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The response of cobalt-free Udimet 700 type alloy to modified heat treatments

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A superalloy based on Udimet 700, in which all of the cobalt had been replaced by nickel, was prepared from hot isostatically pressed pre-alloyed powders. This material was given various heat treatments consisting of partial solutioning and ageing in a sequence of four different temperatures. Comparisons were made of microstructures and mechanical properties. Best results were obtained by partially solutioning at 1145° C and ageing through a sequence of 870, 1030, 650, and 760° C. This heat treatment also provided significantly improved properties for wrought material of the same composition. The results suggest that cobalt free Udimet 700 should be considered as a substitute for Udimet 700 with the standard 17 wt% cobalt content.

1. Introduction

Cobalt is extensively used in superalloys. But the US and the western European countries are almost entirely dependent on imports for their supply. Therefore the US have designated cobalt a critical strategic material and made it the subject of efforts to reduce its consumption in superalloys [1, 2].

Among the superalloys where a reduced cobalt content would be particularly rewarding is Udimet 700*, which contains 17 wt% cobalt. This nickel-based alloy is heat treatable and has a microstructure of about 45% 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 discs and as a hot isostatically pressed powder metallurgy (HIP-PM) product in turbine discs. The role of cobalt in this alloy was examined in the conservation of strategic aerospace materials (COSAM) programme [1]. Alloy modifications were produced in which the cobalt content had been reduced to 12.7, 8.5, 4.3 and 0% and replaced by nickel. The alloys were prepared in the CW and HIP-PM conditions.

The CW alloys were investigated under the sponsorship of the National Aeronautics and Space Administration (NASA) at Columbia University of New York [3]. A portion of the material was heat treated as 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 precipitates 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 discs, allowing a direct comparison with properties obtained by NASA on HIP-PM alloys [4]. The initial partial solutioning heat treatment for discs maintains the original grain size by "pinning" the grain boundaries with coarse γ' particles. The partial solutioning treatment is followed by a sequence of ageing heat treatments at four different temperatures to produce an even distribution of fine and ultrafine γ' particles throughout the matrix. The disc type heat treatments given the various alloy compositions by Jarrett and Tien [3] to CW materials and by Harf [4] to HIP-PM materials are shown in Table I. In tensile tests the CW alloys at room temperature and the HIP-PM alloys at room temperature and 650° C had fairly equal strengths and ductilities at all cobalt levels. 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% cobalt compositions; lives for the 17 and 0% cobalt alloys were nearly equal and minimum creep rates increased at the lower cobalt levels. At 760° C the HIP-PM

TABLE I Heat treatment schedules of modified Udimet 700 alloys (disc type)

Cobalt (wt%)	Quench medium		Ageing treatment for all alloys
	CW (Salt at 310° C then air cool)	HIP-PM (Oil)	
17	1104	1104	870° C, 8 h, air cool
12.7	1118	1118	980° C, 4 h, air cool
8.5	1129	1130	650° C, 24 h, air cool
4.3	1129	1138	760° C, 8 h, air cool
0	1129	1145	

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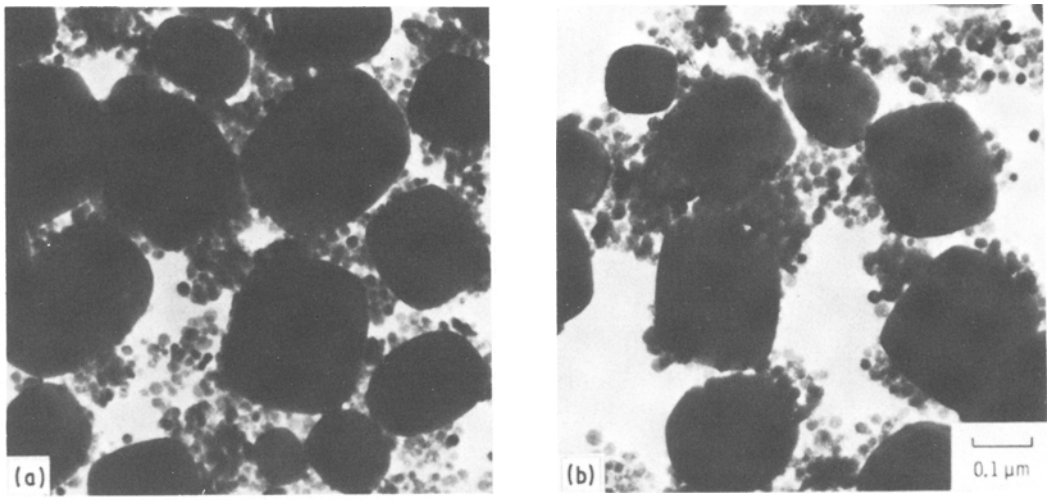


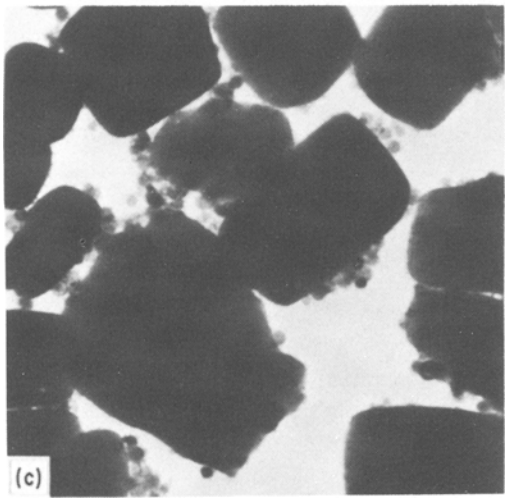


Figure 1 Particles of γ' extracted from HIP-PM Udimet 700 type alloys with disc type heat treatments. Note decreasing amounts of ultrafine γ' particles as cobalt decreases. (a) 17% cobalt, (b) 8.5% cobalt, (c) 0% cobalt.

