Effect of Tantalum Additions to a Cobalt-Chromium-Nickel Base Alloy

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An investigation by electron diffraction, transmission and scanning electron microscopy, and energy-dispersive X-ray analysis has shown that Ta additions to a 40-30-30 Co-Cr-Ni-base alloy strengthen by ordering and by formation of coherent α-Co_3Ta precipitate. However, increasing Ta content increases the proportion of the hexagonal phase and decreases ductility.

The effect of additions of tantalum (Ta) to a 40-30-30 cobalt (Co) -chromium (Cr) - nickel (Ni) alloy has been studied for several years at the University of Michigan. Mechanical properties of a series of these alloys have been reported by Mohammed and Asgar.[1] Those results showed that an alloy containing 13% Ta would have an ultimate tensile strength of 124,000 psi, a yield strength of 90,000 psi, and an elongation of 10%. There is a sharp change in these properties around 12 to 13% Ta.

In the present study, this system was examined by electron diffraction, transmission and scanning electron microscopy, and energy-dispersive X-ray analysis to identify the microstructure associated with these mechanical properties.

Materials and Methods

Specimens were prepared by conventional investment casting techniques with the use of a wax pattern, phosphate-type investment, and centrifugal casting from a zircon crucible under argon. The structures of the as-cast specimens are extremely sensitive to the casting cross-section, which of course influences the cooling rate. Therefore, one series of specimens was cast in the form of 2.5-mm plates; another was cast in 0.6-mm plates. The plates were then ground down mechanically to about 0.15 mm and electropolished in perchloric acid-ethanol to thicknesses suitable for electron microscopy.

Results and Discussion

Alloy compositions containing up to 16.7% Ta consist primarily of a face-centered cubic matrix phase and an interdentritic hexagonal phase. Sometimes minor amounts of σ phase are present. Depending on the Ta content and the casting conditions, there also may be fine precipitates of α-Co_3Ta, β-Co_3Ta, and γ-Co_2Ta.

Figure 1 shows the distribution of the β (hexagonal) phase in these samples as revealed by scanning electron microscopy. The light areas have been identified from electron diffraction patterns as the β phase, which evidently dissolves more slowly in the etching solution than does the surrounding α phase.

The numbers on the micrographs indicate the nominal, as weighed, Ta contents in weight percentages. The actual compositions are somewhat different.

The table lists the results of energy-dispersive X-ray analysis of these alloys. For each specimen type the first row lists the weight percentages of each component as weighed for the casting; the second row indicates the actual compositions as determined by analysis. The castings contained an average of 19% more Ta, 8% more Cr, 9% less Co, and 6% less Ni than weighing indicated. The remaining two rows for each casting represent average compositions of the face-centered cubic (α) and hexagonal (β) phases.

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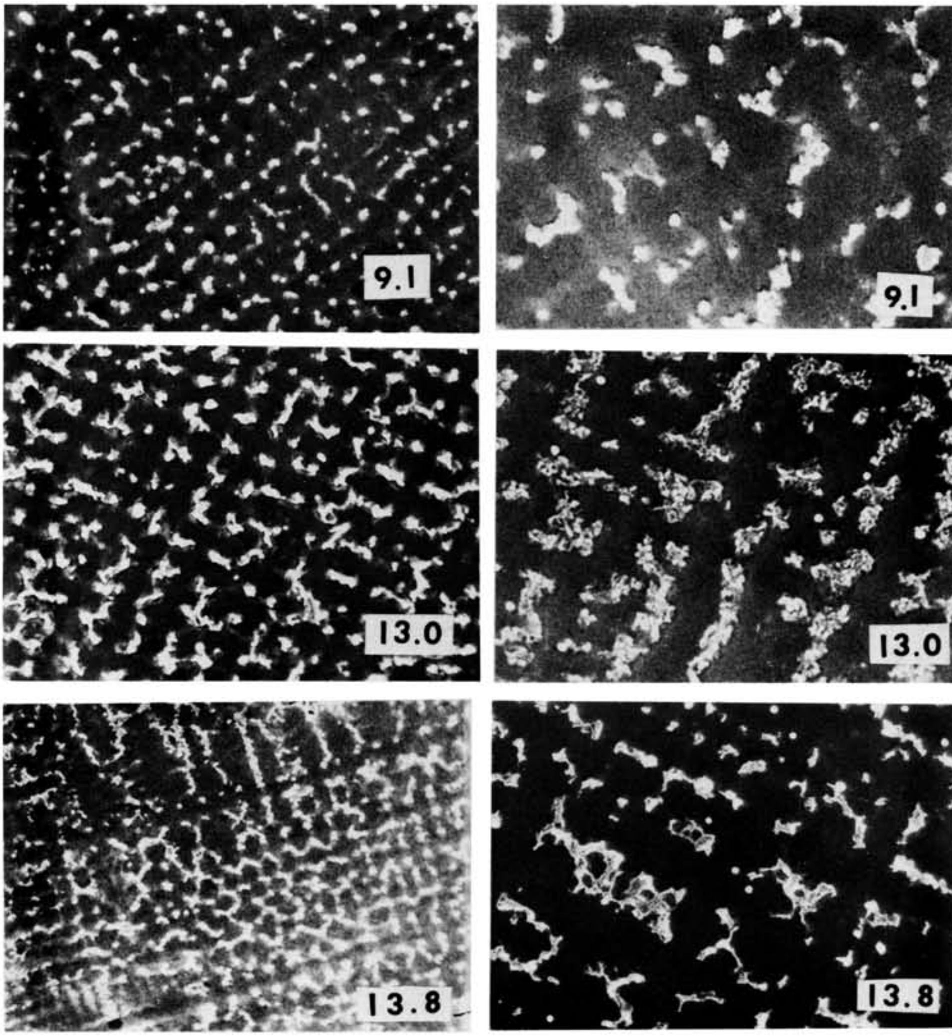

