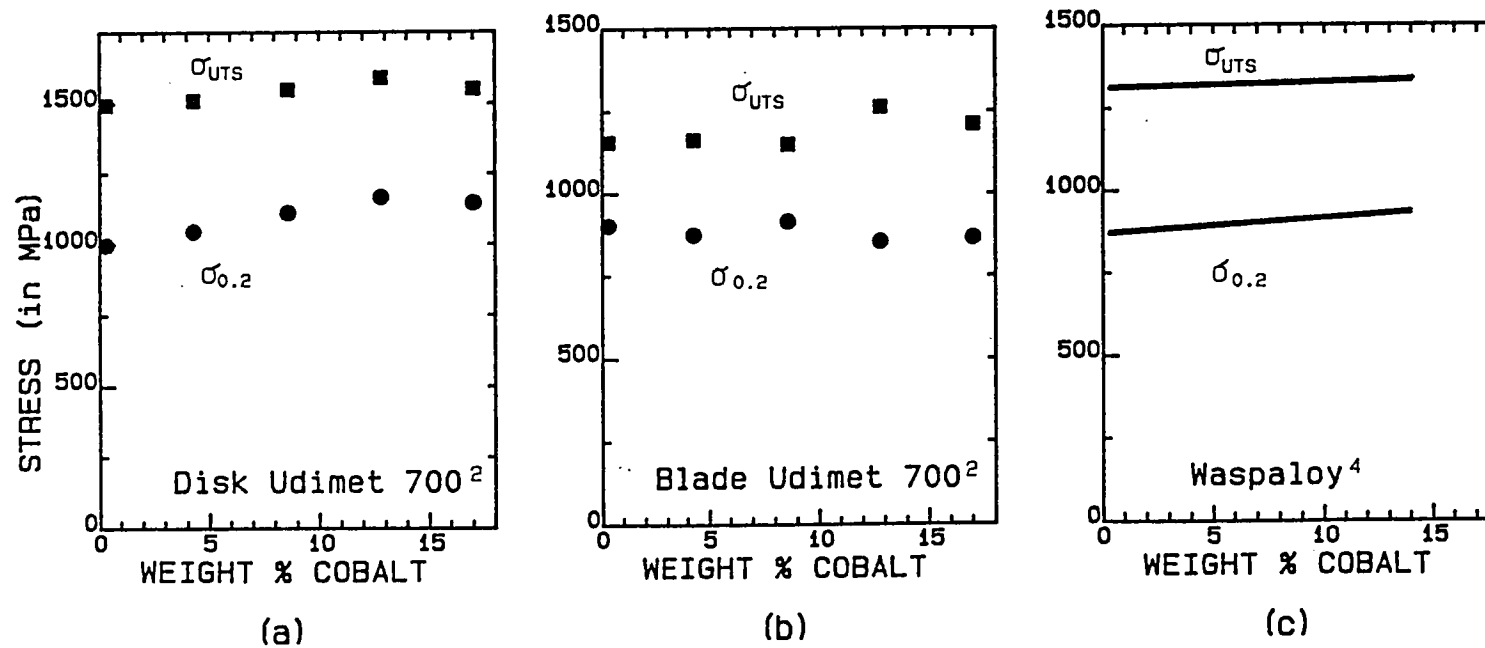
Fig. 6. Room temperature tensile properties of Udimet 700[2] [both (a) blade and (b) disk heat treated] and Waspaloy[4] as a function of cobalt content.