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% 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 disc applications, the cobalt in Udimet 700 could safely be reduced to between 8.5 and 4.3%, 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 ageing treatments for the cobalt-free alloy might result in properties equivalent to those of Udimet 700 with 17% cobalt. For example, the major microstructural difference between alloys at the various cobalt levels which had been given the disc type heat treatment was the amount of ultrafine γ' present. This is evident in the transmission electron micrographs of Fig. 1, which show γ' particles extracted from HIP-PM alloys with 17, 8.5 and 0% cobalt. Fine (~ 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), as presented in Table II.

Van der Molen *et al.* [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 ageing at 760° C because less γ' remains dissolved in the γ 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 which governs deformation at 650° C. But the enhanced rupture properties at intermediate cobalt levels also suggests 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 undertaken 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% 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.

TABLE II Thermal relation of heat treatments (maximum ageing 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 Analysed composition of cobalt free Udimet 700

	Composition (wt %)							
	Co	Cr	Mo	Al	Ti	C	B	Fe
CW [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

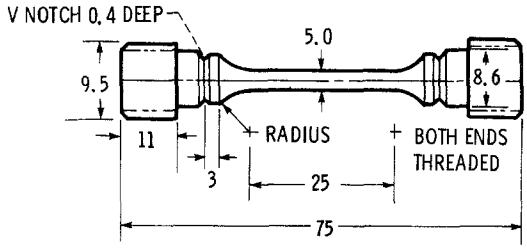


Figure 2 Sketch of test specimen. All dimensions in millimetres.

2. Experimental procedure

2.1. 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 [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 [4] was produced from argon atomized powder which had been hot isostatically pressed at 1210° C for 3 h. The material in the present study comprised what remained after requirements for the more extensive test programmes [3, 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 ageing treatments were followed by air cooling.

2.2. Mechanical tests

Mechanical tests were performed in air and in accordance with applicable ASTM recommended procedures. Test specimens are shown in Fig. 2. The crosshead speed for the tensile tests at room temperature and 650° C was 0.5 mm min^{-1}. 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% 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 [6]. It should be noted that the gauge of their test specimens was 12.7 mm long and 3.2 mm in diameter [3], while for the present tests these dimensions were 25 and 5 mm, respectively (Fig. 2).

3. 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% hydrochloric acid, 33% acetic acid, 33% water and 1% hydrofluoric acid. Specimens for transmission electron microscopy (TEM) were thinned in a methanol solution with 7% perchloric acid and 20% butanol.

The volume fraction of large γ' particles, remaining after partial solutioning was measured by point counting on scanning electron micrographs (SEM) at $\times$ 10 000 magnification, in conformance with ASTM standard recommended practice E562 [7]. Point counting could not be used for determining volume fractions of fine and ultrafine γ' particles, because some 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% citric acid and 1% ammonium sulphate 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.

4. Results

4.1. 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 disc 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 [3, 4]. For the present work with cobalt free alloy the partial

TABLE IV Heat treatments for cobalt free Udimet 700

Heat treatment	Partial solution, oil quench (°C–h)	Ageing steps, air cool (°C–h)			
		1	2	3	4
A [4]	1145–4	870–8	980–4	650–24	760–8
AW [3][a]	1129–4[b]	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
F	1145–4	870–8	1000–3	650–24	760–8
G	1145–4	870–8	1050–1	650–24	760–8

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

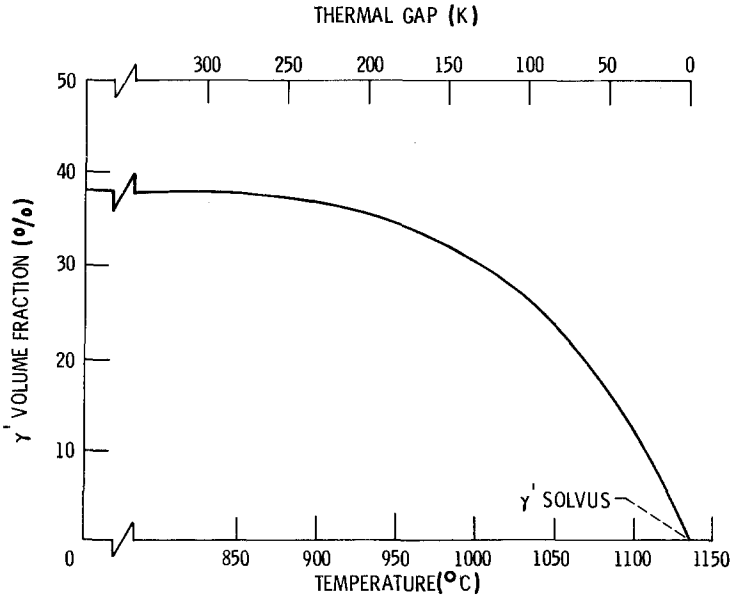


Figure 3 Volume fraction of γ' as a function of temperature (adapted from [5]).

solutioning temperature of 1145° C was again chosen for the HIP-PM material and also used for CW material where in the previous programme of Jarrett and Tien [3] it had been 1129° C. These original heat treatments designated A and AW for HIP-PM and CW alloy respectively, are listed in Table IV.

The four step ageing heat treatment was the same for all CW and HIP-PM alloys in the original studies [3, 4]. This ageing 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 ageing 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 Fig. 3 adapted from the work by Van der Molen *et al.* [5]. The referenced Udimet 700 had a total γ' volume fraction of 38% and was of a composition somewhat different from that used in the present work where 47% of the total weight was γ'. The γ' solvus of the 17% cobalt content alloy [4], as measured by differential thermal analysis, was 1150 as opposed to 1132° C for the referenced alloy [5] and 1188° C for the 0% cobalt alloy.

