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The Response of Cobalt-Free Udimet 700 Type Alloy to Modified Heat Treatments

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SUMMARY

Udimet 700 is a nickel base alloy containing 17 percent cobalt, 15 percent chromium, 5 percent molybdenum, 4 percent aluminum and 3.5 percent titanium. In order to conserve cobalt, almost all of which is imported from foreign sources, an alloy in which all of the cobalt had been substituted for by nickel was prepared in wrought and in hot isostatically pressed powder metallurgy (HIP-PM) form. In a previous study it had been observed, that the mechanical properties of this material were nearly equal to the Udimet 700 with 17 percent cobalt, while alloys with cobalt contents intermediate between 17 and 0 percent generally exceeded the mechanical properties of the 17 percent cobalt alloy. It was also observed that in the 0 percent cobalt alloy ultrafine, 20 nm, γ' particles were less numerous than in the 17 percent cobalt alloy. It was felt that this microstructure and the resulting mechanical properties could be improved by modifying the heat treatment. The original heat treatment consisted of a sequence of partial solutioning at 1145 °C followed by aging in four steps at 870, 980, 650 and 760 °C. In order to increase the quantity of ultrafine particles, the second step of aging was raised to 1030 and to 1050 °C. HIP-PM material which had been given the 1030 °C aging step displayed mechanical properties generally equal to those of the originally heat treated material, except in the important creep rupture tests at 650 °C. Here at a stress of 825 MPa, rupture life was increased from an average 221 to 268 hr and minimum creep rates decreased from 4.3×10^{-8} to 2.7×10^{-8} s^{-1}. This advantage persisted, to a lesser degree at a stress of 900 MPa. At 760 °C, the new heat treatment resulted in properties comparable to the original heat treatment. Aging at 1050 °C produced coarser ultrafine particles, and no mechanical property improvements.

The creep rupture properties at 760 °C of wrought cobalt-free Udimet 700 were significantly improved by heat treatment modification. When the second aging step was raised to 1030 or 1050 °C rupture lives at 475 and 450 MPa were from about 3 to 8 times longer and minimum creep rates up to 10 times lower.

A comparison of the test data shows that with the modified heat treatments the properties of the cobalt-free alloy can be made to closely approach those of standard Udimet 700 with 17 percent cobalt.

The results also signify that the heat treatment of a 0 percent cobalt Udimet 700 type alloy should be designed with its ultimate application in mind and that perhaps even for the 17 percent cobalt Udimet 700 alloy properties could be more closely fitted to the eventual use if heat treatments were modified. It is also suggested that the lower cost cobalt-free modification of Udimet 700 be considered for commercial applications. But the effect of modified heat treatments on other properties, such as fatigue resistance, must be also taken into consideration.

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INTRODUCTION

Cobalt is extensively used in superalloys. But the United States is almost entirely dependent on imports for its supply. Therefore cobalt has been designated a critical strategic material and has become the subject of efforts to reduce its consumption in superalloys (refs. 1 and 2).

Among the superalloys where a reduced cobalt content would be particularly rewarding is Udimet 700[1], which contains 17 weight percent cobalt. This nickel-base alloy is heat-treatable and has a microstructure of about 45 percent γ' phase in a γ phase matrix. Udimet 700 is used as a cast plus wrought (CW) product in aircraft gas engine turbine blades and turbine disks and as a hot isostatically pressed powder metallurgy (HIP-PM) product in turbine disks. The role of cobalt in this alloy was examined in the COSAM (Conservation Of Strategic Aerospace Materials) Program (ref. 1). Alloy modifications were produced in which the cobalt content had been reduced to 12.7, 8.5, 4.3, and 0 percent and replaced by nickel. The alloys were prepared in the CW and HIP-PM conditions.

The CW alloys were investigated under NASA sponsorship at Columbia University (ref. 3). A portion of the material was heat treated for use in turbine blades, where operating temperatures usually exceed 760 °C. This heat treatment fully solutions the γ' phase, promotes grain growth, and then reprecipitates the γ' phase as fine particles, evenly distributed throughout the matrix. Tensile and creep rupture tests at 760 °C showed that alloys at all cobalt levels had nearly equal properties.

Another portion of the CW alloys was given heat treatments suitable for turbine disks, allowing a direct comparison with properties obtained at the NASA Lewis Research Center on HIP-PM alloys (ref. 4). The initial partial solutioning heat treatment for disks maintains the original grain size by "pinning" the grain boundaries with coarse γ' particles. The partial solutioning treatment is followed by a sequence of aging heat treatments at four different temperatures to produce an even distribution of fine and ultrafine γ' particles throughout the matrix. The disk type heat treatments given the various alloy compositions by Jarrett and Tien to CW materials (ref. 3) and by Harf to HIP-PM materials (ref. 4) are shown in table I. Tensile tests of the CW alloys at room temperature and of the HIP-PM alloys at room temperature and 650 °C showed that the alloys at all cobalt levels had fairly equal strengths and ductilities. However, their creep rupture properties were dependent on the cobalt content. The HIP-PM alloys tested at 650 °C with 825 and 900 MPa stress displayed rupture life maxima in the 8.5 percent cobalt compositions; lives for the 17 and 0 percent cobalt alloys were nearly equal and minimum creep rates increased at the lower cobalt levels. At 760 °C the HIP-PM alloys with intermediate cobalt levels again had the longest rupture lives, while those of the CW alloys remained nearly equal for cobalt contents of 17, 12.7, and 8.5 percent and then decreased drastically at lower cobalt levels. Again, at this temperature, the minimum creep rates increased as cobalt contents decreased. A preliminary conclusion, based on these results, was that for turbine disk applications, the cobalt in Udimet 700 could safely be reduced to between 8.5 and

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[1]Udimet 700 is a trademark of Special Metals Corporation.

4.3 percent, and that the properties of the alloy would then be at least equal to those of the original composition.

Microstructural observations further suggested that modifying the aging treatments for the cobalt-free alloy might result in properties equivalent to those of Udimet 700 with 17 percent cobalt. For example, the major microstructural difference between alloys at the various cobalt levels which had been given the disk type heat treatment was the amount of ultrafine γ' present. This is evident in the transmission electron micrographs of figure 1, which show γ' particles extracted from HIP-PM alloys with 17, 8.5, and 0 percent cobalt. Fine (about 100 nm) and ultrafine (about 20 nm) particles can be seen, with the relative quantity of ultrafine particles decreasing with the decrease in cobalt content. This variance in microstructure relates to the increase in the thermal gap or temperature difference between the γ' solvus and the highest temperature at which these alloys were aged (980 °C), presented in table II. Van der Molen, Oblack and Kriege (ref. 5) experimentally confirmed that volume fraction and particle size of the γ' precipitate in Udimet 700 are a function of temperature and time. The volume fraction of γ' increases with the thermal gap while the size of the particles depends on the length of time of exposure at a given temperature. When more γ' is tied up in fine particles fewer ultrafine particles can later be formed by aging at 760 °C because less γ' remains dissolved in the matrix.

It therefore appears, that there is a direct correlation between heat treatment, microstructure and mechanical properties. The size of the ultrafine γ' particles is probably suited to impede the movement of dislocations through the matrix which govern deformation at 650 °C. But the enhanced rupture properties at intermediate cobalt levels also suggest that resistance to dislocation motion does not benefit from what may be an excess of ultrafine particles in the higher cobalt content alloys. Therefore, a study was initiated with the objective to obtain a controlled increase in the quantity of ultrafine γ' particles in the cobalt-free Udimet 700 composition and to thereby enhance the mechanical properties of the alloy so as to make it a more acceptable substitute for the Udimet 700 containing 17 percent cobalt.

This study comprised designing and applying modified heat treatments to the cobalt-free alloy. The material was then subjected to mechanical tests and microstructural examinations.

EXPERIMENTAL PROCEDURE

Materials and Heat Treatments

The cobalt-free CW and HIP-PM alloy used in this work was the product of the same master melt. Separate chemical analyses were run and are presented in table III. The CW material (ref. 3) was cast into 10 cm round ingots, vacuum arc remelted and then cast as 15 cm round ingots. These were then cogged and hot rolled into plate 6 cm wide by 2 cm thick. The HIP-PM material (ref. 4) was produced from argon atomized powder which had been hot isostatically pressed at 1210 °C for 3 hr. The material in the present study comprised what remained after requirements for the more extensive test programs (refs. 3 and 4) had been satisfied and was therefore limited in quantity.

All heat treatments were performed in air. The specimens were quenched in oil after partial solutioning while aging treatments were followed by air cooling.