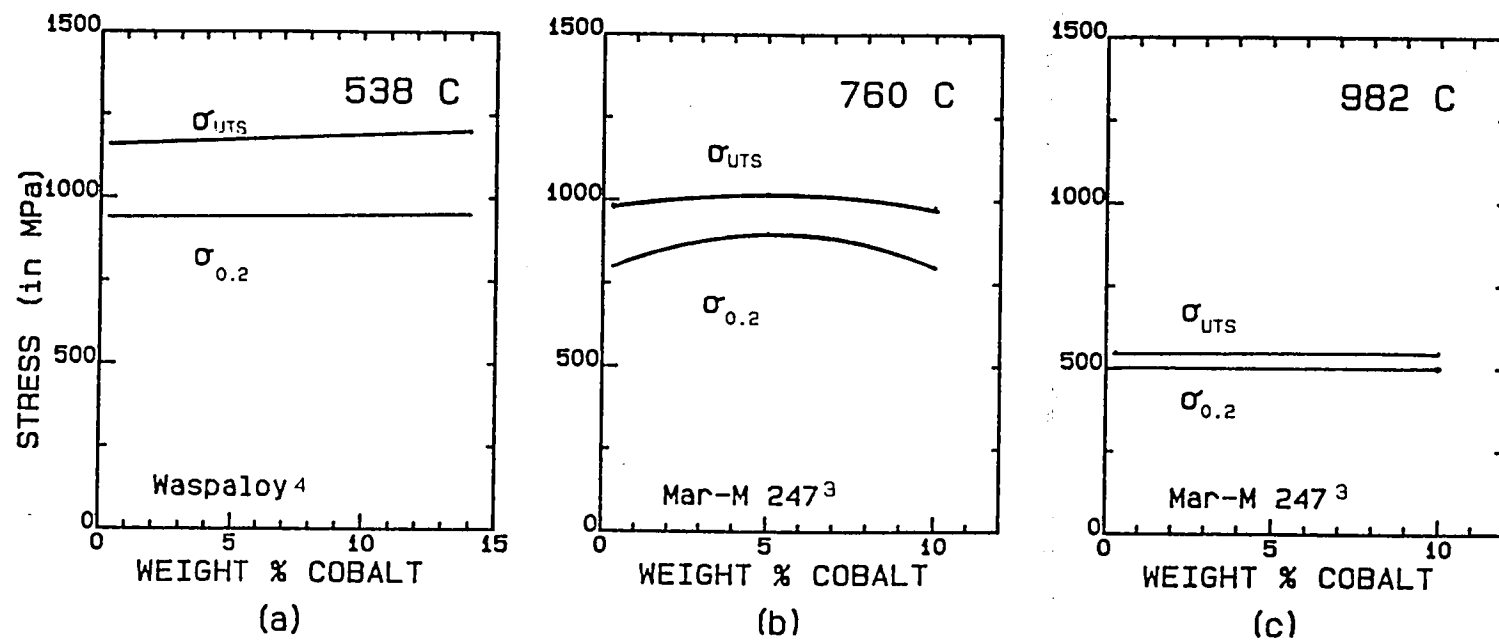
Fig. 7. Elevated temperature properties of (a) Waspaloy[4] at 538°C and Mar-M247[3] at (b) 760°C and (c) 982°C.