From Table II the thermal gaps for the 17 and 0% alloys are 170 and 208° C, respectively. Assuming that the relative proportions of γ' precipitate conform to those shown in Fig. 3 [5], one finds that with a thermal gap of 170° C the volume fraction of γ' is 33%. In the example shown in Fig. 3 the maximum γ' volume fraction was 38%; hence the 33% represents 33/38 or 86.8% of the γ' that can be formed. This leaves about 13% of the γ' available for precipitation as ultrafine particles. However in the cobalt free alloy with a thermal gap of 208° C, 36% of the available γ' should have been precipitated in the first two steps of the ageing heat treatment. This means that only about 5% of the total γ' remains available for forming ultrafine particles. The ultrafine particles formed in the 17% alloy should then be 2.5 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 1a and c). A maximum ageing 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% cobalt alloy. It was expected that amounts of ultrafine γ' particles equal to greater than those found in the 17% cobalt alloy of [4] would be formed by heat treatment B of Table IV. The time of exposure at 1030° C was set to 2 h in order to maintain a γ' fine particle size equal to that obtained in the earlier work (Fig. 10 in [5]).

While the second ageing 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 the 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 behaviour at 650° C where strengthening by γ' particles should be most effective because failures are transgranular. (At 760° C, due to grain boundary slip, failures tend to become intergrangular.) Earlier tests had shown that the alloy with the 17% cobalt content, which had the lowest minimum creep rate, did not display the longest rupture life at 650° C [4]. As shown in Fig. 4 definite rupture life maxima occurred in the alloy with 8.5% 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.

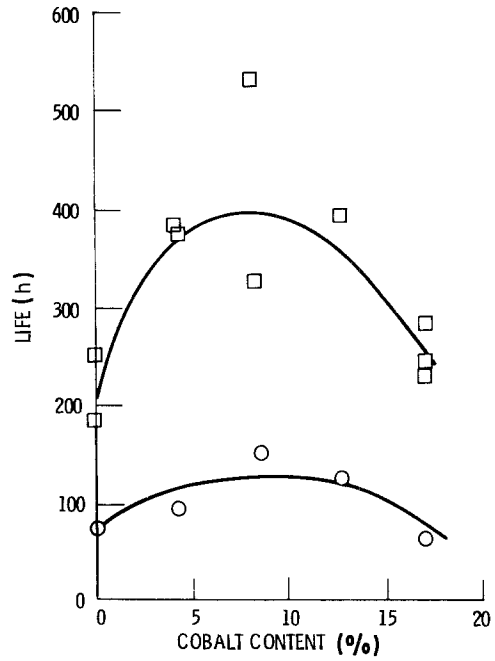


Figure 4 Stress rupture life at 650° C of HIP-PM Udimet 700 alloys with reduced cobalt contents (from [4]). (□) 825 MPa, as heat treated, (○) 900 MPa, as heat treated.

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% cobalt alloy originally tested in [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% 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 ageing 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% was good with heat treatment D, but poor with heat treatment C. It appeared that the omission of step 1 ageing in heat treatment C had resulted in reduced mechanical properties compared to heat treatment B. This fact suggested that adding step 1 ageing 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 ageing steps remained the same as in [3, 4].

4.2. Mechanical tests

Tensile test results for heat treatments B and G and comparative data for the HIP-PM alloy as originally tested in [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 [4], and the reductions of area, which were similar at room temperature in all three conditions, were lower for B and G than for A heat treated specimens at 650° C.

As shown by the creep rupture test results at 650° C in Table V, 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 to 1 and 2% total strain. The minimum creep rate was reduced to about one-fourth and ductility remained adequate. Specimens with heat treatment G had an inferior response, their times to failure, to 1 and 2% total strain, as well as the minimum creep rate essentially equalled 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, presented in Table VII indicate that for the HIP-PM alloy neither heat treatment B nor G represents an improvement over the original heat treatment A. 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

TABLE V Summary of creep rupture test results for HIP-PM cobalt free Udimet 700 at 650° C

Stress (MPa)	Heat treatment	Life (h)	Time (h) for total strain of		Minimum creep rate (sec^{-1})	After rupture	
			1%	2%		Elongation (%)	Reduction of area (%)
825	A	188	5.2	60	4×10^{-8}	6.7	10.2
825	A	255	8.5	75	4.7×10^{-8}	7.1	3.7
825	B	239	45	133	2.9×10^{-8}	3.7	10.2
825	B	296	25	117	2.5×10^{-8}	3.9	19.4
825	C	254	< 0.01	61	3.1×10^{-8}	3.4	10.2
825	C	256	1.8	73	3.2×10^{-8}	4.2	9.7
825	D	274	19	104	3.1×10^{-8}	5.0	10.2
825	D	236	14	81	3.3×10^{-8}	2.8	9.7
825	F	210	22	100	3.1×10^{-8}	1.7	7.8
825	F	263	8	78	2.9×10^{-8}	3.6	5.2
825	G	212	7	64	3.8×10^{-8}	4.4	7.8
825	G	195	6	51	3.8×10^{-8}	5.8	10.7
900	A	74	0.5	5.5	1.6×10^{-7}	3.8	10.7
900	B	87	3.5	19.8	1.2×10^{-7}	19.6	16.3
900	G	62	2.5	11.6	2.0×10^{-7}	6.7	11.6

TABLE VI Tensile test results for HIP-PM Udimet 700 with three cobalt concentrations

Cobalt content	Test temperature (°C)	Heat treatment	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction of area (%)
0% 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
17% cobalt	25	[4][a]	1440	967	16.5	21.2
	650		1244	914	15.0	17.7
4.3% cobalt	25	[4][a]	1335	969	10.5	13.5
	650		1182	874	18.4	18.3

[a]Average results, 2 tests each.