Mechanical Tests

Mechanical tests were performed in air and in accordance with applicable ASTM recommended procedures. Test specimens are shown in figure 2. The crosshead speed for the tensile tests at room temperature and 650 °C was 0.5 mm/min. Creep rupture tests at 650 and 760 °C used linear variable differential transformers, anchored in grooves machined on the shoulders of the test specimens to detect linear extensions which were transmitted to a computer for processing into strain and creep rate measurements and data storage. The creep data reported here are times to failure, to 1 and 2 percent total strain (inelastic plus elastic strain, including strain on loading) and minimum creep rates.

Some comparisons are made with creep data obtained at 760 °C by Jarrett and Tien (private communication). It should be noted that the gage of their test specimens was 12.7 mm long and 3.2 mm in diameter (ref. 3), while for the present tests these dimensions were 30 and 5 mm, respectively (fig. 2).

MATERIAL CHARACTERIZATION

Specimens for metallographic examination were ground and then polished to 0.5 μm finish. For optical examination, the γ' was preferentially dissolved by a solution of 33 percent hydrochloric acid, 33 percent acetic acid, 33 percent water and 1 percent hydrofluoric acid. Specimens for transmission electron microscopy were thinned in a methanol solution with 7 percent perchloric acid and 20 percent butanol.

The volume fraction of large γ' particles, remaining after partial solutioning was measured by point counting of scanning-electron-micrographs at 10 000 x magnification, in conformance with ASTM standard recommended practice E562. Point counting could not be used for determining volume fractions of fine and ultrafine γ' particles, because the shallow depressions from which particles had been etched out could not be distinguished from the matrix. Therefore, for fully aged materials, weight fractions of the total γ' content were determined from phase extractions. The γ' phase was extracted by dissolving the γ phase electrolytically in a solution of 1 percent citric acid and 1 percent ammonium sulfate in water at a current density of 0.075 A/cm^2. Weights were determined for the solid specimens before and after the extraction, and for the γ' residue collected by filtration.

RESULTS

Selection of Heat Treatments

In the original concept of comparing the properties of Udimet-700 type alloys with decreased cobalt levels, the comparison was made with a minimum of change in heat treatment between the various compositions. A major compromise in the disk-type heat treatments had been to adjust the partial solutioning temperature to maintain a nearly constant temperature difference from the γ'

solvus, in particular in the HIP-PM alloys, as can be seen from tables I and II (Refs. 3 and 4). For the present work with cobalt free alloy the partial solutioning temperature of 1145 °C was again chosen for the HIP-PM material and also used for CW material where in the previous program of Jarrett and Tien it had been 1129 °C (ref. 3). These original heat treatments designated A and AW for HIP-PM and CW alloy respectively, are listed in table IV.

The four-step aging heat treatment was the same for all CW and HIP-PM alloys in the original studies (refs. 3 and 4). This aging heat treatment can be divided into two sequences each comprised of a lower temperature to induce nucleation and a higher temperature to promote the growth of γ' particles. The sequence of 870 and 980 °C (table I) produced the fine γ' particles of an average size of 100 nm while the ultrafine particles of about 20 nm formed during heat treating at 650 and 760 °C. The ultrafine particles grew from the residual γ' dissolved in the γ matrix. Their quantity decreased noticeably with decreasing cobalt content (fig. 1). This can be explained on the basis of the increase in the thermal gap between the γ' solvus temperature and the maximum aging temperature (table II). As the thermal gap increases, less γ' remains dissolved in the γ matrix and available for precipitation as ultrafine particles. This is in accord with figure 3 adapted from the work by Van der Molen, Oblack, and Kriege (ref. 5). The referenced Udimet 700 had a total γ' volume fraction of 38 percent and was of a composition somewhat different from that used in the present work where 47 percent of the total weight was γ'. The γ' solvus of the 17 percent cobalt content alloy (ref. 4), as measured by DTA, was 1150° versus 1132 °C for the alloy in reference 5 and 1188 °C for the 0 percent cobalt alloy.

From table II the thermal gaps for the 17 and 0 percent alloys are 170 and 208 °C, respectively. Assuming that the relative proportions of γ' precipitate conform to those shown in figure 3 (ref. 5), one finds that with a thermal gap of 170 °C the volume fraction of γ' is 33 percent. In the example shown in figure 3 the maximum γ' volume fraction was 38 percent; hence the 33 percent represents 33/38 or 86.8 percent of the γ' that can be formed. This leaves about 13 percent of the γ' available for precipitation as ultrafine particles. However in the cobalt free alloy with a thermal gap of 208 °C 36 percent of the available γ' should have been precipitated in the first two steps of the aging heat treatment. This means that only about 5 percent of the total γ' remains available for forming ultrafine particles. The ultrafine particles formed in the 17 percent alloy should then be 2-1/2 times more numerous than in the cobalt-free alloy and this is in general agreement with the microstructural differences observed between the two compositions (figs. 1(a) and (c)). A maximum aging temperature of 1030 °C was therefore chosen for heat treatment B (table IV); this represents a thermal gap of 160 °C, or slightly less than the 170 °C employed in the heat treatment of the 17 percent cobalt alloy. It was expected that amounts of ultrafine γ' particles equal or greater than those found in the 17 percent cobalt alloy of reference 4 would be formed by heat treatment B of table IV. The time of exposure at 1030 °C was set to 2 hr in order to maintain a γ' fine particle size equal to that obtained in the earlier work (fig. 10 in ref. 5).

While the second aging step controls the amount of γ' left in solution, the first step, apart from inducing nucleation, also can cause discrete $M_{23}C_6$ particles to form within grains and grain boundaries. In view of the low carbon content of the cobalt-free alloy, few such particles should form, so that two heat treatments, C and D, were chosen in which step 1 was omitted. The

thermal gap for heat treatment D was 140 °C and it was chosen so that more γ' would remain in solution for formation of ultrafine γ' particles.

A series of screening tests were run to determine the creep rupture behavior at 650 °C where strengthening by γ' particles should be most effective because failures are transgranular. (At 760 °C, due to grain boundary slip, intergranular failures are more normal.) Earlier tests had shown that the alloy with the 17 percent cobalt content, which had the lowest minimum creep rate, did not display the longest rupture life at 650 °C (ref. 4). As shown in figure 4 definite rupture life maxima occurred in the alloy with 8.5 percent cobalt under stresses of 825 and 900 MPa. The thermal gap for this alloy was 190 °C. Heat treatment F (table IV) has a thermal gap of 190 °C.

Specimens given heat treatments B, C, D, and F were tested at 650 °C in creep rupture with 825 MPa stress. The results are presented in table V along with the data for the 0 percent cobalt alloy originally tested in reference 4 (heat treatment A). The specimens with heat treatment B (160 °C thermal gap) showed the greatest improvement over the original specimens. On the basis of rupture life, time to 1 and 2 percent strain, minimum creep rate, and ductility, heat treatment B was selected for more extensive mechanical tests. Heat treatment F (190 °C thermal gap) did not show much improvement and was dropped from further testing.

Compared to heat treatment A, the specimens in which the first step of the aging heat treatment had been omitted (heat treatments C and D) had better rupture lives and minimum creep rates with adequate ductility. The time for total strain to 1 and 2 percent was good with heat treatment D, but poor with heat treatment C. It appeared that the omission of step 1 aging in heat treatment C had resulted in reduced mechanical properties compared to heat treatment B. This fact suggested that adding step 1 aging to heat treatment D should result in superior properties. A new combination, designated G in table IV, was therefore selected as an additional heat treatment for more extensive mechanical tests. Heat treatments B and G also were chosen for testing the CW material. As in the previous tests the final two aging steps remained the same as in references 3 and 4.

Mechanical Tests

Tensile test results for heat treatments B and G and comparative data for the HIP-PM alloy as originally tested in reference 4 are presented in table VI. These tests, performed at room temperature and at 650 °C showed that there was no great differences in ultimate and yield strengths for the three types of heat treatment. However, the elongations were greater for heat treatments B and G than for heat treatment A (ref. 4) and while the reductions of area were similar at room temperature in all three conditions, they were lower for the B and G specimens at 650 °C.

As shown by the creep rupture test results at 650 °C, summarized in table V and figure 5, specimens with heat treatment B had the best combination of properties under 825 and 900 MPa stress. This heat treatment resulted in an improvement over the original heat treatment A in time to failure, as well as times for 1 and 2 percent total strain. The minimum creep rate was reduced by about one-fourth (fig. 6) and ductility remained adequate. Specimens with heat treatment G had an inferior response, their times to failure, to 1 and to

2 percent total strain, as well as the minimum creep rate essentially equaled those of the alloy with the original heat treatment A. Heat treatment G under 825 MPa stress was also inferior to D from which it had been derived.

