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Summary

The fluidized-bed heating and cooling technique was used to evaluate the comparative thermal-fatigue and oxidation resistances of alloys based on the wrought Udimet 700 alloy system. Cobalt was replaced by nickel (the base metal) in making five modified alloys of which the cobalt levels were 0, 4.3, 8.6, 12.8, and 17.0 wt %. All cobalt levels were evaluated in both bare and coated conditions. The coating was a plasma-sprayed NiCrAlY overlay coating.

This investigation is part of the COSAM (Conservation of Strategic Aerospace Materials) program, which seeks ways to reduce the need for strategic materials such as cobalt for use in gas-turbine engines. These tests were performed at the Illinois Institute of Technology Research Institute under contract (NAS3–17787) to the Lewis Research Center.

The same specimen geometry (single-wedge) and test conditions were used to evaluate all samples. Triplicate specimens (both bare and coated) of the five alloy heats (30 specimens) were simultaneously tested with duplicate specimens of three control alloys (6 specimens). The 36 specimens were split into two groups of 18, which were thermally cycled between fluidized beds operating at 1010 and 288 °C (1850 and 550 °F) for the first 5500 cycles. At that time the heating bed was increased 40 °C (72 °F) through the 14 000-cycle limit of testing. Immersion time in each bed was always 3 min. The number of cycles to initiate a crack on the wedge radius was the measure of its thermal-fatigue resistance. In addition, oxidation resistance (percent weight loss) was determined, and the results of a metallurgical study are included in this report.

A regression analysis showed that best thermal-fatigue resistance is obtained for the alloy containing about half the normal cobalt content. The thermal-fatigue lives ranged from 6750 cycles to greater than 14 000 cycles. After 13 500 cycles (675 hr of heating time) all bare wedges had weight losses of 10 to 13 percent. The coating drastically reduced these weight losses to 0.05 to 1.15 percent. The coating reduced the thermal-fatigue resistance of the substrate alloy, but only for the cobalt composition levels of 4.3 and 8.6 wt %. Considerable deformation of the specimens was observed during testing with the bars becoming hotdog shaped (the wedge section became concave, and the opposite edge convex along the length).

Introduction

Thermal-fatigue cracking of a material results from cyclic temperature changes which induce cyclic strains. Thermal-fatigue resistance is a major criterion for material selection of components subjected to fluctuating temperatures. As an example, in current aircraft gas-turbine engines, thermal-fatigue cracking is the predominant failure mode of the first-stage turbine airfoils (ref. 1).

Aircraft gas-turbine engine components, especially the hot-section components, are usually fabricated from nickel-base superalloys that contain cobalt, chromium, tantalum, or columbium as a major alloying element. In the aerospace industry these four metals have been identified as strategic materials (ref. 2). The United States imports in excess of 90 percent of each of these metals with one country controlling a major portion of the U.S. supply (ref. 3) for each metal. The NASA Lewis Research Center initiated a research program called Conservation of Strategic Aerospace Materials (COSAM) in order to reduce the need for strategic materials used in gas-turbine engines (refs. 4 to 6).

This investigation pertains specifically to cobalt and is part of the COSAM program. The single largest use for cobalt is as a major alloying element in nickel-base superalloys. Over 97 percent of the cobalt used in the United States is imported, mostly from Zaire and Zambia in southern Africa.

The purpose of this study was to evaluate how reduced cobalt levels in a superalloy affect its thermal-fatigue resistance. A secondary objective was to evaluate the oxidation resistance for the cobalt-modified alloys, including coating effects.

Udimet 700, a wrought nickel-base superalloy (18.5 wt % cobalt), was selected for this study. Five alloy heats were fabricated in which nickel was systematically substituted for cobalt. Cobalt levels of 0, 4.3, 8.6, 12.8, and 17.0 wt % were evaluated. Triplicate wedge specimens (prismatic bars with single-wedge cross section) for each composition level in both the bare and coated (NiCrAlY overlay) condition were fabricated and tested.

Thermal-fatigue tests were carried out in a fluidized-bed facility that was designed, built, and operated by the Illinois Institute of Technology Research Institute (IITRI) under contract (NAS3–17787) to the Lewis Research Center. Fluidized beds were first applied in the rapid cyclic heating and cooling of thermal fatigue specimens by E. Glenny and

his coworkers at the National Gas Turbine Establishment in England in 1958 (ref. 7). Since that time, fluidized-bed cycling has become widely used for evaluating the thermal fatigue behavior of both alloys and components (refs. 8 to 13). Other thermal fatigue tests conducted in the IITRI fluidized beds are reported in references 14 to 28.

Initial test conditions for the thermal-fatigue cycling were such that the maximum metal temperature would be 982 °C (1800 °F), which represents the expected use temperature in an aircraft gas-turbine engine. All heats of the material were simultaneously tested by using bed temperatures of 1010 and 288 °C (1850 and 550 °F) for 5500 cycles. As no cracking resulted after this testing, the maximum bed temperature was increased to 1050 °C (1922 °F) to achieve cracking before the 14 000-cycle limit of testing. Failure was defined as a crack on the specimen wedge area visible by using a microscope with a magnification of 30. Immersion time in each bed was always 3 min. A metallurgical study of the bars before and after testing was also conducted.

Materials and Test Specimens

Alloy Compositions and Fabrication

The compositions for the five modified Udimet 700 alloys used in this program are given in table I (ref. 29). The five compositions were vacuum-induction melted and cast into 10.2-cm- (4-in.-) diameter ingots. These became consumable electrodes in a vacuum-arc remelt furnace for further alloy and grain refinement. Products of the vacuum-arc remelt furnace were 15.3-cm- (6-in.-) diameter ingots, which were then forged into 6.3-cm (2.5-in.) round-cornered square bars. Each bar was hot-rolled at 1000 to 1100 °C (1832 to 2012 °F) to form a 6.3-cm- (2.5-in.-) wide by 1.8-cm- (0.71-in.-) thick flat plate. As shown in table I, the compositions of these plates differ significantly only in the amount of cobalt (< 0.1, 4.3, 8.6, 12.8, and 17.0 wt %) and hence, nickel. A separate chemical analysis of the heat with the lowest cobalt level showed essentially 0 wt % cobalt. The flat plates were cut into specimen blanks prior to heat treatment.

TABLE I.—COMPOSITION OF WROUGHT ALLOYS[a]

[Ref. 29.]