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 ageing heat treatment also raised the partial solutioning temperature by 16 K over that which was given the material tested previously [3]. Furthermore, the testing of specimens of different dimensions in another laboratory could have had some influence on the performance of the material.

4.3. Microstructures

The microstructure of partially solutioned HIP-PM cobalt free alloy is shown in Fig. 5. The material was essentially 100% dense. The mixture of recrystallized and unrecrystallized grains had an ASTM grain size number of about 6.5 and retained some residual prior particle boundaries (Fig. 5a). Coarse partially solutioned γ' particles of nearly 1 μm in diameter were present mostly as ogdoadic clusters (Fig. 5b) with no concentrations in grain boundaries. These undissolved particles occupied about 13.5 vol % of the sample [4]. Higher magnification TEM revealed outlines of very fine γ' particles or their precursors measuring from about 50 nm to probably under 1 nm in diameter (Fig. 5c).

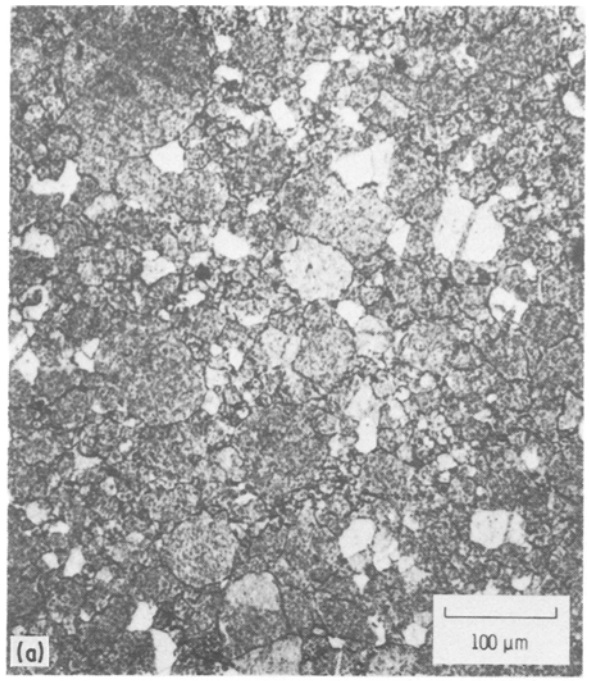
The shapes of the undissolved γ' particles in the partially solutioned CW material were more irregular (Fig. 6). Many measured over 3 μm in cross-section, they were often located in grain boundaries and occupied about 18 vol % of the sample.

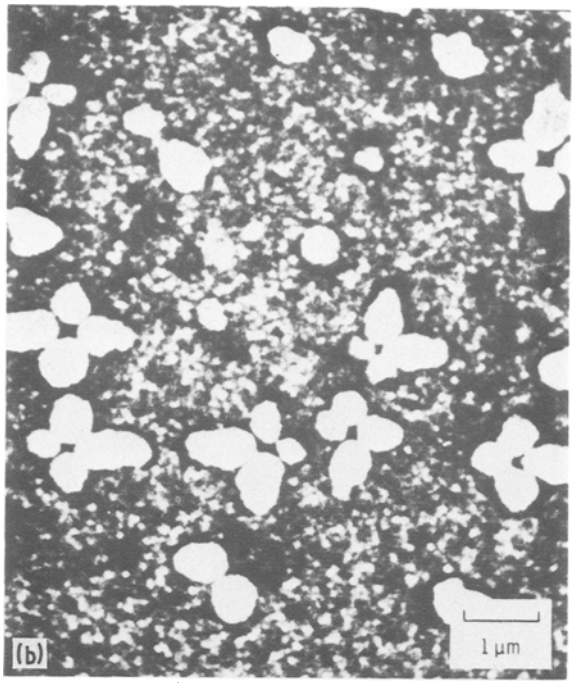
The microstructures after the various ageing heat treatments are shown by SEM in Fig. 7. The microstructure of the original ageing heat treatment A [4] displayed many rows of contiguous fine γ' particles about 100 nm in diameter in addition to the ogdoadic clusters of partially solutioned γ' (Fig. 7a). The higher, 1030° C, temperature of the second ageing step in heat treatment B resulted in fewer rows of fine particles which averaged about 200 nm in diameter (Fig. 7b). Eliminating the first ageing step (heat treatment C) greatly reduced the number of fine γ' particles which again approached 200 nm in size (Fig. 7c). The microstructure after heat treatment D (Fig. 7d), in which the first ageing 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. 7e), in which 1000° C was the second ageing temperature, the microstructure closely resembled that of heat treatment A, with numerous rows of particles in the 100 nm range. Heat treatment G, which combined the first ageing step with the highest (1050° C) ageing temperature in step 2, produced the fewest fine particles of about 200 nm (Fig. 7f) cross-section.

TABLE VII Creep rupture test results for cobalt free Udimet 700 at 760° C

Stress (MPa)	Heat treatment	Life (h)	Time (h) for total strain of		Minimum creep rate (sec^{-1})	After rupture	
			1 %	2 %		Elongation (%)	Reduction of area (%)
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 [6].