The creep rupture test results at 760 °C, summarized in table VII and figure 7 indicate in that for the HIP-PM alloy neither heat treatment B nor G represents an improvement over the original heat treatment. It should be noted that grain boundary sliding dominates at 760 °C and that the heat treatments were not aimed at altering the grain boundary conditions. In contrast, the rupture test results of the CW material, seem to indicate a substantial improvement. But it should be recalled that the heat treatment for the CW material in addition to changing the aging heat treatment also raised the partial solutioning temperature by 16 °C over that which was given the original material (ref. 3). Furthermore, the testing of specimens of different dimensions in another laboratory could have had some influence on the performance of the material.

Microstructures

The microstructure of partially solutioned HIP-PM cobalt free alloy is shown in figure 8. The material was essentially 100 percent dense and had an ASTM grain size number of about 6.5 with a mixture of recrystallized and unrecrystallized grains with some residual prior particle boundaries (fig. 8(a)). The large partially solutioned γ' particles of nearly 1 μm in diameter were present mostly as ogdoadic clusters (fig. 8(b)) with no concentrations in grain boundaries. These undissolved particles occupied about 13.5 volume percent of the sample (ref. 4). Higher magnification transmission electron microscopy revealed outlines of very fine γ' particles or their precursors measuring from about 50 nm to probably under 1 nm in diameter (fig. 8(c)).

The shapes of the undissolved γ' particles in the partially solutioned CW material were more irregularly shaped (fig. 9). Many measured over 3 μm in cross section, they were often located in grain boundaries and occupied about 18 volume percent of the sample.

The microstructures after the various aging heat treatments are shown by scanning electron micrography in figure 10. The microstructure of the original aging heat treatment A (ref. 4) displayed many rows of contiguous fine γ' particles about 100 nm in diameter in addition to ogdoadic clusters of partially solutioned γ' (fig. 10(a)). The higher, 1030 °C, temperature of the second aging step in heat treatment B resulted in fewer rows of fine particles which averaged about 200 nm in diameter (fig. 10(b)). Eliminating the first aging step (heat treatment C) greatly reduced the number of fine γ' particles which again approached 200 nm in size (fig. 10(c)). The microstructure after heat treatment D (fig. 10(d)), in which the first aging step had been omitted and the second step raised to 1050 °C, was not much different from that of heat treatment C in the quantity and size of the fine γ' particles. After heat treatment F (fig. 10(e)), in which 1000 °C was the second aging temperature, the microstructure closely resembled that of the "standard" heat treatment A, with numerous rows of particles in the 100 nm range. Heat treatment G, which combined the first aging step with the highest (1050 °C) aging temperature in step 2, produced the fewest fine particles of about 200 nm (fig. 10(f)) cross section.

Figure 11 compares the ultrafine particles, of between 10 and 50 nm in diameter produced by the various heat treatments. Raising the aging temperature of the second step from 980 to 1030 °C in heat treatment B resulted in a considerable increase in ultrafine, 10 to 20 nm particles (fig. 11(b)), compared to the original heat treatment A (fig. 11(a)). The particles after heat treatment C were even more numerous, and of the same size (fig. 11(c)). The ultrafine particles, observed when step 1 had been omitted and step 2 raised to 1050 °C, (heat treatment D) were less numerous than after heat treatment C, and also larger, measuring mostly 20 to 30 nm in cross section (fig. 11(d)). Aging at the lower step 2 aging temperature of 1000 °C (heat treatment F) resulted in numerous particles measuring about 10 nm. Finally, combining step 1 aging with 1050 °C in step 2 (heat treatment G), produced a mixture of particles ranging from 10 to 50 nm (fig. 11(f)).

DISCUSSION

The cobalt-free variation of Udimet 700 has little tendency toward supersaturation in the undercooled state. As can be seen in figure 8, the γ matrix of the alloy, oil quenched from the partial solutioning temperature of 1145 °C, had rejected the γ' which formed extremely fine particles which could sometimes be resolved at x100 000 magnification.

Aging at elevated temperature has two effects. First, as shown in figure 3, any temperature increase produces partial solutioning of the γ' in the γ matrix. Second, some fine γ' particles undergo diffusion-controlled coarsening at rates that are functions of time and temperature (ref. 5). By aging the alloys through two temperature sequences, each consisting of a nucleation and a growth step, two distinct sizes of particles form from the γ' precursor shapes in the matrix. Since the higher temperature of the first sequence essentially causes a partial solutioning, the dissolved γ' reconstitutes itself during air cooling. This does not account for the larger γ' particles produced in heat treatments D and G. The second step of the aging treatment took place at 1050 °C and was followed by air cooling. This suggests that during cooling the material passed too slowly through the elevated temperature range which induced more particle growth and deprived the structure of sufficient nuclei for proper strengthening by ultrafine 20 nm particles in aging through the 650 to 760 °C sequence (fig. 11(d) and (f)). The absence of the ultrafine particle strengthening resulted in the lower than expected properties obtained with heat treatment D and G. It can be argued that had the specimens been given a more rapid quench after aging step 2, the formation of the less than ultrafine particles would have been suppressed and heat treatments D and G would have produced better properties.

On the whole, heat treatment B yielded results superior to heat treatment A. Tensile yield and ductility in room temperature tests exceeded the original test results for HIP-PM 17 and 4.3 percent cobalt content alloys (table VI and ref. 4). At 650 °C the improvement persisted with good ductility and while strength of the 0 percent cobalt alloy approached that of the 17 percent cobalt alloy it clearly exceeded that of the 4.3 percent cobalt alloy. The creep rupture properties of heat treatment B at 650 °C and 825 MPa were substantially improved over heat treatment A and the life of the 0 percent cobalt alloy now exceeded that of the 17 percent cobalt alloy (fig. 5). The single test result at 900 MPa is less suitable for comparisons. At 760 °C and 475 MPa there appeared to be no advantage for heat treatments B or G over heat treatment A

for the HIP-PM alloy. However, the few tests which could be performed with the CW material (table VII) showed that both heat treatments B and G produced substantial property improvements in creep rupture at 760 °C compared with the heat treatment used by Jarrett and Tien (ref. 3). Yet the properties were lower than those of the HIP-PM material.

Microstructurally there was now a striking similarity between the amounts of ultrafine γ' present in the HIP-PM 0 percent cobalt content alloy with heat treatment B (fig. 11(b)) and the alloys with 17 and 4.3 percent cobalt heat treated and tested previously (ref. 4). The structures of these alloys are shown in figure 12. Obviously control of the microstructure by heat treatment is essential in evaluating these alloys and in developing their optimum properties. The heat treatment should be designed to suit the application where feasible. This is practiced to some extent with Udimet 700 where different heat treatments are employed for turbine blades and for turbine disks. But the data obtained here suggest that further refinement of the heat treatment may be appropriate. For example the creep rates of the alloy with heat treatment B were superior in creep-rupture tests at 650 °C. But at 760 °C the specimens given heat treatment G showed improved promise. A heat treatment giving this material controlled, somewhat coarser ultrafine particles may be desirable for this temperature regime. Certainly the results obtained with the CW material point in this direction.

SUMMARY OF RESULTS

Mechanical properties and microstructures of a cobalt free modification of Udimet 700 were compared after applying different heat treatments. The heat treatments were intended for turbine disk applications and comprised partial solutioning and aging through a sequence of four different temperatures. Comparisons were made with an original heat treatment in which the second aging step was at 980 °C. It was found that:

A. In HIP-PM alloy,

1. Raising the temperature of the second aging step to 1030 °C improved the rupture life and creep resistance at 650 °C. This was attributed to the microstructure which contained an increased quantity of ultrafine, 20 nm, γ' particles.

2. Raising the temperature of the second aging step to 1050 °C was of no benefit. The ultrafine γ' particles, while more numerous, had often grown beyond a 20 nm size.

3. Omitting the first step of the aging heat treatment did not appear to improve creep rupture properties over the original heat treatment.

4. Creep rupture properties at 760 °C were not improved by raising the temperature of the second step of the aging heat treatment, since grain boundary sliding controls creep of Udimet 700 type alloys at this temperature.

B. In CW alloy, where the partial solutioning temperature had been changed to 1145 °C from 1129 °C, raising the temperature of the second aging step to 1030 or 1050 °C substantially increased the creep rupture life and decreased the creep rate at 760 °C.

CONCLUDING REMARKS

The heat treatment study conducted here, along with the work previously performed (refs. 4 and 5) substantiates that an alloy based on Udimet 700 in which all the cobalt has been substituted for by nickel is a viable superalloy for use in turbine disk applications. This statement applies to both the cast-and-wrought and the hot-isotatically-pressed prealloyed powder processed alloy. Jarrett and Tien (ref. 4) had previously reported that the alloy, when given a different heat treatment, might also qualify for use in turbine blades. It is suggested that this alloy be considered for future use in aerospace and land-based turbine applications. It also appears, that even for standard 17 percent cobalt Udimet 700, the potential for improving properties by heat treatment modifications should be explored.