served invariance of the strengthening γ' fraction with cobalt after this treatment. Volume fraction dependence can likewise explain the observed yield strength trend in Waspaloy. Equation (1) also can qualitatively explain the slight strength peak observed at the intermediate cobalt level in the high γ' volume fraction Mar-M247 (3). Nathal and Maier (3) observed the opposing trend of the γ' APB strengthener tungsten increasing in the γ' and the volume fraction of γ' decreasing as cobalt was removed from the alloy. Equation (1) would predict a strength maximum at intermediate cobalt levels for such element partitioning and phase equilibria behavior. Interestingly, Nathal and Maier observed no peak at 982°C (3). This is consistent with the decrease in the effectiveness of APB's at temperatures above 800°C.

Earlier studies on cobalt effects also show the relative insensitivity of strength on cobalt content. For example, the yield strength of a Soviet high strength nickel-base superalloy was observed to be insensitive to cobalt content (26). Generally, it is tempting to conclude that increasing cobalt content has a small effect in increasing γ' fraction and that through a parabolic relationship (see Eq. (1)) this small effect is translated to an even smaller impact on yield strength. Furthermore, for a chemically well-endowed alloy, such as the tungsten containing Mar-M247, where γ' precipitate cutting and Γ_{APB} can be the predominant strengthening mode, the effect of increasing cobalt content on decreasing the solubility of, say, tungsten in the γ' precipitates can in effect counterbalance any positive γ' fraction effect.

The tensile ductility of all three alloys is found also to be either invariant or only marginally dependent on cobalt content. In Udimet 700, there is a slight increase in ductility as cobalt is increased above 8.6 w/o (2). The increase in ductility, although resolvable, is small--from about 9% to 13% in the coarse grain material and from about 22% to 28% in the fine grain material. Maurer et al. (4) observed basically no effect of cobalt on room temperature and elevated temperature tensile ductilities. Nathal and Maier found no trends between tensile ductility and cobalt over the temperature range of 649°C to 982°C.

The slightly lower ductilities in Udimet 700 may be related to the previously discussed increase in carbide inclusion fraction as the cobalt content in the alloy is decreased by more than one-half the initial content (2). More systematic analysis on tensile fracture and crack initiation behavior is needed before any firm conclusions can be made.