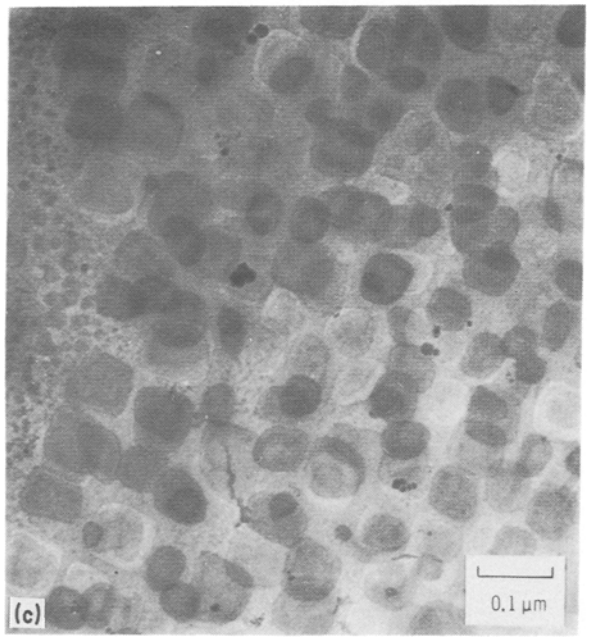


Figure 5 Microstructure of partially solutioned HIP-PM Udimet 700 type alloy with 0% cobalt. (a) Light microscopy, (b) scanning electron microscopy, (c) transmission electron microscopy.

5. Discussion

The cobalt free variation of Udimet 700 has little tendency toward supersaturation in the undercooled state. As can be seen in Fig. 5, the γ matrix of the alloy, oil quenched from the partial solutioning temperature of 1145° C, had rejected the γ' to form extremely fine particles which could sometimes be resolved at $\times$ 100 000 magnification.

Ageing at elevated temperature has two effects. First, as shown in Fig. 3, a temperature increases produces more partial solutioning of the γ' in the γ matrix. Second, some fine γ' particles undergo diffusion-controlled coarsening at rates that are functions

Fig. 8 compares the ultrafine particles, of between 10 and 50 nm in diameter produced by the various heat treatments. Raising the ageing 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. 8b), compared to the original heat treatment A (Fig. 8a). The particles after heat treatment C were even more numerous, and of the same size (Fig. 8c). 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. 8d). Ageing at the lower step 2 ageing temperature of 1000° C (heat treatment F) resulted in numerous particles measuring about 10 nm. Finally, combining step 1 ageing with 1050° C in step 2 (heat treatment G), produced a mixture of particles ranging from 10 to 50 nm (Fig. 8f).

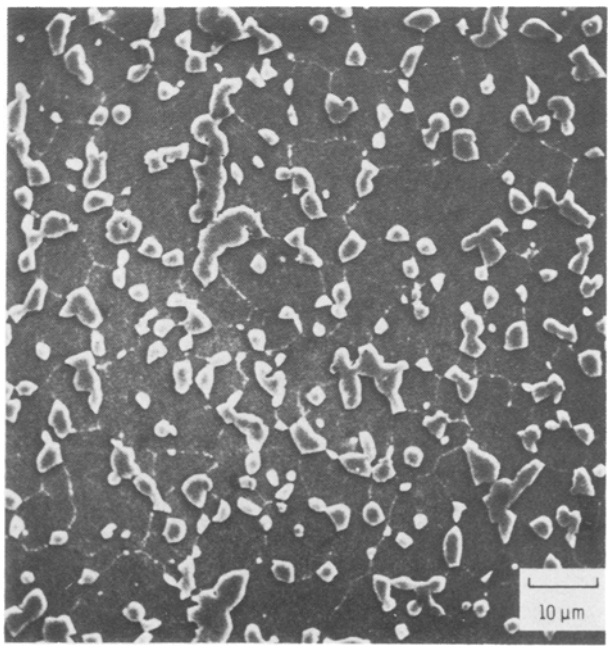


Figure 6 Microstructure of partially solutioned CW Udimet 700 type alloy with 0% cobalt content.