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TABLE I. - HEAT TREATMENT SCHEDULES
FOR MODIFIED UDIMET 700 ALLOYS
(DISK TYPE)

(a) Partial solutioning: 4 hr at °C

Percent cobalt	CW	HIP-PM
17	1104	1104
12.7	1118	1118
8.5	1129	1130
4.3	1129	1138
0	1129	1145
Quench medium	Salt at 316 °C then air cool	Oil

(b) Aging for all alloys

870 °C	8 hr	air cool
980 °C	4 hr	air cool
650 °C	24 hr	air cool
760 °C	8 hr	air cool

(Refs. 3 and 4)

TABLE II. - THERMAL RELATION
OF HEAT TREATMENTS
[Maximum aging temperature, 980° C.]

Cobalt content, wt%	Gamma prime solvus, °C	Thermal gap, K
17	1150	170
12.7	1160	180
8.5	1170	190
4.3	1180	200
0	1188	208

TABLE III. - ANALYZED COMPOSITION OF COBALT-FREE UDIMET 700

	wt %							
	Co	Cr	Mo	Al	Ti	C	B	Fe
CW (ref. 3)	<0.1	15.1	5.0	4.00	3.5	0.06	0.025	0.11
HIP	0	14.9	5.0	4.12	3.51	0.06	0.019	0.10

TABLE IV. - HEAT TREATMENTS FOR COBALT-FREE UDIMET 700

°C-hr					
Heat treatment	Partial solution, oil quench	Aging steps, air cool			
		1	2	3	4
A (ref. 4)	1145-4	870-8	980-4	650-24	760-8
AW (ref. 3)[a]	[b]1129-4	870-8	980-4	650-24	760-8
B	1145-4	870-8	1030-2	650-24	760-8
C	1145-4	-----	1030-2	650-24	760-8
D	1145-4	-----	1050-1	650-24	760-8
E	1145-4	870-8	1000-3	650-24	760-8
F	1145-4	870-8	1050-1	650-24	760-8

[a]For wrought material.
[b]Quenched into salt at 316 °C, then air cooled.

TABLE V. - SUMMARY OF CREEP RUPTURE TEST RESULTS FOR HIP-PM COBALT-FREE UDIMET 700 at 650 °C

Stress, MPa	Heat treatment	Life, hr	Time, hr, for total strain of -		Minimum creep rate, s^{-1}	After rupture	
			1 percent	2 percent		Elongation, percent	Reduction of area, percent
825	A	188	5.2	60	$4x10^{-8}$	6.7	10.2
825	A	255	8.5	75	$4.7x10^{-8}$	7.1	3.7
825	B	239	45	133	$2.9x10^{-8}$	3.7	10.2
825	B	296	25	117	$2.5x10^{-8}$	3.3	19.4
825	C	254	<0.01	61	$3.1x10^{-8}$	3.4	10.2
825	C	256	1.8	73	$3.2x10^{-8}$	4.2	9.7
825	D	274	19	104	$3.1x10^{-8}$	5.0	10.2
825	D	236	14	81	$3.3x10^{-8}$	2.8	9.7
825	F	210	22	100	$3.1x10^{-8}$	1.7	7.6
825	F	263	8	78	$2.9x10^{-8}$	3.6	5.2
825	G	212	7	64	$3.8x10^{-8}$	4.4	7.8
825	G	195	6	51	$3.8x10^{-8}$	5.3	10.7
900	A	74	0.5	5.5	$1.6x10^{-7}$	7.8	10.7
900	B	87	<0.01	12.9	$1.2x10^{-7}$	19.6	16.3
900	G	62	2.5	11.6	$2.0x10^{-7}$	6.7	11.6

TABLE VI. - TENSILE TEST RESULTS FOR HIP-PM UDIMET 700 WITH THREE COBALT CONCENTRATIONS

Test temperature, °C	Heat treatment	Ultimate tensile strength, MPa	Yield strength, MPa	Elongation, percent	Reduction of area, percent
No Cobalt					
25	A	1405	966	11.4	13.5
		1385	957	12.0	16.3
	B	1405	985	19.6	16.3
	G	1405	973	19.6	16.4
650	A	1222	895	12.5	19.9
		1171	858	13.1	16.8
	B	1240	900	21.7	13.6
	G	1208	884	20.1	10.6
Cobalt content, 17 percent					
25	Ref. 4[a]	1440	967	16.5	21.2
650		1244	914	15.0	17.7
Cobalt content, 4.3 percent					
25	Ref. 4[a]	1335	969	10.5	13.5
650		1182	874	18.4	18.3

[a]Average results, 2 tests each.

TABLE VII. - CREEP RUPTURE TEST RESULTS FOR COBALT-FREE UDIMET 700 AT 760 °C

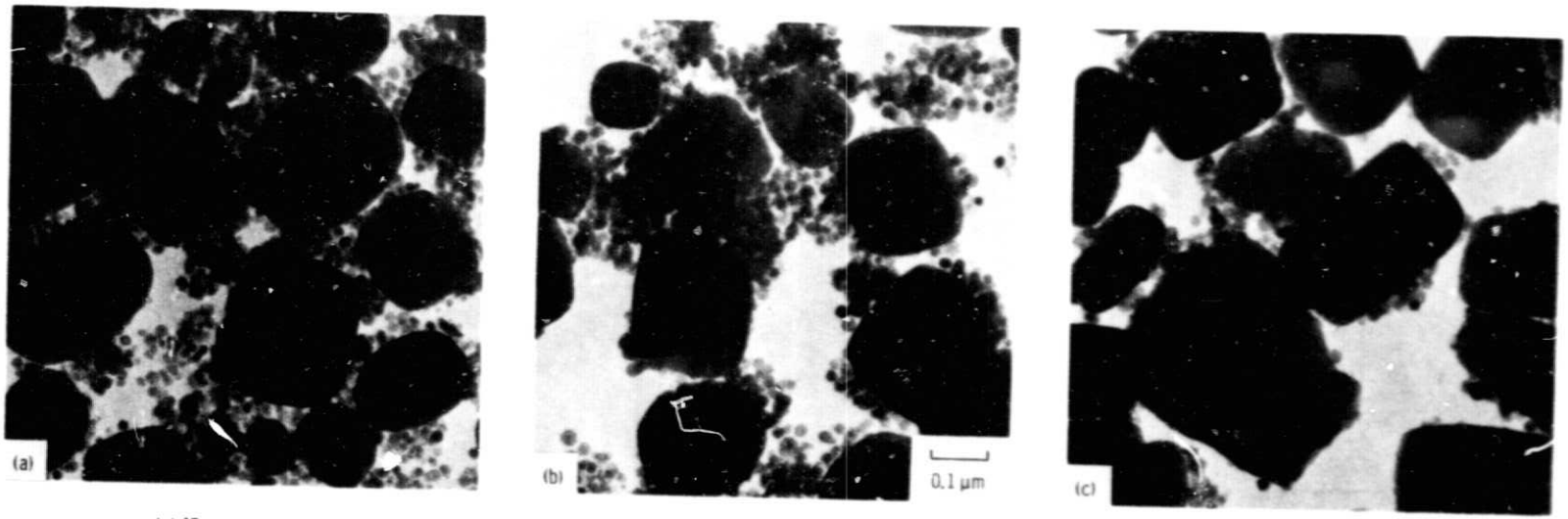
Stress, MPa	Heat treatment	Life, hr	Time, hr, for total strain of -		Minimum creep rate, s^{-1}	After rupture	
			1 percent	2 percent		Elongation, percent	Reduction of area, percent
HIP-PM							
475	A	50.7	19	42	9.2×10^{-8}	1.1	3.7
475	B	46.2	15	36	9.5×10^{-8}	4.9	3.9
475	G	43.5	8	34	8.4×10^{-8}	2.5	3.0
CW							
[a]483	AW	6.8			2.8×10^{-6}	15.0	
475	B	20.8	2.0	5.8	5.4×10^{-7}	17.5	16.8
475	G	36.3	4.1	13.5	2.7×10^{-7}	12.7	23.3
[a]448	AW	8.7			1.7×10^{-6}	15.5	
450	B	44.1	9.5	18.5	1.9×10^{-7}	15.0	23.1
450	G	66.0	5.7	20.7	1.6×10^{-7}	16.0	26.0

[a]Data furnished by Jarrett and Tien, Columbia University.