Heat	Ni	Co	Cr	Mo	Ti	Al	C	B	Fe
	Composition, wt %								
D5-1884	72.1	<0.1	15.1	5.0	3.5	4.12	0.06	0.025	0.11
D5-1885	67.7	4.3	15.1	4.9	3.6	4.14	.07	.024	.15
D5-1886	63.6	8.6	15.0	5.1	3.5	4.05	.06	.022	.11
D5-1932	59.6	12.8	14.7	5.0	3.6	4.10	.06	.023	.12
D5-1933	55.2	17.0	14.9	5.0	3.6	4.08	.06	.028	.11

[a]The trace elements are the following: O < 10 ppm; N < 16 ppm; S < 20 ppm; Bi, Th < 0.1 ppm; Pb, Tl, Ca < 0.2 ppm.

Heat Treatment and Grain Size

Available specimen blanks were heat treated to a fine grain structure suitable for use in aircraft-engine turbine disks. Because of the relatively high maximum test temperature used in this program, the actual heat treatment was not important as long as all blanks had about the same initial average grain size.

The fine grain structure was produced by a partial solution heat treatment below the γ' solvus in order to retain a fraction of γ' which pinned the boundaries. The undissolved γ' fraction was kept low since it reduced the amount of γ' available later as the fine grain strengthening precipitates. The material vendor found that the γ' solvus temperature decreased as the cobalt content in the alloy increased. Three different partial solution schedules were established because of this variation in solvus temperature (ref. 29). (See table II.) The partial solution temperatures reflect alterations in the highest temperature step used to obtain a constant initial grain size. The average grain size was 13 μm (0.00051 in.) for the 0 and 4.3 wt % cobalt levels, 12 μm (0.00047 in.) for the 8.6 wt % cobalt level, 11 μm (0.00043 in.) for the 12.8 wt % cobalt level, and 11.5 μm (0.00045 in.) for the 17 wt % cobalt level. All specimen blanks received the identical quench and age heat treatment.

TABLE II.—HEAT-TREATMENT SCHEDULES

[Ref. 29.]

Cobalt, wt %	Temperature, °C	Duration of treatment, hr	Comment
Solution treatment			
0	1129	4	Dependent on composition
4.3	1129		
8.6	1129		
12.8	1118		
17.0	1104		
Salt quench treatment			
All compositions	To 316	---	Air cooled
Age treatment series[a]			
All compositions	871	8	Air cooled after each step
	982	4	
	649	24	
	760	8	

[a]Treatment is series of four steps.

Test Specimens

The geometry of the thermal-fatigue wedge specimen (prismatic bar with single-wedge cross section) is given in figure 1. The end notches were used to loosely contain the specimens in the holders. Six specimens of each cobalt level were machined from the 1.8-cm- (0.71-in.-) thick flat plate with the rolling direction of the plate coincident with the 10-cm
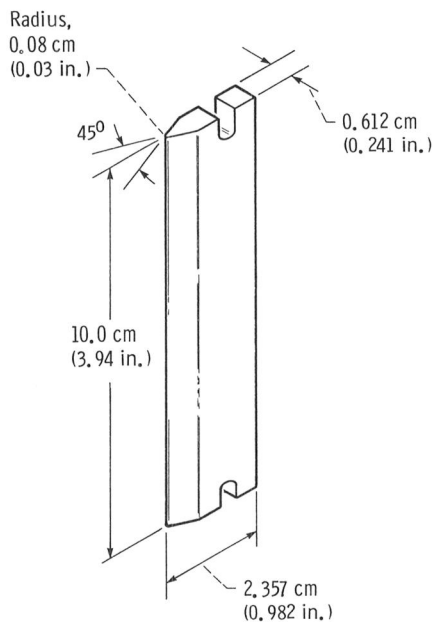
Figure 1.—Geometry of single-wedge specimen.

(3.94-in.) length. Three specimens of each cobalt variation were coated; the result was 15 bare and 15 coated specimens.

Coating

An overlay coating of Ni–18Cr–12Al–0.5Y was applied to one-half of the specimens. Before coating, specimens were grit blasted with aluminum oxide particles. The time between blasting and coating was kept to a minimum. Coating was done by using the arc-plasma spray process in a low-pressure chamber. Specimens were preheated to 870 to 980 °C (1600 to 1800 °F) in a protective environment under 0.07 atm of argon. The specimens were then plasma-sprayed at Mach 2 to 3 with particles of the coating composition that were less than 400 mesh. A uniform coating thickness of 0.1 to 0.15 mm (0.004 to 0.006 in.) was deposited on all surfaces.

Experimental Facility and Procedure

Fluidized-Bed Facility

Figure 2 shows a cutaway drawing of the fluidized-bed test facility. This facility includes one heating bed mounted between two cooling or intermediate temperature beds. The three beds consist of retorts filled with 300- to 500-μm-(0.012- to 0.021-in.-) diameter alumina particles through which air is pumped. Adjustment of the airflow allows the particles to develop a churning, circulating action; hence the name "fluidized." The large number of particles in the beds and their fluid action promote uniform, high heat-transfer rates. A pneumatic, automatically controlled, coupled transfer mechanism was used to transport two specimen holders between beds.

The heating bed is 23 cm (9 in.) in diameter, contains approximately 110 kg (250 lb) of alumina, and has a power
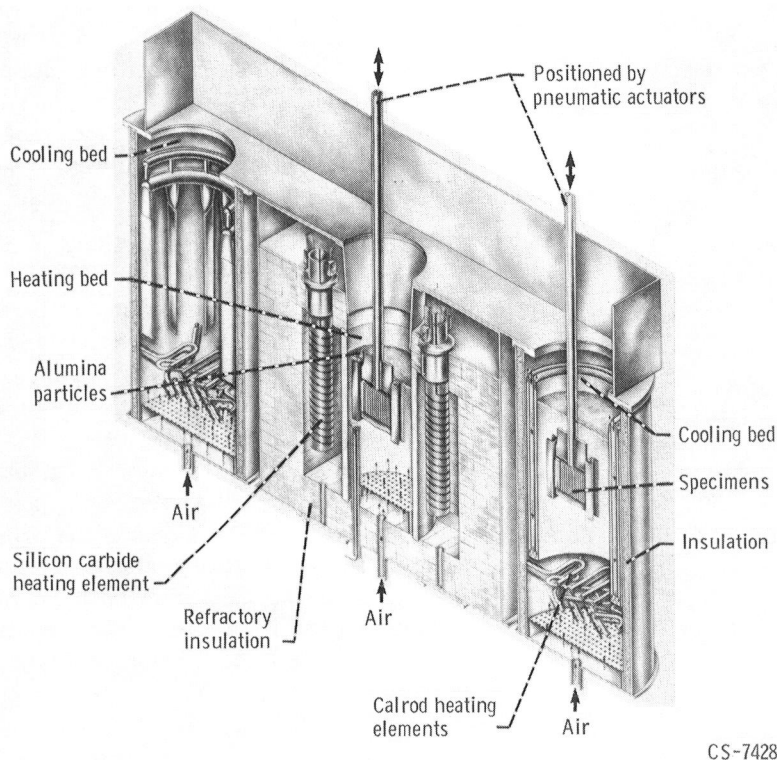
Figure 2.—Fluidized-bed test facility.