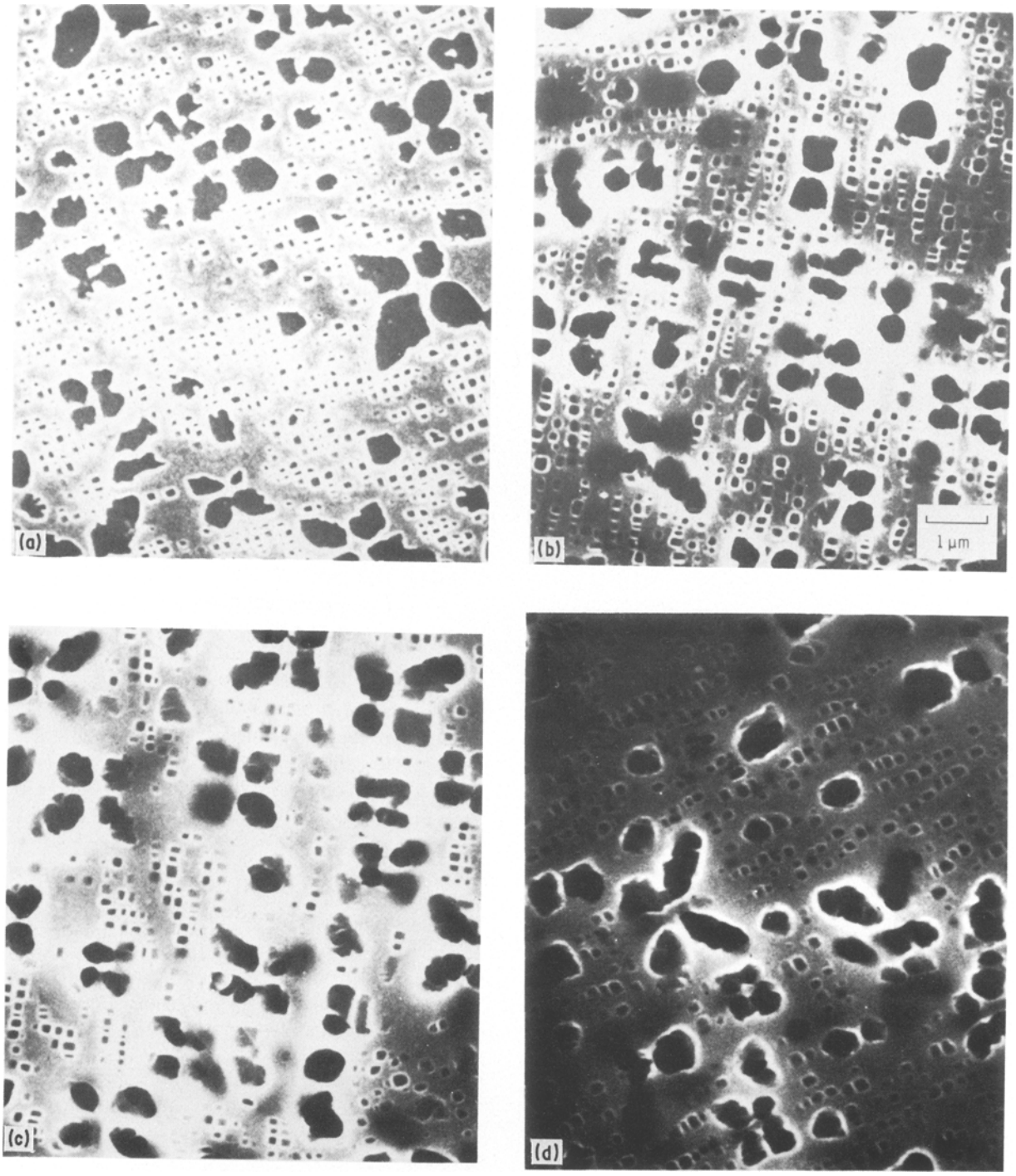


Figure 7 Microstructures by SEM of Udimet 700 type alloy with 0% cobalt content given indicated heat treatment. Partially solutioned and fine particles are shown. (a) "Original" heat treatment A, (b) heat treatment B, (c) heat treatment C, (d) heat treatment D, (e) heat treatment F, (f) heat treatment G.

of time and temperature [5]. Ageing the alloys through two temperature sequences, each consisting of a nucleation and a growth step, generates two distinct sizes of particles from the γ' precursor shapes in the matrix. The higher temperature in the first sequence essentially causes partial solutioning, which reverses during air cooling, so that the dissolved γ' reconstitutes itself. But it does not account for the larger ultrafine γ' particles produced in heat treatments D and G, for which the second step of the ageing treatment was 1050° C followed by air cooling. It 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 ageing by the 650 to 760° C sequence (Figs 8d 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 ageing step 2, the formation of the less than ultrafine particles could 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% cobalt content alloys

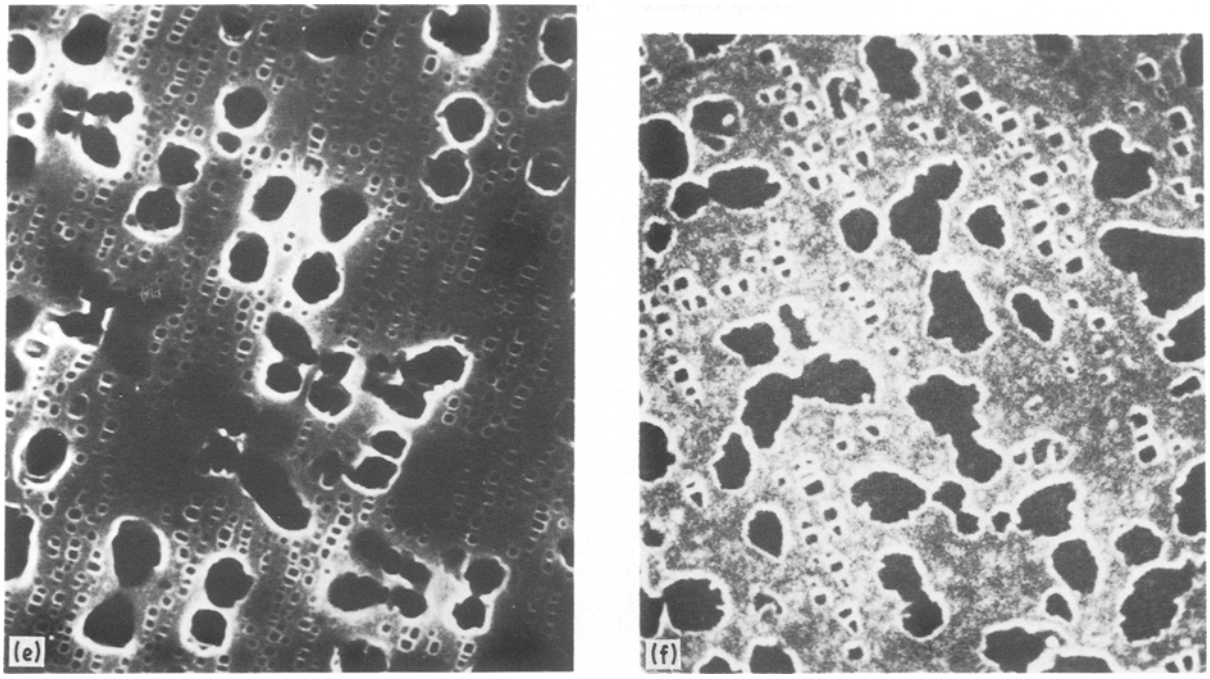


Figure 7 Continued.

(Table VI and [4]). At 650° C the improvement persisted with good ductility and, while strength of the 0% cobalt alloy approached that of the 17% cobalt alloy, it clearly exceeded that of the 4.3% cobalt alloy. The creep rupture properties of heat treatment B at 650° C were effectively improved over heat treatment A and the life of the 0% cobalt alloy now exceeded that of the 17% cobalt alloy (Table VIII). At 760° C and 475 MPa there appeared to be no advantage in 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 VIII) 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 [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% cobalt content alloy with heat treatment B (Fig. 8b) and the alloys with 17 and 4.3% cobalt heat treated and tested previously [4]. The structures of these alloys are shown in Fig. 9. 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

TABLE VIII Comparison of average creep rupture behaviour for Udimet 700 type alloys with various cobalt contents

Test conditions		Cobalt content (%)	Heat treatment	Life (h)	Time (h) for total strain of		Minimum creep rate (sec^{-1})	After rupture	
Temperature (°C)	Stress (MPa)				1%	2%		Elongation (%)	Reduction of area (%)
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
		0	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	3.5	19.8	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	AW	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	36.3	5.1	13.5	2.7×10^{-7}	12.7	23.3

[a]See Table I.