3.2 Creep and Stress Rupture

The minimum creep rates and stress rupture lives of Udimet 700 and Mar-M247 are summarized as a function of cobalt content in
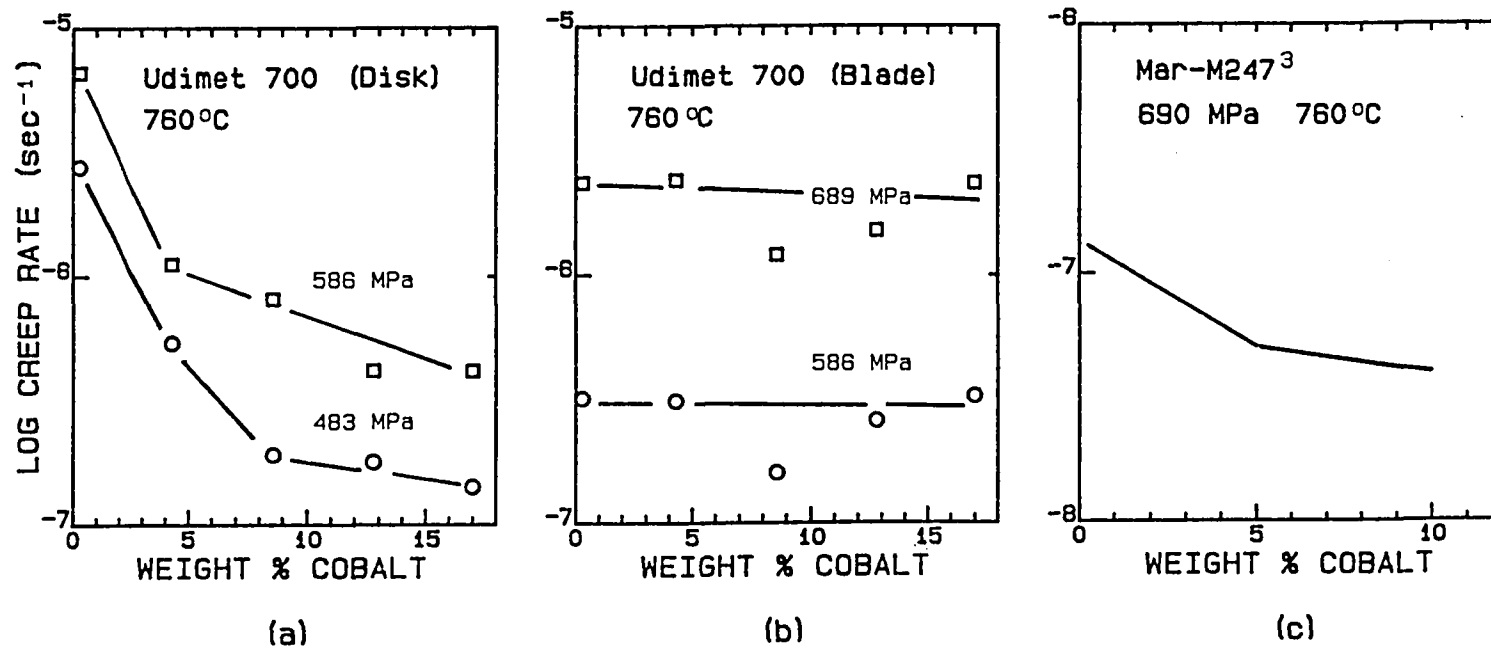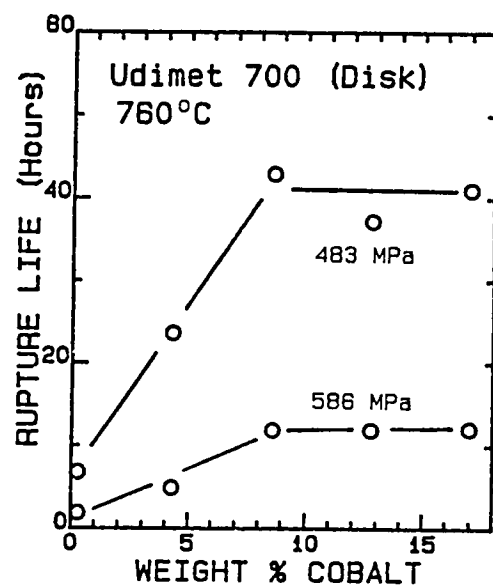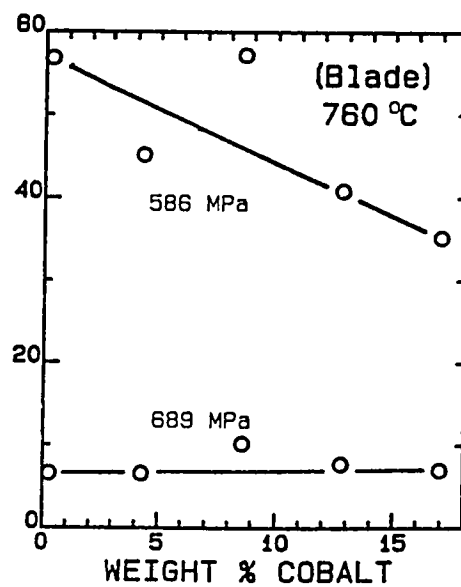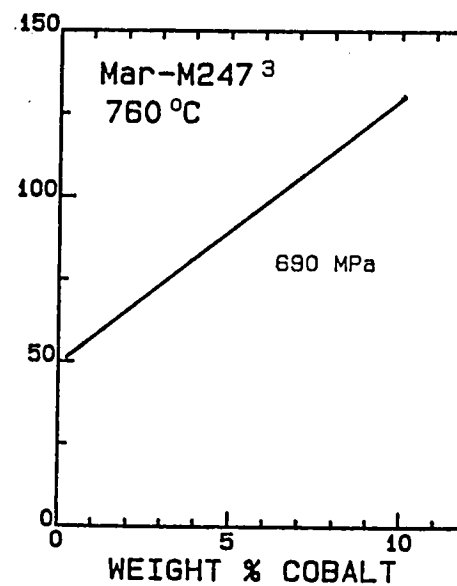
Fig. 8. Minimum or steady state creep rates of Udimet 700[2] [both (a) disk and (b) blade] and and Mar-M247[3] at 760°C.

Fig. 9.   Stress Rupture Life of Udimet 700[2] [both (a) disk and (b) blade] and Mar-M247[3] at 760°C.