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input of 55 kW. The airflow rate of the heating bed is 17 m³/hr (600 ft³/hr). Each cooling bed is 36 cm (14 in.) in diameter and contains about 150 kg (340 lb) of alumina. Each cooling bed uses 12 kW of power and has an airflow of 60 m³/hr (2100 ft³/hr).

Thermal-Fatigue and Oxidation Test Procedure

Comparative thermal-fatigue resistance was determined by simultaneously testing specimens of similar geometry from the different cobalt levels, both bare and coated, and comparing the number of cycles required to initiate the first crack. Triplicate specimens of each of the five cobalt levels in both bare and coated conditions resulted in a total of 30 specimens to be evaluated. Six control (two each of Haynes 188, Inconel 625, and Incoloy 800) and four dummy specimens were also included. The fluidized-bed thermal-fatigue resistance of the three control alloys had been previously determined. The control specimens were included to confirm that data on this series agreed with previous data. Dummy specimens were inserted at the ends of each holder (fig. 3(b)) to ensure similar thermal loading of all test specimens. Figure 3(a) shows the specimen-holding fixture with 20 double-wedge bars (a previous specimen design) mounted. The identical fixture was

5 cm

(a)

Fixture ends

Test specimens

Dummy specimen   Dummy specimen

(b)

(a) Fixture for supporting specimens in fluidized beds.
(b) Section showing arrangement of single-wedge specimens in fixture.

Figure 3.—Specimen-holding fixture.

used for this study except that the single-wedge specimens were alternately positioned as shown in figure 3(b). Each holder contained one of each of the three control alloys and 15 randomly selected bare and coated test specimens; all were placed in positions also chosen at random. The random selection and position was again varied at each inspection time.

During testing the two holders were simultaneously cycled between beds such that one holder was always immersed in the heating bed and the other holder was in either of the two cooling beds, except during the <5-sec transfer time. A cycle consisted of 3 min in the heating bed immediately followed by a 3-min immersion in one of the cooling beds. For the first 5500 cycles of testing, the heating-bed temperature was maintained at 1010 °C (1850 °F) and the cooling-bed temperature at 288 °C (550 °F). From 5501 cycles through the 14 000 cycle limit of testing the heating-bed temperature was increased to 1050 °C (1922 °F) in order to achieve the thermal-fatigue failures. All test specimens were cycled the 14 000-cycle limit except for two bare specimens of the 4.3 wt % cobalt level which were deformed to such an extent after 13 500 cycles that they could no longer be retained in the holder.

Prior to testing and every 500 cycles thereafter, the leading edge of each specimen was visually examined by using a microscope with a magnification of 30. At these examination periods the specimens were also individually weighed to obtain oxidation data. Only the surfaces within ±3.8 cm (±1.5 in.) of midspan were examined for both crack nucleation and growth, thus, end effects on crack behavior were eliminated. The number of cycles to crack initiation was taken as the average of the number of cycles at the last inspection without a crack and the number of cycles at the first inspection with a crack.

Metallographic Procedures

At the completion of cyclic testing, longitudinal- and transverse-cut metallographic specimens were taken from the center of the leading edge of each specimen. The leading edge was chosen as the location for the metallographic specimens because the thermal stresses were higher and the cracks were usually initiated within this area. Figure 4 illustrates the orientations of the metallographic sections. Longitudinal-cut metallographic sections were used to investigate crack initiation and propagation. Transverse-cut sections were used to analyze the interaction between coating and substrate. All specimens were mounted in Bakelite and polished according to ASTM procedures. The specimens were then etched with a reagent containing 33 percent nitric acid, 33 percent acetic acid, 33 percent water, and 1 percent hydrofluoric acid.

Microhardness measurements were taken and averaged at the coating layer, the coating-substrate interface, and the substrate of each coated transverse-cut metallographic section. Measurements were made by using a 100-g load and a pyramid indenter in a Buehler microhardness testing unit. Both diagonals of the diamond-shaped indentation were averaged
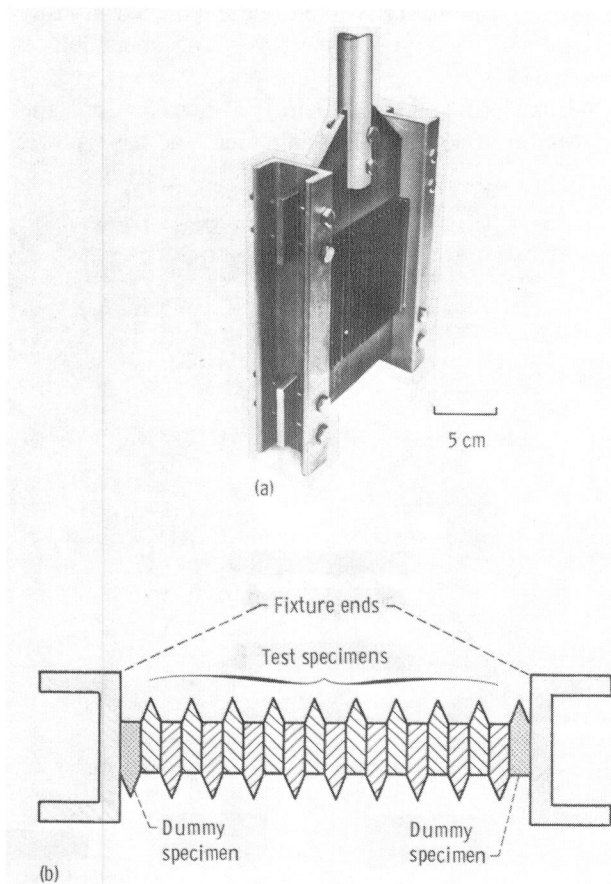
(a) Transverse cut.
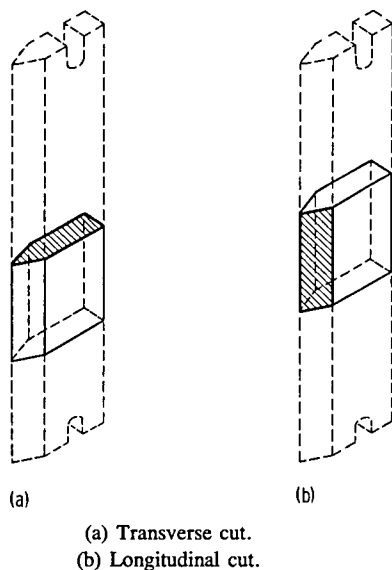(b) Longitudinal cut.