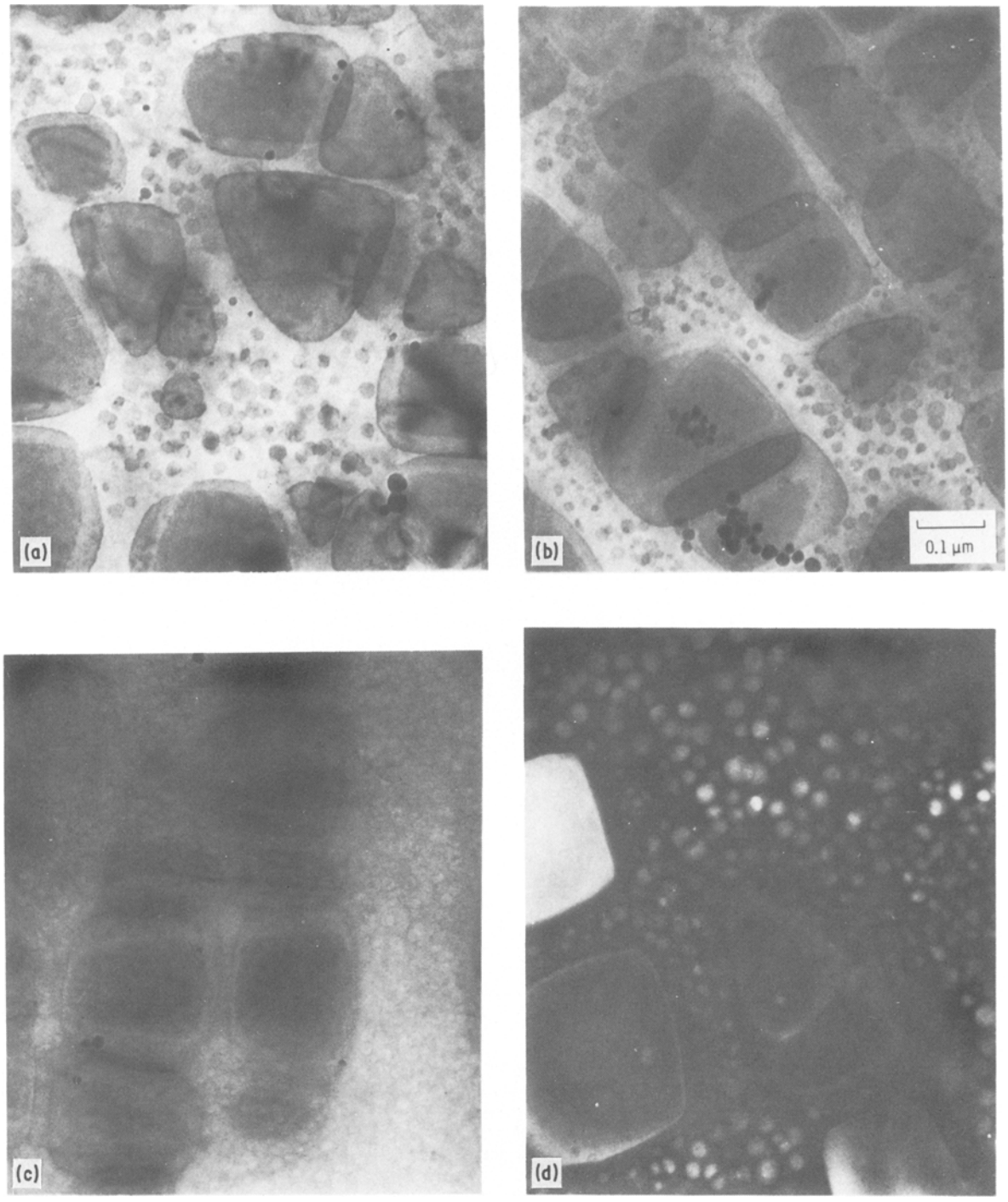


Figure 8 TEM comparing ultrafine particles in Udimet 700 type alloys with 0% cobalt content given indicated heat treatment. (a) "Original" heat treatment A, (b) heat treatment B, (c) heat treatment C, (d) heat treatment D, (e) heat treatment F, (f) heat treatment G.

treatments are employed for turbine blades and for turbine discs. 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.

6. Summary

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 disc applications and comprised partial solutioning and ageing through a sequence of four different temperatures. Comparisons were made with an original heat treatment in which the second ageing step was at 980° C. It was found in the HIP-PM alloy:

1. Raising the temperature of the second ageing step to 1030° C improved the rupture life and creep resistance at 650° C. This was attributed to the microstucture which contained an increased quantity of ultrafine, 20 nm, γ' particles.
2. Raising the temperature of the second ageing step to 1050° C was of no benefit. The ultrafine γ'