TABLE VIII. - COMPARISON OF AVERAGE CREEP RUPTURE BEHAVIOR FOR UDIMET 700 TYPE ALLOYS WITH VARIOUS COBALT CONTENTS

Test conditions		Cobalt content, percent	Heat treatment	Life, hr	Time, hr, for total strain of -		Minimum creep rate, s^{-1}	After rupture	
Temperature, C	Stress, MPa				1 percent	2 percent		Elongation, percent	Reduction of area, percent
HIP-PM									
650	825	17	(a)	251	124	200	1.1×10^{-8}	3.2	6.8
		4.3	(a)	381	27	86	2.0×10^{-8}	4.7	11.3
		U	A	222	6.9	67	4.3×10^{-8}	6.9	9.3
		0	B	268	35	125	2.7×10^{-8}	3.8	14.8
	900	17	(a)	62	~15	-----	4.3×10^{-8}	1.6	5.4
		4.3	(a)	96	5.5	25.2	1.1×10^{-7}	7.2	14.9
		0	A	74	0.5	5.5	1.6×10^{-7}	3.8	10.7
		0	B	87	0.1	12.9	1.2×10^{-7}	19.6	16.3
760	475	17	(a)	60.5	27	41	4.2×10^{-8}	4.1	5.4
		4.3	(a)	98.2	21	66	6.1×10^{-8}	2.4	4.0
		0	A	50.7	19	42	9.2×10^{-8}	1.1	3.7
		0	B	46.2	15	36	9.5×10^{-8}	4.9	3.9
CW									
760	483	17	(a)	41.0			1.4×10^{-7}	18.8	
	483	4.3	(a)	23.6			5.3×10^{-7}	19.9	
	483	0	(a)	6.8			2.8×10^{-6}	15	
	475	0	B	20.8	2.0	5.8	5.4×10^{-7}	17.5	16.8
	475	0	G	363	4.1	13.5	2.7×10^{-7}	12.7	23.3

[a]See Table I.



(a) 17 percent cobalt.

(b) 8.5 percent cobalt.

(c) 0 percent cobalt.

Figure 1. - Particles of γ' extracted from HIP-PM Udimet 700 type alloys with disk-type heat treatments. Note decreasing amounts of ultrafine γ' particles as cobalt decreases.

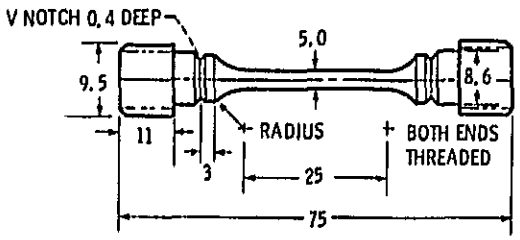


Figure 2. - Sketch of test specimen. All dimensions in millimeters.

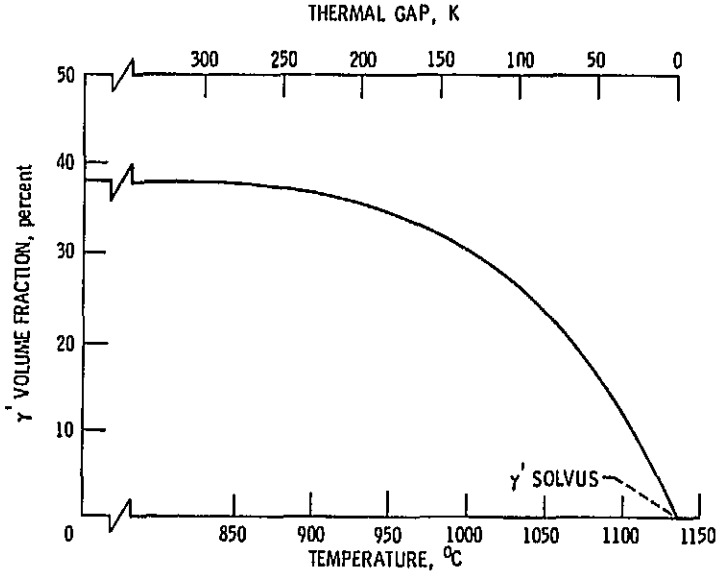


Figure 3. - Volume fraction of γ' as a function of temperature (adapted from Ref. 5).

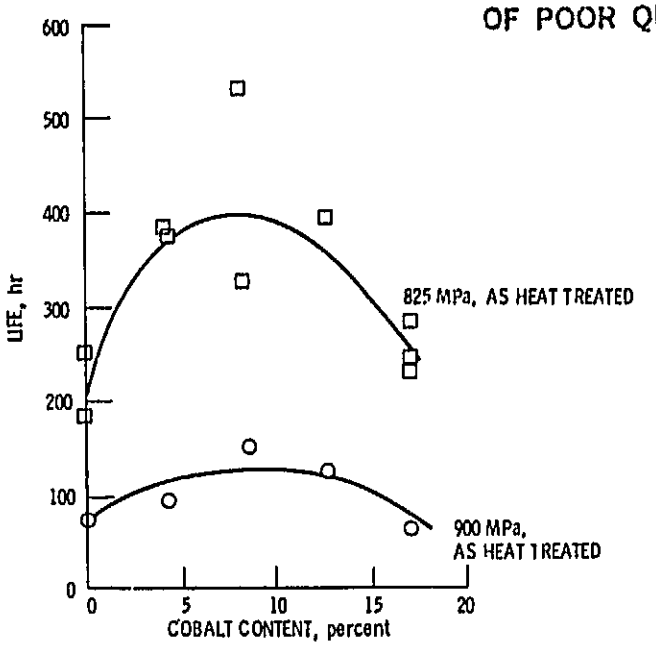


Figure 4. - Stress rupture life at 650 °C of HIP-PM Udimet 700 alloys with reduced cobalt contents (Ref. 4).

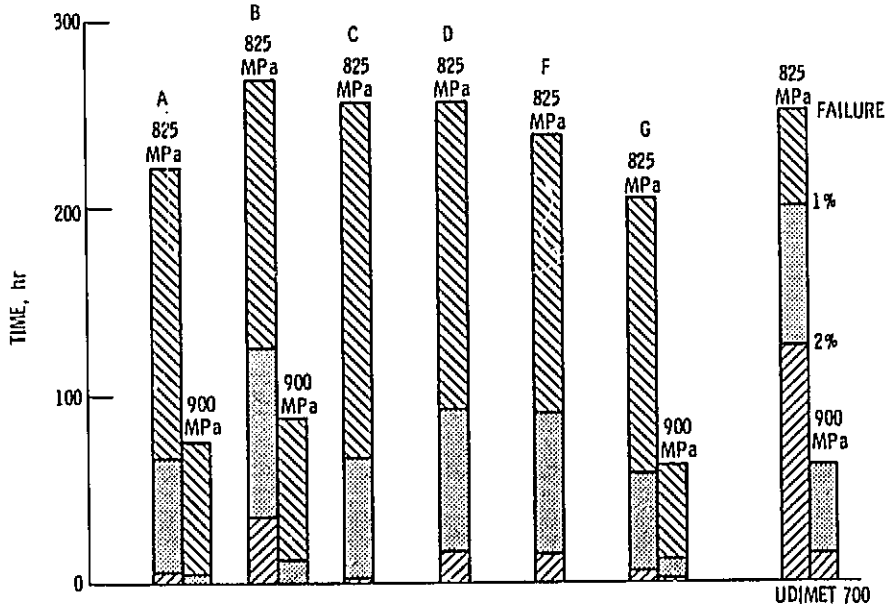


Figure 5. - Times to 1% and 2% total strain and to failure in creep rupture tests at 650 °C for HIP-PM cobalt-free alloy with different heat treatments. HIP-PM Udimet 700 is shown on right for comparison.

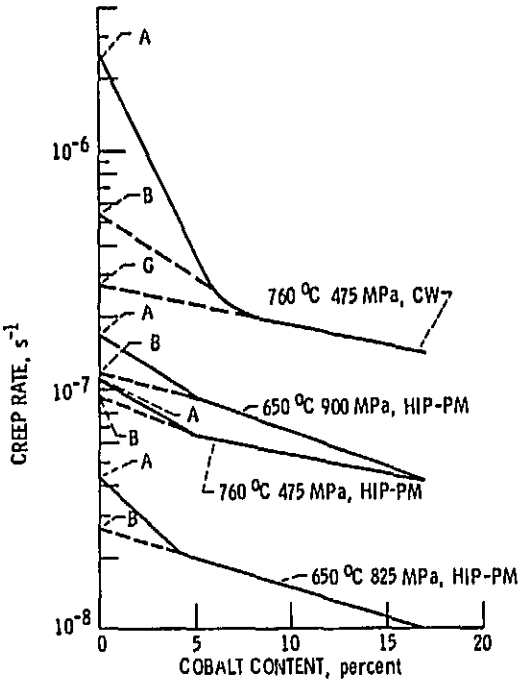


Figure 6. - Minimum creep rates of Udimet 700 alloy with reduced cobalt contents. Cobalt-free alloy is represented with 2 heat-treatments in HIP-PM and 3 heat treatments in CW conditions.