Figs. 8 and 9. The creep and stress rupture resistance of Waspaloy, like those of Mar-M247 (3) and the disk heat treated Udimet 700 (2), decreases when cobalt is removed (4). We have concluded that cobalt effects on creep resistance can be accounted for by the modified creep equation developed for superalloys (2,22)

$$\dot{\epsilon}_m = A'(\gamma_{SFE})^4\{[\sigma - \sigma_p(f)]/E\}^4 \exp[-(Q_o/RT)]\qquad(2)$$

where $\dot{\epsilon}_m$ is the minimum creep rate, γ_{SFE} is the already defined stacking fault energy, σ is the applied stress, $\sigma_p(f)$ is the particle contribution to creep resistance and is a function of γ' volume fraction, E is Young's Modulus, Q_o is the true activation energy for creep or self-diffusion, A' is an alloy constant, and RT has the usual meaning. As can be seen, creep resistance, and corresponding stress rupture resistance (since rupture lives are generally inversely proportional to minimum creep rates in superalloys), increases when either γ_{SFE} decreases or the volume fraction of γ' increases.

By analyzing the creep results of Udimet 700 after the disk-type heat treatment and the blade heat treatment, respectively, it was concluded that cobalt's effect on γ' volume fraction, and not on γ_{SFE}, affected creep and stress rupture resistance as cobalt was removed (2), the argument being that the γ matrix composition, and hence γ_{SFE}, was not affected by the two solutioning temperatures that distinguish blade heat treatment from disk heat treatment, but that they did affect cobalt's effect on the fraction of the strengthening γ' precipitates. In particular, cobalt was determined not to affect the strengthening γ' fraction after the blade-type heat treatment, consistent with the observed insensitivity of creep rates to cobalt content, but after the disk-type heat treatment, the strengthening γ' was determined to have decreased from about 36% to 29%, which was considered sufficient to lower the creep resistance (or increase the creep rate) by the observed one order of magnitude (2,27,28). For the case of the lower γ' fraction Waspaloy, Maurer et al. argued that volume fraction alone could not fully account for the decrease in creep resistance as cobalt was fully removed from the alloy, but that γ_{SFE} had to play a role (4). Nathal and Maier argued that in the very high γ' fraction Mar-M247 case, the observed threefold increase in creep rates as the cobalt was removed was due to the observed decrease in the γ' fraction (3). That the observed large decrease in γ' fraction, from 59% to 41%, causing only a threefold maximum increase in creep rates is perturbing given the Udimet 700 results, where a smaller strengthening γ' fraction decrease, from 36% to 29%, resulted in a tenfold increase in creep rates. The rationalization of this apparent inconsistency may rest either in an error in γ' fraction determination or in that for the high γ' fraction, cast alloys creep is not as sensitive to γ' fraction since γ' cutting would be the predominant strengthening mode and
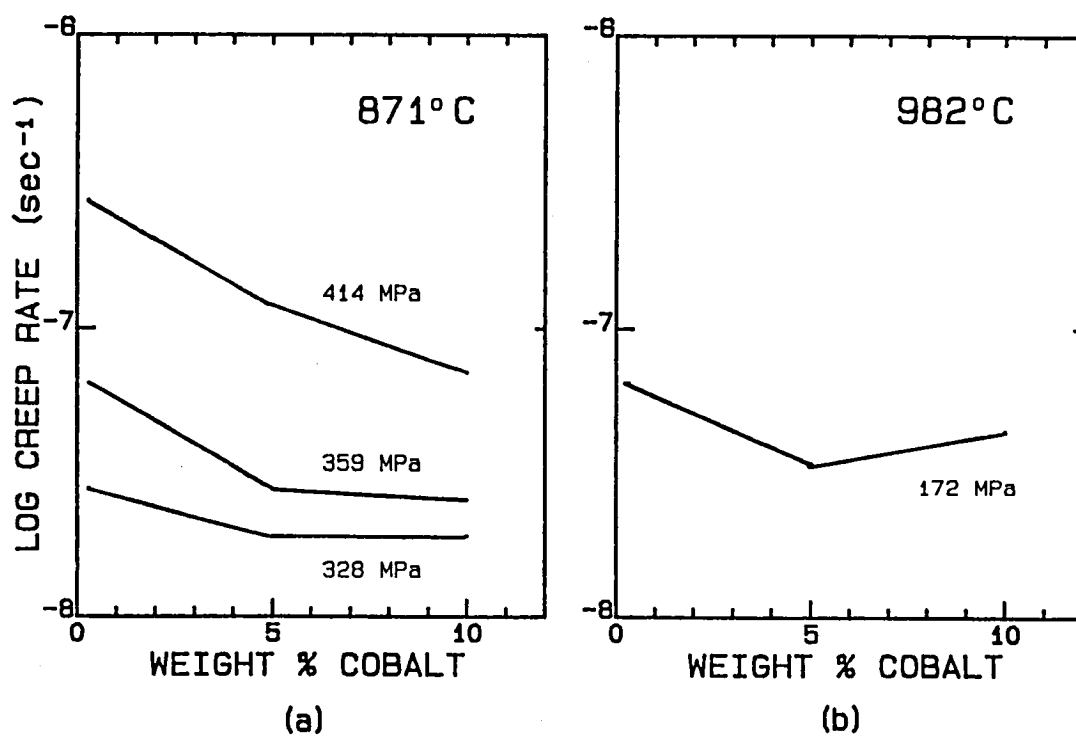
Fig. 10. Creep Rates of Mar-M247[3] at (a) 871°C and (b) 982°C.