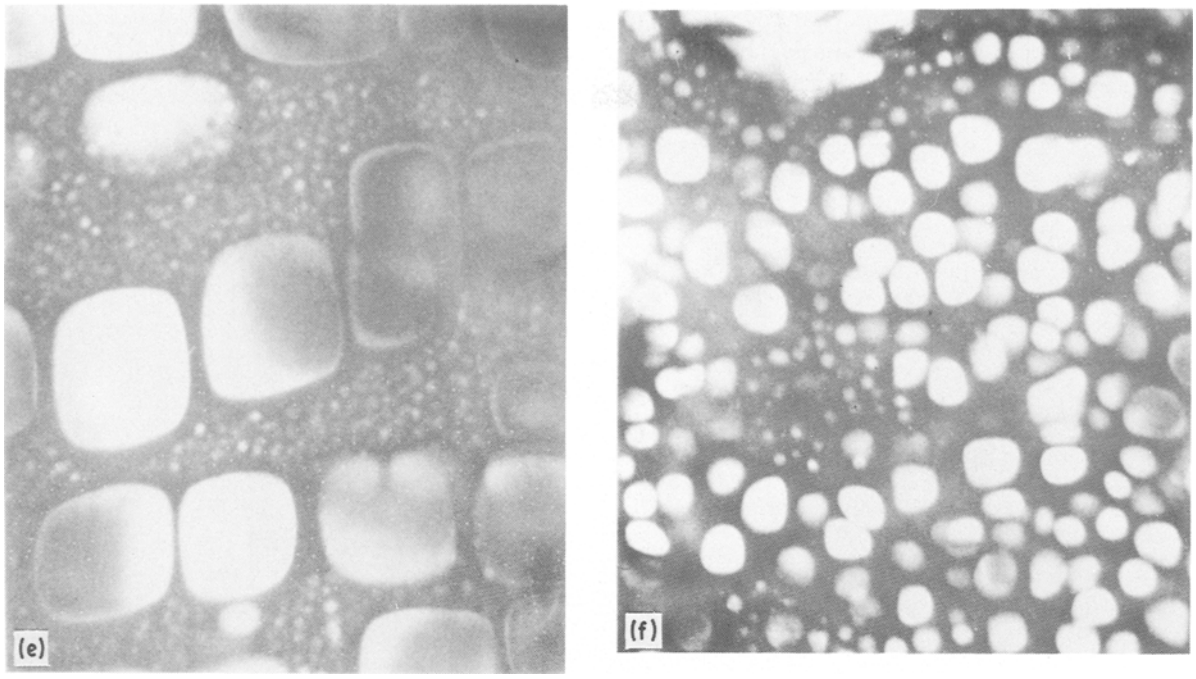


Figure 8 Continued.

particles, while more numerous, had often grown beyond a 20 nm size.

3. Omitting the first step of the ageing 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 ageing heat treatment, since grain boundary sliding controls creep of Udimet 700 type alloys at this temperature.

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

7. Concluding remarks

The heat treatment study conducted here, along with the work previously performed [4, 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 disc applications. This statement applies to both the cast and wrought and the hot-isostatically-pressed pre-alloyed powder processed alloy. Jarrett and Tien [3] had previously reported that the alloy, when given a different heat

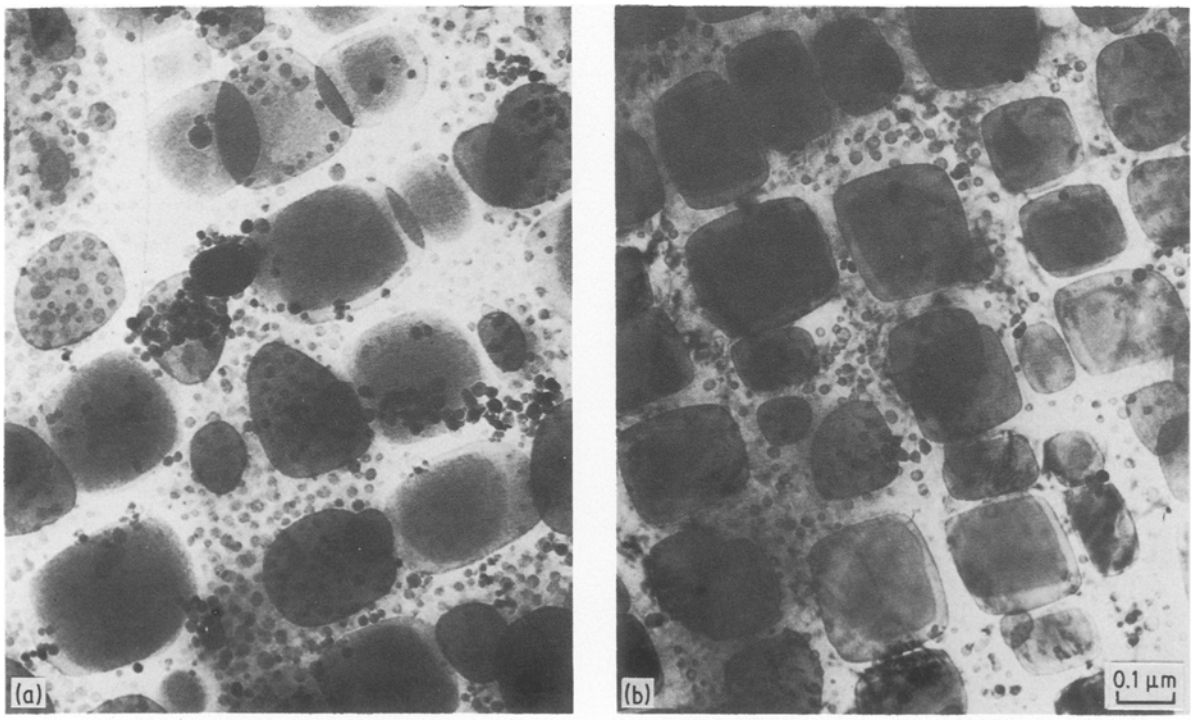


Figure 9 TEM of Udimet 700 type alloys, in the fully aged condition. (a) 17% cobalt, (b) 4.3% cobalt.

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% cobalt Udimet 700, the potential for improving properties by heat treatment modifications should be explored.

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