Figure 4.—Orientation of sections for metallographic study.

and used as a basis for calculation of the Vickers hardness number. These measurements determine if there is a correlation between hardness and thermal-fatigue resistance or oxidation resistance with respect to cobalt content.

Results and Discussion

Thermal Fatigue

The numbers of cycles required to initiate cracks in the triplicate specimens of the five bare and five coated cobalt-modified Udimet 700 alloy are listed in table III and plotted in figure 5. For the same specimen geometry and test conditions, the crack initiation varied from 6750 cycles to greater than 14 000 cycles. At the 14 000-cycle limit of testing, five bare and two coated specimens had not cracked. The reproducibility of the test data was good for all but the bare 17 wt % cobalt specimens.

Results of the triplicate tests for each cobalt level plotted in figure 5 were determined by averaging the three cyclic lives. In cases where all specimens for a given composition failed, the result is the average of the three failure lives. In cases where one or two specimens of a given composition did not fail during cycling, the cycles achieved (either 13 500 or 14 000) were assigned to the unfailed specimen(s) and then included in the average. Figure 5 denotes each of the seven unfailed specimens with an arrow at the top of the bar.

The thermal-fatigue results show the best thermal-fatigue life (both bare and coated) to be at 8.6 wt % cobalt. An increase or decrease of cobalt from 8.6 wt % seems detrimental to the thermal-fatigue life. Interestingly, for both the 4.3 and 8.6 wt % cobalt, thermal-fatigue life for coated material was less than that for the bare material.

A regression analysis of the bare specimen data was performed by using the method of reference 30, which

TABLE III.—SUMMARY OF THERMAL-FATIGUE AND OXIDATION DATA

Cobalt, wt %	Bare or overlay coated[a]	Cycles to first crack	Statistical prediction for runout tests	Weight change at 13 500 cycles, percent
0	Bare	8 750	------	−11.22
		6 750	------	−12.58
		8 750	------	−8.68
	Coated	12 250	------	−0.075
		12 250	------	−.113
		9 250	------	−.135
4.3	Bare	>13 500	16 700	−12.15
		>13 500	16 700	−12.62
		10 250	------	−12.64
	Coated	11 250	------	−0.190
		11 250	------	−.134
		12 250	------	−.081
8.6	Bare	>14 000	17 800	−13.14
		13 750	------	−12.19
		>14 000	17 800	−12.99
	Coated	>14 000	------	−0.058
		10 750	------	−.135
		10 250	------	−.27
12.8	Bare	9 250	------	−12.43
		9 250	------	−10.62
		8 250	------	−8.28
	Coated	10 750	------	−0.196
		10 250	------	−.194
		9 750	------	−.150
17.0	Bare	8 250	------	−9.09
		>14 000	16 000	−15.54
		8 750	------	−10.40
	Coated	9 250	------	−0.50
		>14 000	------	−.179
		10 250	------	−1.15

[a]The Ni-18Cr-12Al-0.5Y overlay was 0.1 to 0.15 mm (0.004 to 0.006 in.) thick.

accounts for unfailed units or censored observations. The method involves obtaining an initial least-squares fit by treating the censored data as failures. Then, based upon this initial fit, the expected failure life for each censored observation is estimated. These estimates are then used, instead of the censoring times, to obtain a revised least-squares fit, and new expected failure lives are estimated for the censored values. These are then used in a further least-squares fit. The procedure is iterated until convergence is achieved.

Results of the regression analysis are given in table III and plotted in figure 6. The solid line in the figure includes all data, while the dashed line excludes the unfailed test for
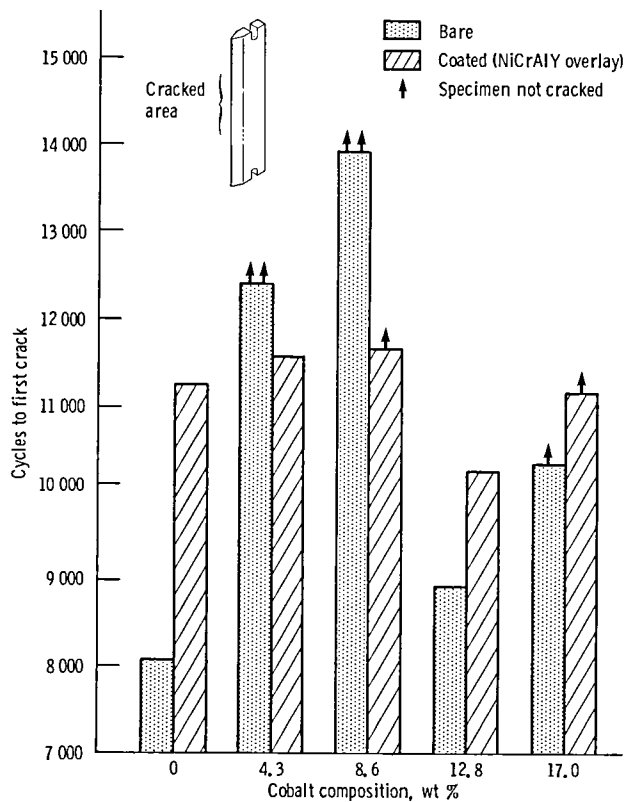
Figure 5.—Comparative thermal-fatigue resistance of cobalt-modified Udimet 700 alloy determined by fluidized-bed cycling.
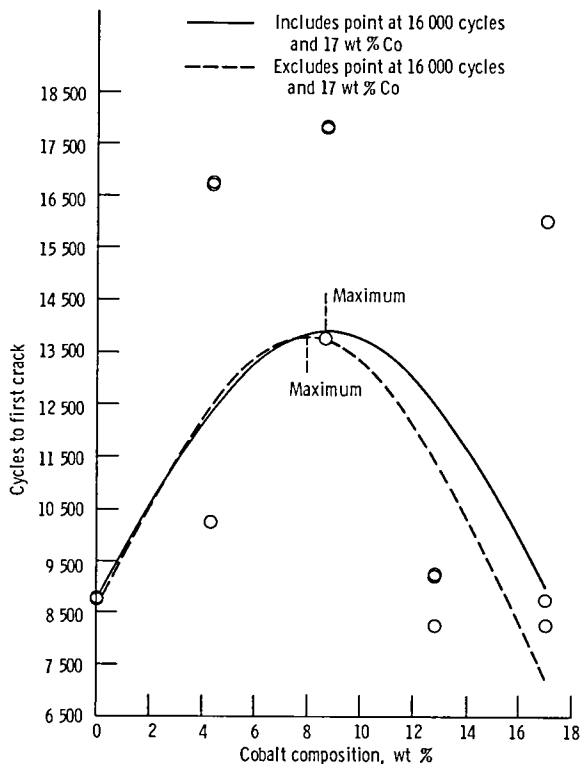
17 wt % cobalt. It was statistically determined that this point was outside the range of data scatter. Excluding the point decreased the lives for levels of cobalt above 8 wt %. Exclusion of the point also decreased the maximum thermal-fatigue life from the 8.6-wt %-cobalt level to the 7.9-wt %-cobalt level, which is about half of the alloy specification. The maximum thermal-fatigue life was determined by setting the first derivative of the best-fit parabola equation to zero and solving for the cobalt level.