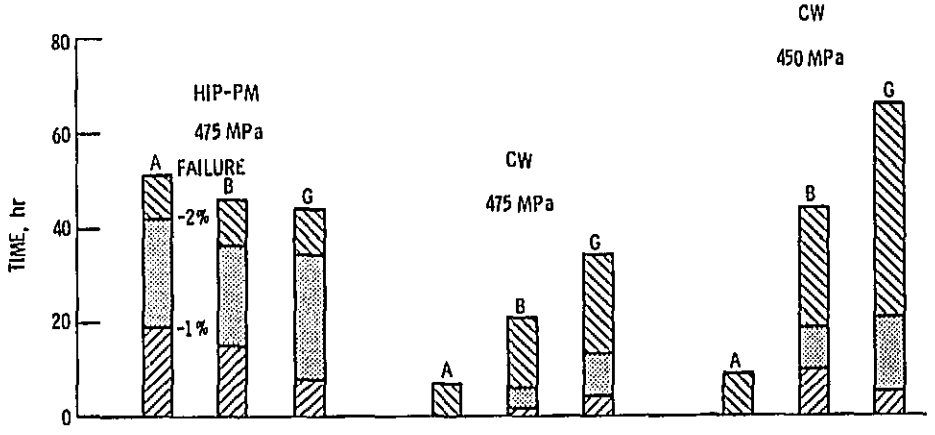
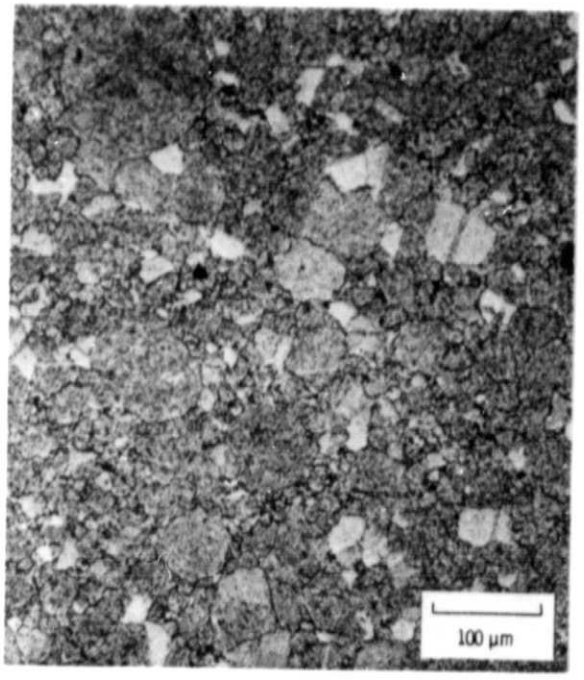
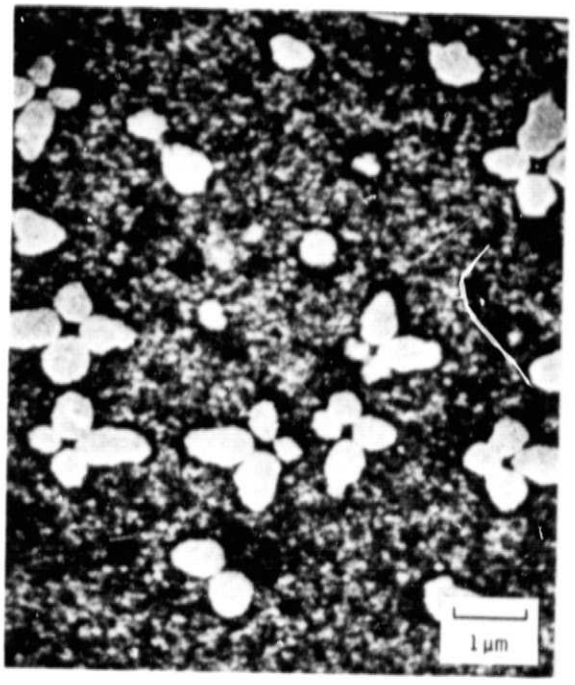


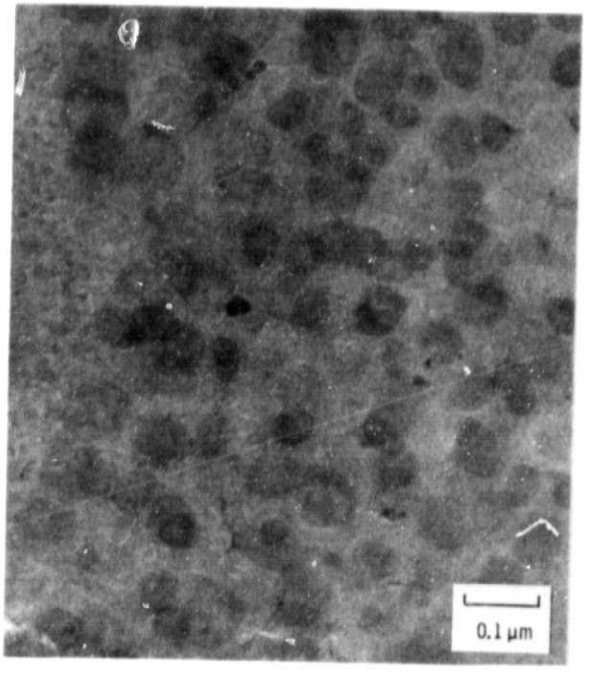
Figure 7. - Times to 1 and 2% total strain and to failure in creep rupture tests at 760 °C for cobalt-free Udimet 700 in HIP-PM and cast-and-wrought conditions with three heat treatments.



(a) Light microscopy.



(b) Scanning electron microscopy.



(c) Transmission electron microscopy.

Figure 8. - Microstructures of partically solutioned HIP-PM Udimet 700 type alloy with 0 percent cobalt.

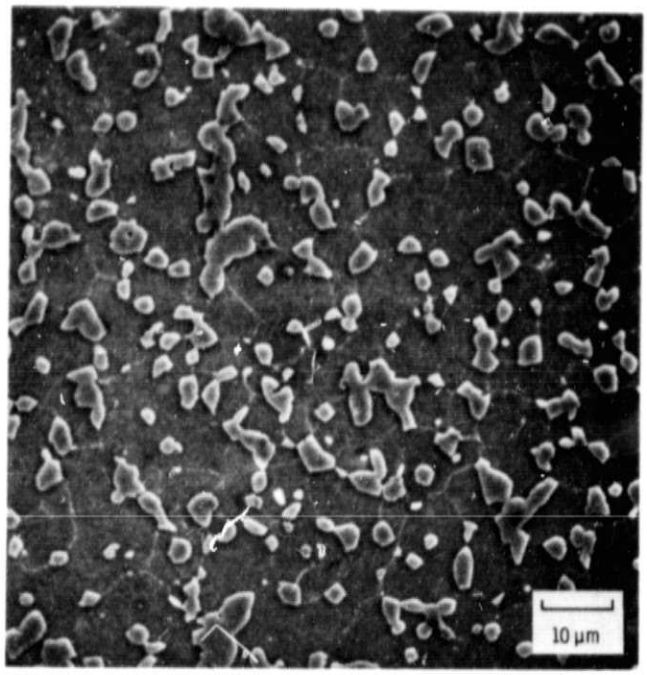
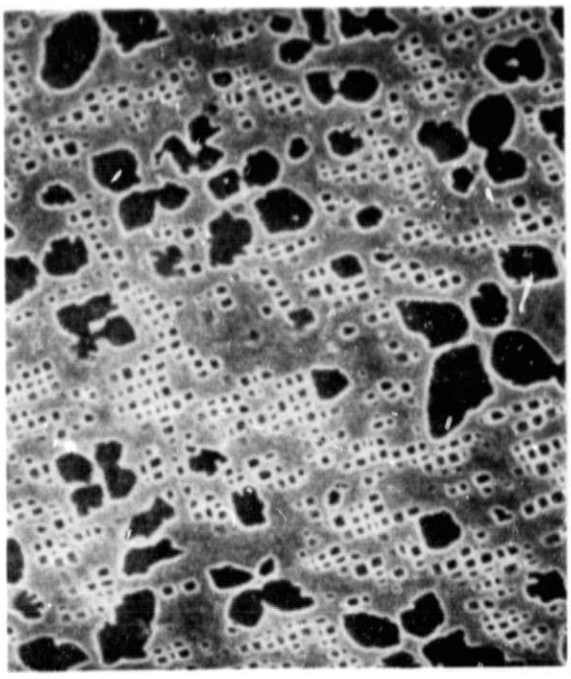
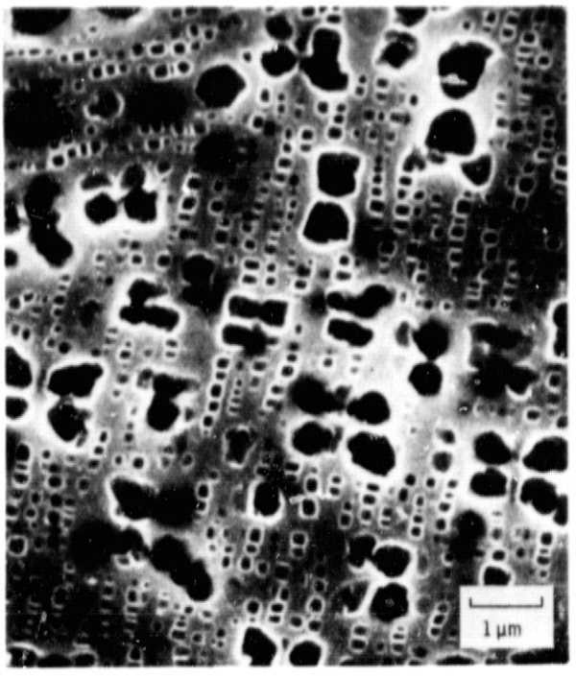