that such cutting would occur at both the high end and the low end of the observed γ' fractions in Mar-M247. Whereas, in Udimet 700, the bowing mechanism would be sensitive to the γ' fraction ranges observed in the cobalt-containing and cobalt-free alloys.

The results of Nathal and Maier also show that at the highest temperature (about 982°C), the cobalt effect decreases to less than twofold (3), see Fig. 10. This is consistent with earlier Japanese observations (29), where cobalt was seen not to affect creep and stress rupture in a high strength nickel-base superalloy, also at about 982°C. The observations that cobalt can enhance creep and stress rupture resistance at lower temperatures also are consistent with results from earlier studies (30,31).

Stress rupture ductilities are observed to be very insensitive to cobalt content for all three of the recently studied alloys (2-4). In Udimet 700, this is the case in spite of the higher volume of carbides at the grain boundaries of the lower cobalt and cobalt-free alloys and the feather-like sigma phases in the higher cobalt alloys (2). The extra grain boundary carbides may account for the slightly higher stress rupture resistance of the cobalt-free Udimet 700 after the blade heat treatment.

In general, it appears that cobalt's effect on creep and stress rupture resistance can be much more pronounced than its effect on tensile properties. However, the Udimet 700 experience also demonstrates that appropriate heat treatments can replace the positive role of cobalt in promoting creep and stress rupture resistance.

4. CONCLUDING REMARKS

This paper discusses the role of cobalt in Udimet 700, which is a representative nickel-base superalloy nominally containing 17% or more cobalt. The study spanned the spectrum of micro-structural, microchemical, and mechanical behavior aspects, which together form a basis for superalloy performance in jet engines. The single most significant result is that cobalt's role in the alloy is extremely subtle, and hence, difficult to discern. It impacts on the partitioning of the elements between the γ matrix, γ' precipitate, and carbide phases, but only slightly so. The resultant enhancement of the strengthening γ' volume fraction is small so that it does not significantly affect tensile properties, even when all the cobalt in the alloy is replaced by nickel, which is the alloy-base metal and the nearest chemical and physical kin to cobalt. Depending on the details of the heat treatment, cobalt is seen to promote creep and stress rupture resistance. However, even there the appropriate heat treatment can result in no cobalt effect. Indeed, an interesting conclusion is that the optimum

Udimet 700 wrought, blade-type alloy is one which contains no cobalt instead of the standard Udimet 700 which contains at least 17% cobalt.