Oxidation

Results of oxidation resistance (percent weight loss) are listed in table III and plotted in figure 7. The weight change given is after the 13 500 fluidized-bed cycle, as it was the last inspection to have a complete set of data. At this inspection two of the bare 4.3-wt % bars were removed because of severe deformation.

The oxidation results show that all bare cobalt-modified specimens exhibited weight losses between 10 and 13 percent with no agreement between weight loss and cobalt level. The coated material, however, as noted in figure 7, had weight losses which increased with an increase in cobalt composition. The NiCrAlY overlay coating drastically decreased the weight loss (e.g., at the 0 wt % cobalt level the average weight loss of bare material was 100 times that of the coated material).

Figure 6.—Regression analysis for thermal-fatigue resistance of bare cobalt-modified Udimet 700 alloy.
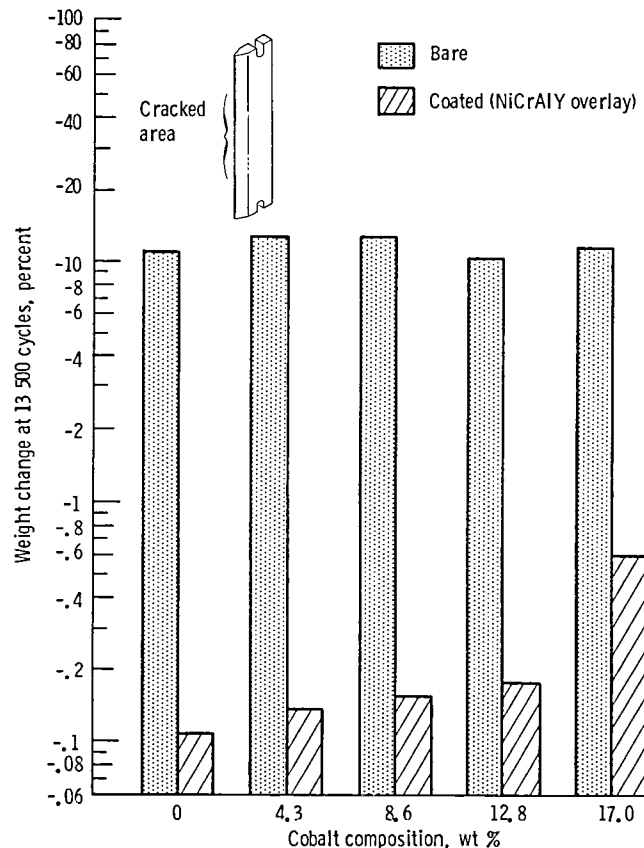
Figure 7.—Comparative oxidation resistance of cobalt-modified Udimet 700 alloy determined by fluidized-bed cycling.

Even at the 17-wt %-cobalt level, the average weight loss of bare material was 21 times that of the coated material.

Metallography

Figure 8 shows representative bare and coated specimens at each cobalt level after testing. All specimens were greatly deformed with the leading edge becoming concave and the trailing edge becoming convex along the 100-mm (3.94-in.) length.

The longitudinal-cut metallographic sections of bare and coated modified Udimet 700 alloy were compared to determine if a correlation existed among cobalt levels, crack initiation, and crack propagation. For each cobalt level (fig. 9), bare specimens exhibited heat checks in the oxide layer along the leading edge. The cracks propagated farther into the oxide diffusion zone for the higher cobalt levels. Microstructures of the longitudinal-cut as-coated specimens (fig. 10) revealed adherence of the NiCrAlY coating to the substrate decreased
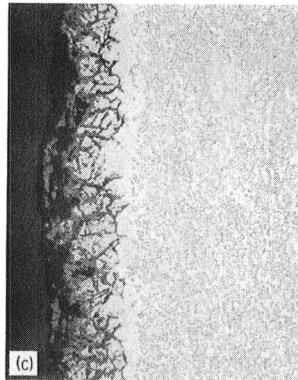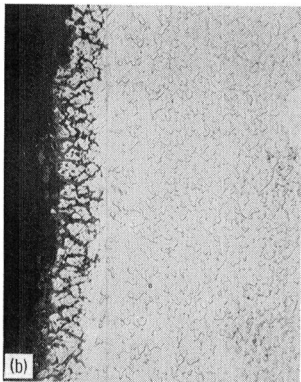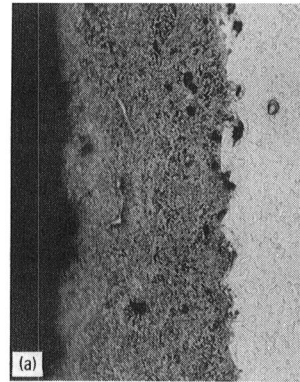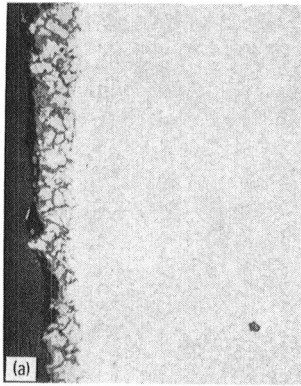