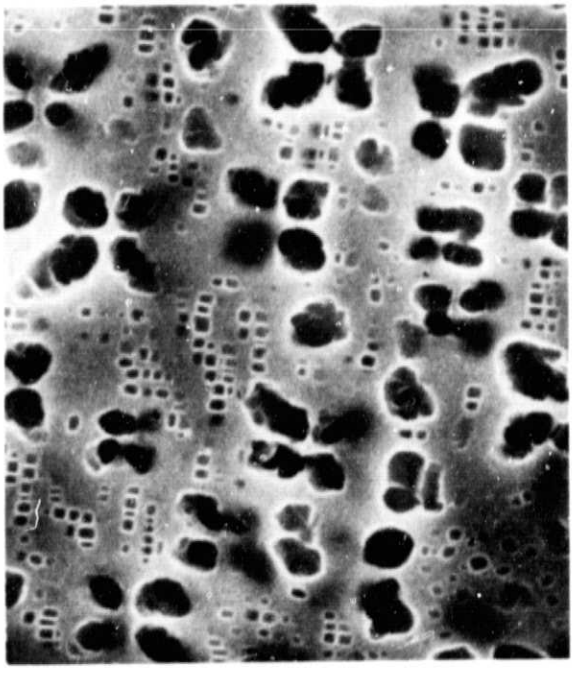
Figure 9. - Microstructure of partially solutioned CW Udimet 700 type alloy with 0 percent cobalt content.



(a) ''Standard'' A.

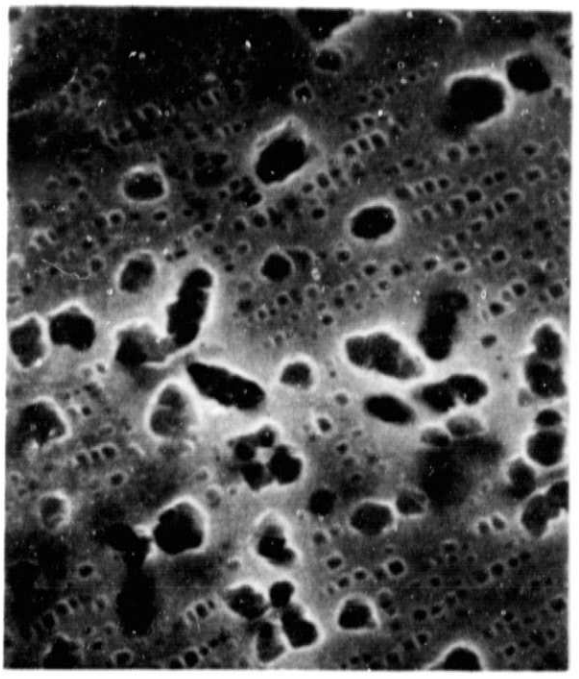


(b) B.

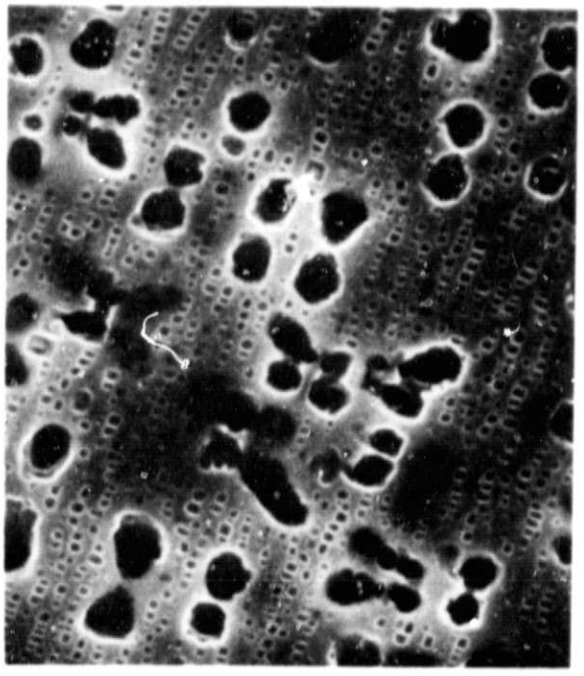


(c) C.

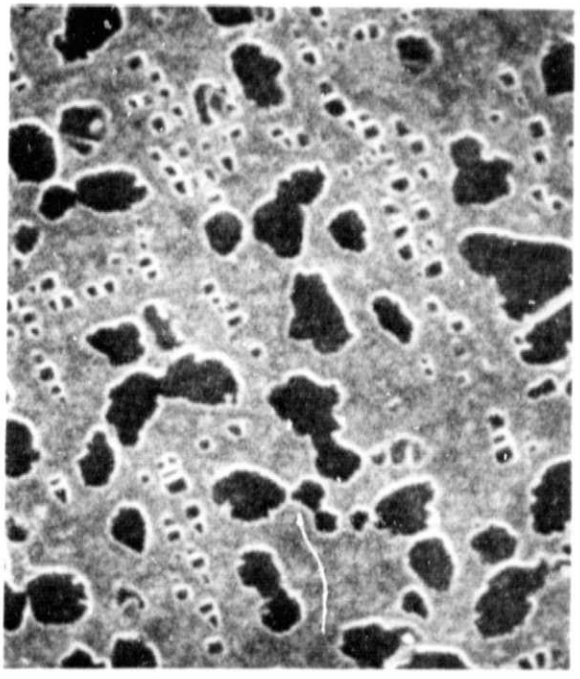
Figure 10. - Microstructures by scanning electron microscopy of Udimet 700 type alloy with 0 percent cobalt content given indicated heat treatment. Partially solutioned and fine particles are shown.



(d) D.

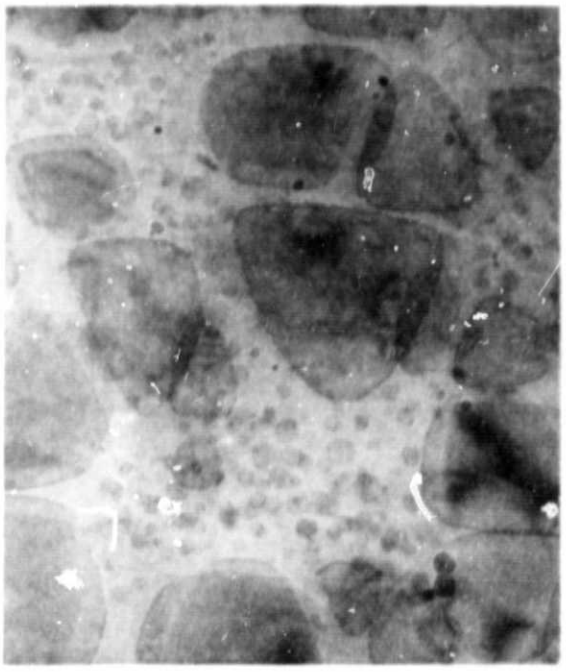


(e) F.

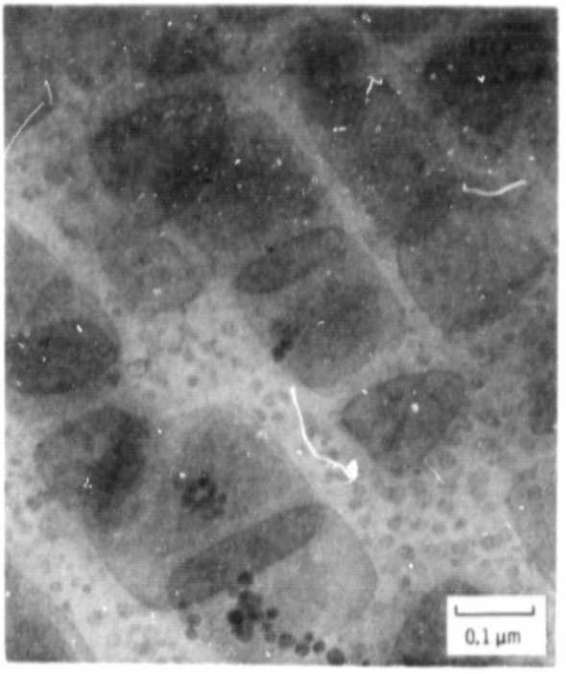


(f) G.