Less subtle is the discovery that in the alloy studied, and in two other recently studied nickel-base superalloys, cobalt promotes fewer carbides by stabilizing the MC-type carbides instead of the $M_{23}C_6$-type carbides. This implies that lowering cobalt content in nickel-base superalloys may result in the need to lower carbon content. There are reported indications that, in alloys with generically higher carbon content, workability may be affected when cobalt is lowered with no attendent modification of carbon levels. Cobalt is also seen to widen the solid solution temperature range. Accordingly, it may come to pass that lowering cobalt content may reduce the heat treatability of certain nickel-base superalloys.

In terms of long-term alloy stability, we present results and arguments that show cobalt can have a destabilizing effect instead, as previously believed, of the stabilizing effect on sigma phase formation. Also, for the alloy studied, it appears that cobalt plays a small role in γ' coarsening.

Certainly, the effects of cobalt on other properties such as high cycle fatigue, low cycle fatigue, thermal fatigue, and oxidation and hot corrosion, require determination and understanding. Such studies are under way. Furthermore, the subtle effects of cobalt on fine and ultrafine γ' precipitation and their effects on elevated temperature mechanical properties require further study.

5. ACKNOWLEDGMENTS

6. REFERENCES

1. J.K. Tien, T.E. Howson, G.L. Chen and X.S. Xie: 1980, Journal of Metals, Vol. 32, No. 10, pp. 12-20.

2. R.N. Jarrett and J.K. Tien: 1982, Met. Trans. A, Vol. 13A, No. 6, pp. 1021-1032.

3. M.V. Nathal and R.D. Maier: 1981, NASA Report No. NASA CR-165384, pp. 104.

4. G.E. Maurer, L.A. Jackman and J.A. Domingue: 1980, "Superalloys 1980," ed. J.K. Tien et al., pp. 43-52.

5. O.H. Kriege and J.M. Baris: 1969, Trans. ASM, Vol. 62, pp. 195-200.

6. R.W. Guard and J.H. Westbrook: 1959, Trans. Met. Soc. AIME, Vol. 215, pp. 807-814.

7. C.H. Lund, M.J. Woulds and J. Hockin: 1968, "Structural Stability in Superalloys," ed. by Joint Committees of ASTM, ASME, ASM and AIME, pp. 25-46.

8. E.H. Van der Molen, J.M. Oblak and O.H. Kriege: 1971, Met. Trans., Vol. 2, No. 6, pp. 1627-1633.

9. J. Heslop: Sept. 1964, Cobalt, Vol. 24, pp. 128-137.

10. J. Schramm: Dec. 1941, Z. Metallkunde, Vol. 33, pp. 403-409.

11. C.K.L. Davies, P. Nash, R.N. Stevens: 1980, J. Mat. Sci., Vol. 15, pp. 1521-1532.

12. A. Taylor: Oct. 1956, Trans. AIME, Vol. 206, pp. 1356.

13. V. Ya. Markiv, V.V. Burnashova, L.I. Pryakhina and K.P. Myasnikova: 1969, Iz. Ak. Nauk SSSR, Met., No. 5, pp. 180-185.

14. W. Peter and H. Müller: 1965, Archiv für das Eisenhüttenwesen, Vol. 36, No. 11, pp. 835-841.

15. W.J. Boesch and H.B. Canada: Apr. 1968, Journal of Metals, Vol. 20, No. 4, pp. 46-50.

16. L.R. Woodyatt, C.T. Sims and H.J. Beattie, Jr.: Apr. 1966, Trans. Met. Soc. AIME, Vol. 236, pp. 519.

17. S.P. Rideout and P.A. Beck: 1953 NACA Report No. 1122.

18. W.J. Boesch and J.S. Slaney: July 1964 Metal Progress, Vol. 86, No. 1, pp. 109-111.

19. J.R. Mihalisin, C.G. Bieber and R.T. Grant: Dec. 1968, Trans. AIME, Vol. 242, pp. 2399-2414.

20. F. Cosandey, T.J.T. Tang, C. Cheng, R.N. Jarrett and J.K. Tien, "The Effects of Cobalt on γ' Coarsening Kinetics and Microchemistry in Udimet 700,' to be published.