(a) 0 wt %.
(b) 4.3 wt %.
(c) 8.6 wt %.
(d) 12.8 wt %.
(e) 17.0 wt %.
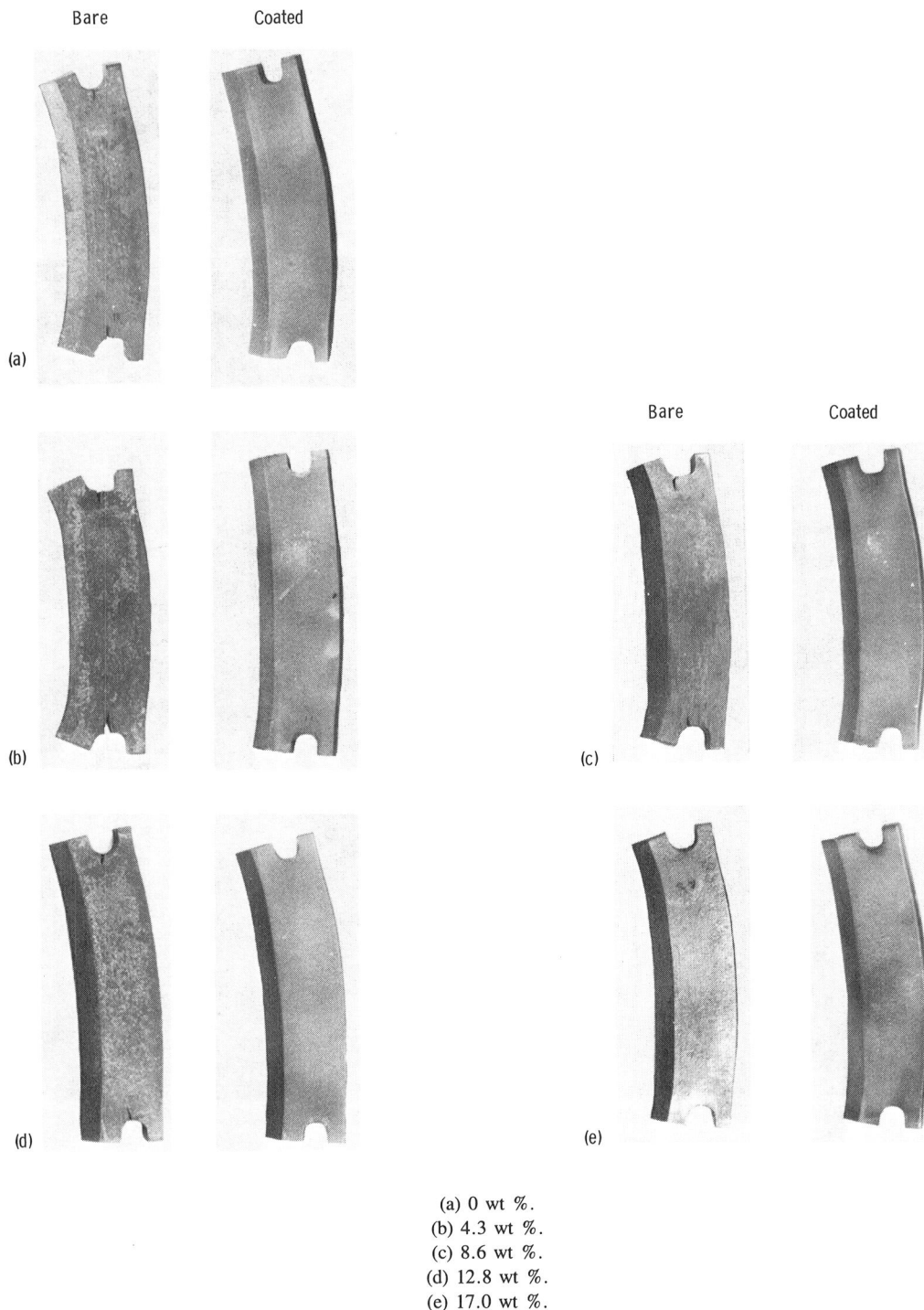
Figure 8.—Deformation of specimens at each cobalt level.
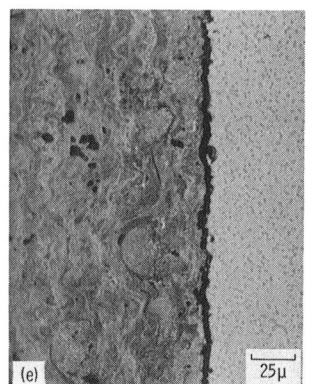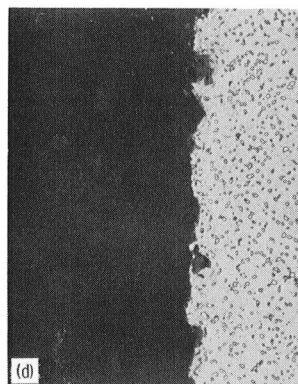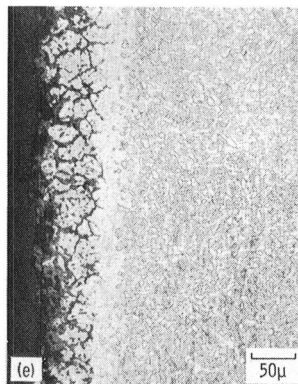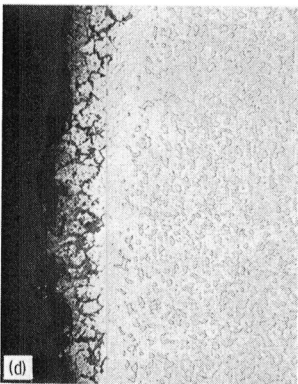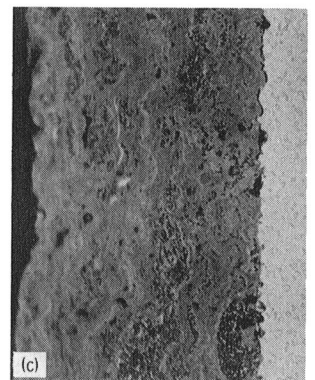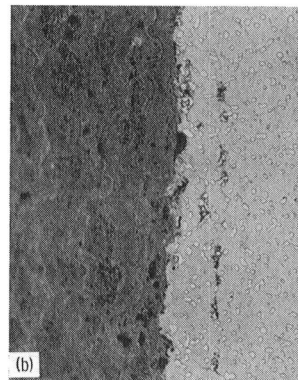
(a) 0 wt %.
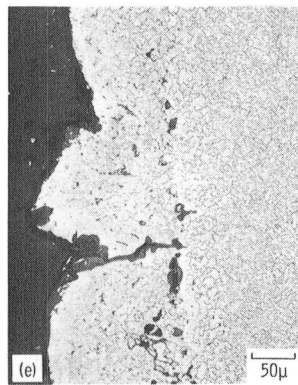(b) 4.3 wt %.
(c) 8.6 wt %.
(d) 12.8 wt %.
(e) 17.0 wt %.