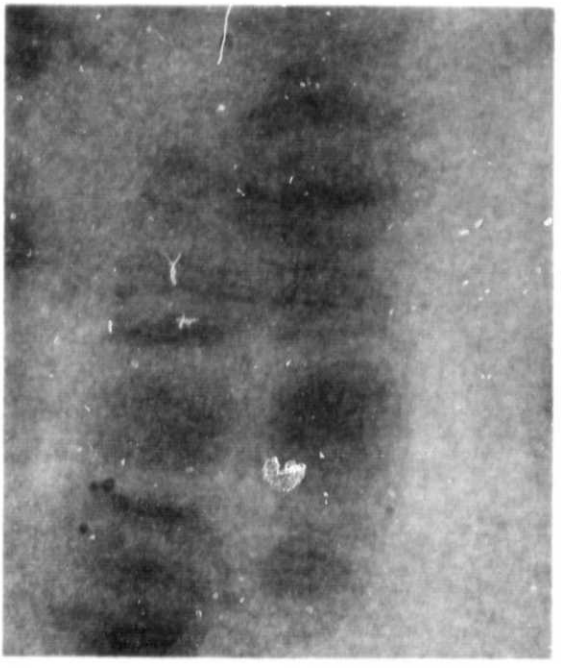
Figure 10. - Concluded.



(a) "Standard" A.



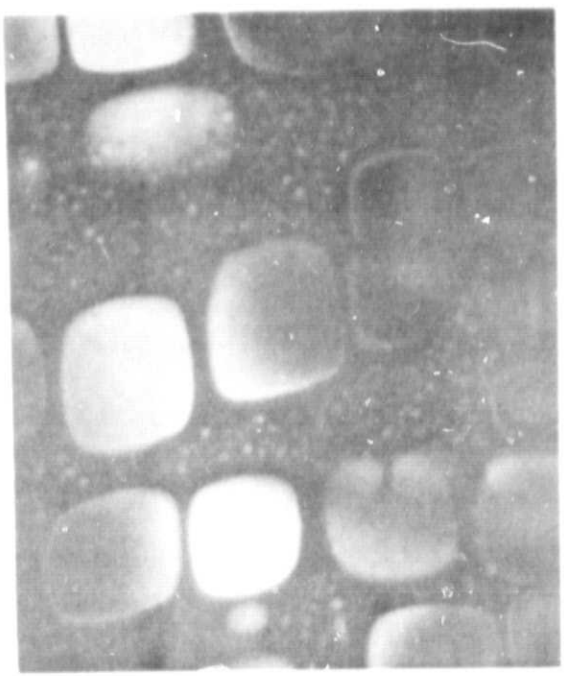
(b) B.



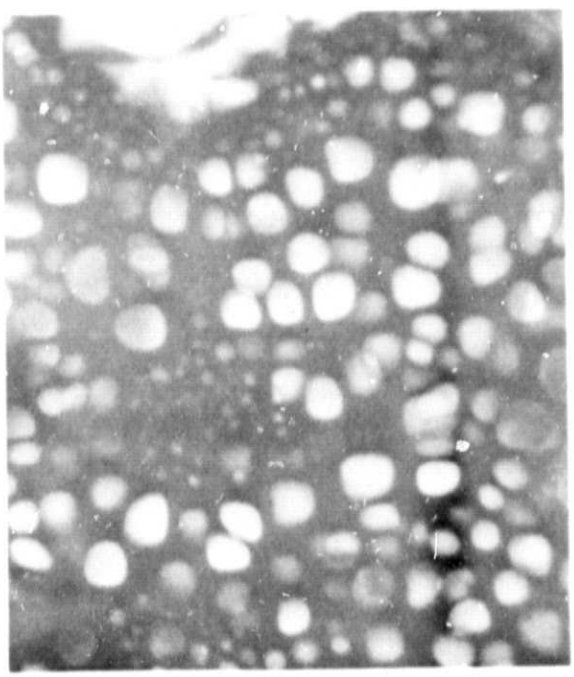
(c) C.

Figure 11. - Transmission electron micrographs comparing ultrafine particles in Udimet 700 type alloys with 0 percent cobalt content given indicated heat treatment.

(d) D.

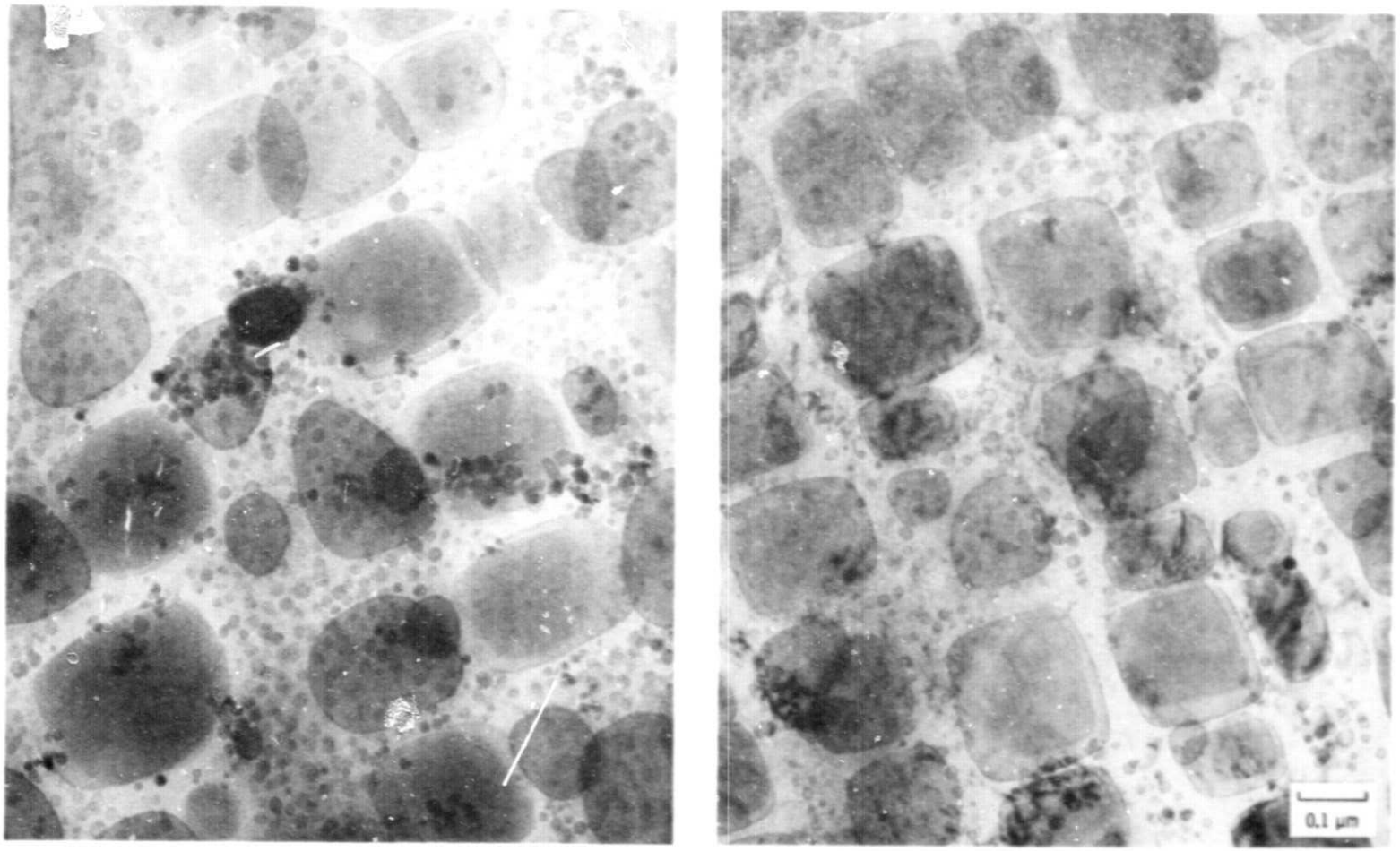


(e) F.



(f) G.

Figure 11. - Concluded.



(a) 17 percent cobalt.

(b) 4.3 percent cobalt.

Figure 12. - Transmission electron micrographs of Udimet 700 type alloys, in the fully aged condition.