21. C.R. Barrett and O.D. Sherby: 1965, Trans. Met. Soc. AIME, Vol. 233, pp. 1116-1119.

22. X.S. Xie, G.L. Chen, P.J. McHugh and J.K. Tien: May 1982, Scripta Met., Vol. 16, pp. 483-488.

23. B.E.P. Beeston, I.L. Dillamore and R.E. Smallman: 1968, J. Met. Sci., Vol. 2, pp. 12-14.

24. B.E.P. Beeston and L.K. France: 1968, J. Inst. Metals, Vol. 96, pp. 105-107.

25. L.M. Brown and R.K. Ham: 1971, "Strengthening Mechanisms in Crystals," ed. A. Kelly and R.B. Nicholson, pp. 12-135.

26. N.F. Lashko, O.A. Khromova, A.A. Burmistrova and N.I. Zhuravleva: 1970, "Structure and Properties of Heat-Resistant Metals and Alloys," ed. M.V. Pridantsev, pp. 200-204.

27. V. Lupinc and T.B. Gibbons: 1978, "High Temperature Alloys for Gas Turbines," ed. D. Coutsouradis et al., pp. 335-358.

28. J.J. Jackson, M.J. Donachie, R.J. Henricks and M. Gell: 1977, Met. Trans. A, Vol. 8A, pp. 1615-1620.

29. R. Watanabe and T. Kuno: 1976, Trans. Iron and Steel Inst. Jap., Vol. 16, pp. 437-446.

30. J. Heslop: 1962/1963, J. Inst. of Metals, Vol. 91, pp. 28-33.

31. A.M. Borzdyka: Nov-Dec. 1977, Metal Science and Heat Treatment, Vol. 19, pp. 937-939.

1. Report No. NASA CR-168308	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Effects of Cobalt in Nickel-Base Superalloys		5. Report Date December 1983
		6. Performing Organization Code
7. Author(s) John K. Tien and Robert N. Jarrett		8. Performing Organization Report No. None
		10. Work Unit No.
9. Performing Organization Name and Address Columbia University Center for Strategic Materials Henry Krumb School of Mines New York, New York 10027		11. Contract or Grant No. NAG 3-57
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code 505-33-1A

15. Supplementary Notes

16. Abstract

The role of cobalt in a representative wrought nickel-base superalloy was recently determined. The results show cobalt affecting the solubility of elements in the γ matrix, resulting in enhanced γ' volume fraction, in the stabilization of MC-type carbides, and in the stabilization of sigma phase. In the particular alloy studied, these microstructural and microchemistry changes are insufficient in extent to impact on tensile strength, yield strength, and in the ductilities. Depending on the heat treatment, creep and stress rupture resistance can be cobalt sensitive. In the coarse grain, fully solutioned and aged condition, all of the alloy's 17% cobalt can be replaced by nickel without deleteriously affecting this resistance. In the fine grain, partially solutioned and aged condition, this resistance is deleteriously affected only when one-half or more of the initial cobalt content is removed. The structure and property results are discussed with respect to existing theories and with respect to other recent and earlier findings on the impact of cobalt, if any, on the performance of nickel-base superalloys.

17. Key Words (Suggested by Author(s)) Superalloys Cobalt Nickel Substitution	18. Distribution Statement Unclassified - unlimited STAR Category 26		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 25	22. Price* A02

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

SPECIAL FOURTH CLASS MAIL
BOOK

NASA

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return