Figure 9.—Photomicrographs of longitudinal-cut bare specimens at each cobalt level after 14 000 cycles.
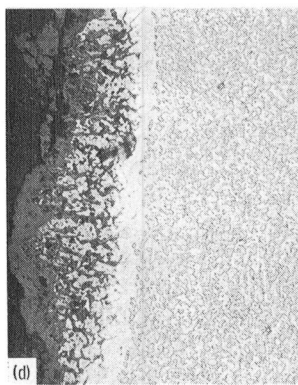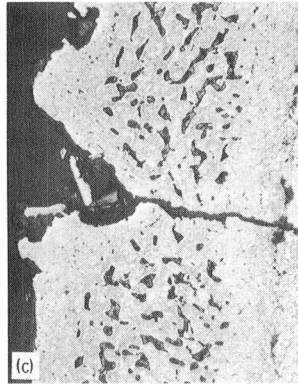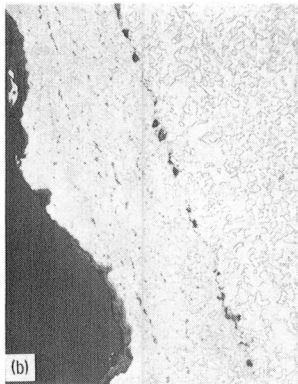
(a) 0 wt %.
(b) 4.3 wt %.
(c) 8.6 wt %.
(d) 12.8 wt %.
(e) 17.0 wt %.

Figure 10.—Photomicrographs of as-coated longitudinal-cut specimens at each cobalt level.
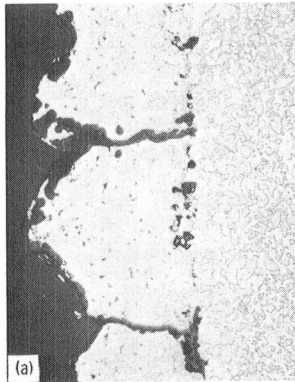
(a) 0 wt %.
(b) 4.3 wt %.
(c) 8.6 wt %.
(d) 12.8 wt %.
(e) 17.0 wt %.

Figure 11.—Photomicrographs of coated longitudinal-cut specimens at each cobalt level after 14 000 cycles.

with increasing cobalt levels. It can be seen in figure 11 that the longer heat checks initiated at sites of greater coating degradation and were propagated through voids between the coating and metal interface.

For transverse-cut as-coated specimens, adherence of the NiCrAlY coating to the substrate was poor. (See fig. 12.) The photomicrograph for the 12.8 wt % specimen was not available. The coating-substrate interface at each cobalt level was very porous. The coating itself consisted of large, unevenly distributed particles. The transverse-cut section of the leading edge at each cobalt level after cyclic testing can be seen in figure 13. These microstructures illustrate a greater degradation of the coating as cobalt content increases. Confirmed in figure 7, figure 13 illustrates that the percent weight loss in the coating increases as cobalt content increases. The oxidation resistance of the bare specimens was very poor but did not depend on cobalt content. From the percent weight change data in figure 7, the coated modified Udimet 700 alloy specimens with the lower cobalt levels demonstrate the best oxidation resistance. As the cobalt content increased, the oxidation resistance decreased.

Since the specimens with lower cobalt levels illustrated both superior oxidation resistance and adherence to the substrate, one might expect that they would possess superior crack resistance; however, the contrary was true. The specimen containing 8.6 wt % cobalt showed the best crack initiation and propagation behavior but possessed very poor oxidation resistance. The coating was extremely porous, but major cracks were initiated only at severe surface defects. Cracks propagated beyond the coating-substrate interface and into the substrate only at portions of severe coating degradation.

The Vickers microhardness numbers taken after testing of the coating, coating-substrate interface, and substrate are presented in table IV. The coating of the specimen containing 8.6 wt % cobalt showed increased hardness over its substrate, whereas, other specimens showed only a slight increase or softening effect relative to their respective substrates. This significant increase in hardness may have contributed to the increase in thermal-fatigue resistance of the specimen containing 8.6 wt % cobalt.
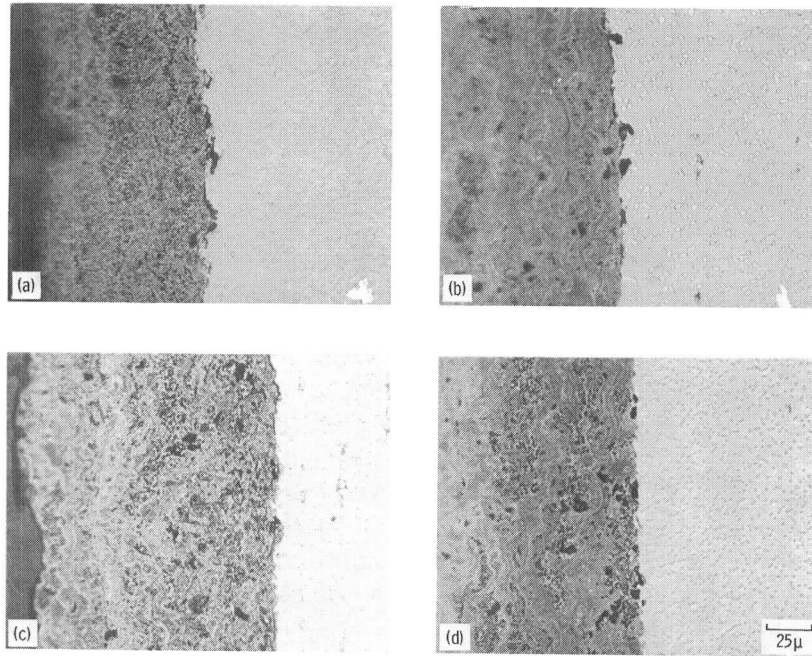
(a) 0 wt %.
(b) 4.3 wt %.
(c) 8.6 wt %.
(d) 17.0 wt %.

Figure 12.—Photomicrographs of as-coated transverse-cut specimens at four cobalt levels.

TABLE IV.—SUMMARY OF
MICROHARDNESS DATA

Cobalt, wt %	Vickers microhardness		
	Coating	Coating-substrate interface	Substrate
0	290	320	316
4.3	314	310	308
8.6	382	359	344
12.8	322	345	383
17.0	312	348	370

(a) 0 wt %.
(b) 4.3 wt %.
(c) 8.6 wt %.
(d) 12.8 wt %.
(e) 17.0 wt %.

Figure 13.—Photomicrographs of coated transverse-cut specimens at each cobalt level after 14 000 cycles.

Summary of Results

The effect on thermal-fatigue and oxidation resistance of modifying the cobalt level in wrought Udimet 700 alloy was determined by using the fluidized-bed technique. Cobalt was replaced by nickel in making five modified alloys of which the cobalt compositions were 0, 4.3, 8.6, 12.8, and 17.0 wt %. Triplicate specimens of all heats were simultaneously tested in both the bare and coated (NiCrAlY overlay) conditions by thermally cycling single-wedge specimens between fluidized-bed furnaces. Bed temperatures were 1010 and 288 °C (1850 and 550 °F) for the first 5500 cycles, after which the hot-bed temperature was increased to 1050 °C (1922 °F) through the 14 000-cycle limit of testing. Immersion time in each bed was 3 min. Thermal-fatigue resistance was based on the number of cycles required to initiate a crack. The oxidation resistance (percent weight loss) is presented for 13 500 thermal cycles. The major results obtained are as follows:

(1) The best thermal-fatigue resistance (both bare and coated) was obtained for 8.6 wt % cobalt. A regression analysis for the bare specimen data showed the optimum composition to be between 7.9 and 8.6 wt % cobalt (i.e., about half the level normally specified for the alloy).

(2) All five bare alloys exhibited weight losses between 10 and 13 percent after 13 500 thermal cycles.

(3) The coated material had greater weight losses the larger the cobalt composition, although coating drastically decreased the weight loss compared to bare material.

(4) During testing, all specimens greatly deformed with the leading edge becoming concave and the trailing edge becoming convex along the 100-mm (3.94-in.) length.

(5) All bare specimens exhibited heat checks in the oxide layer along the leading edge. The cracks propagated farther into the diffusion zone for the higher cobalt levels.

(6) The greatest degradation of the NiCrAlY coating occurred with the highest cobalt composition. Oxidation resistance increased as cobalt content decreased.
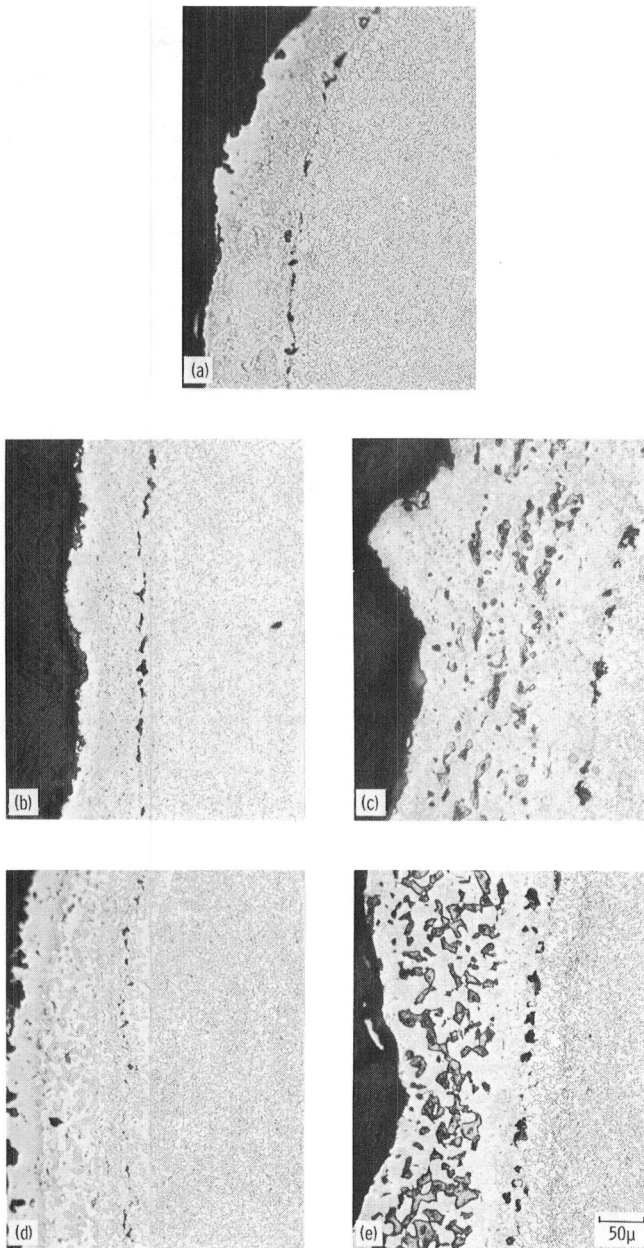
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National Aeronautics and Space Administration
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15. Supplementary Notes

16. Abstract

Comparative thermal-fatigue and oxidation resistances of cobalt-modified wrought Udimet 700 alloy (obtained by reducing the cobalt level by direct substitution of nickel) were determined from fluidized-bed tests. Bed temperatures were 1010 and 288 °C (1850 and 550 °F) for the first 5500 symmetrical 6-min cycles. From cycle 5501 to the 14 000-cycle limit of testing, the heating bed temperature was increased to 1050 °C (1922 °F). Cobalt levels between 0 and 17 wt % were studied in both the bare and NiCrAlY overlay coated conditions. A cobalt level of about 8 wt % gave the best thermal-fatigue life. The conventional alloy specification is for 18.5 wt % cobalt, and hence, a factor of 2 in savings of cobalt could be achieved by using the modified alloy. After 13 500 cycles, all bare cobalt-modified alloys lost 10 to 13 percent of their initial weight. Application of the NiCrAlY overlay coating resulted in weight losses of 1/20 to 1/100 of that of the corresponding bare alloy.

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