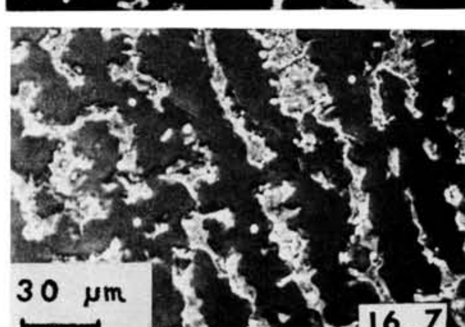

FIG 1.—Scanning electron micrographs show distribution of β phase in Co-Cr-Ni-Ta alloys. *Top,* 0.6-mm castings; *right,* 2.5-mm castings.

TABLE
ENERGY DISPERSIVE X-RAY ANALYSES OF CO-CR-NI-TA ALLOYS

Casting	Phase Fraction of β		Ni	Co	Cr	Ta
Thin castings (0.6 mm)						
		Weighed	27.3	36.3	27.3	9.1
9.1% Ta	0.19	Analyzed	26.3	34.0	30.1	9.6
		α	26.5	34.5	36.0	3.0
		β	15.2	21.0	17.6	46.2
		Weighed	26.1	34.8	26.1	13.0
13.0% Ta	0.35	Analyzed	24.2	32.3	27.7	15.8
		α	25.8	35.2	35.6	3.4
		β	16.1	21.7	17.8	44.4
		Weighed	25.9	34.5	25.9	13.8
13.8% Ta	0.41	Analyzed	24.5	31.3	28.2	16.0
		α	25.9	34.2	34.6	5.3
		β	18.7	23.5	18.8	39.0
Thick castings (2.5 mm)						
		Weighed	27.3	36.3	27.3	9.1
9.1% Ta	0.16	Analyzed	25.8	33.2	30.0	11.0
		α.	26.4	35.0	31.0	7.6
		β	17.2	21.9	20.2	40.7
		Weighed	26.1	34.8	26.1	13.0
13.0% Ta	0.33	Analyzed	24.4	31.6	28.2	15.8
		α	25.9	33.7	30.2	10.2
		β	16.9	23.9	18.8	40.4
		Weighed	25.9	34.5	25.9	13.8
13.8% Ta	0.37	Analyzed	24.6	31.3	28.2	15.9
		α	24.8	33.1	30.3	11.8
		β	15.1	22.5	16.4	46.0
		Weighed	25.0	33.3	25.0	16.7
16.7% Ta	0.47	Analyzed	21.9	29.0	26.6	22.5
		α	24.2	32.9	29.7	13.2
		β	13.2	19.1	17.0	50.7

Note: All values reported as weight percentages.

Analyses of σ phase are not available for each of the castings, but a typical analysis is 23% Ni, 27% Co, 24% Cr, and 25% Ta.

As the casting cooled, the α phase was the first to solidify. Its Ta content ranged from 3 to 13% for the various compositions, but was always less than the overall Ta content. As the temperature decreased, the remaining, Ta-rich (40 to 45%) material solidified in a hexagonal structure, despite the fact that Ta additions are reported to favor the face-centered cubic structure.[2] The Co-Ta binary phase diagram,[3] for example, shows no hexagonal phase for a Ta content greater than 7%.

FACTORS AFFECTING DUCTILITY.—The system studied here showed an increasing amount of hexagonal phase with increasing Ta content, and it is in this phase that failure is initiated. Figure 2 is a scanning electron micrograph of a longitudinal section of a tensile bar pulled to failure and shows cracks in the β phase. Figure 3 is another such specimen in which there is evidence of pulling apart at the α-β interface. Fracture surfaces of the high-Ta, low-ductility specimens suggest that failure has occurred by interface shearing; the dendritic structure was left (Fig 4).

The thinner castings showed slightly more β phase than did the thicker ones, and the α phase contained less Ta. In short, there was less time for α formation and Ta segregation to occur before the solidus was reached.

Also, in the thinner specimens, the distribution of α and β phases was on a much finer scale than that in the thicker castings of the composition (Fig 1).

STRENGTHENING MECHANISMS.—At 9.1% Ta (charge composition), both the α and β phases were solid solutions (Fig 5). At 13%,

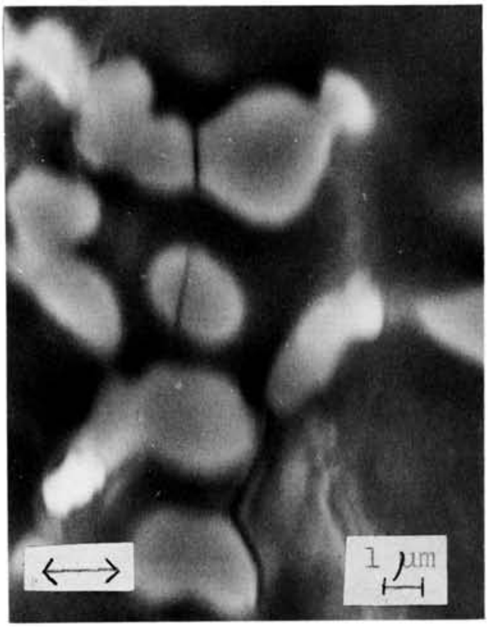

FIG 2.—Scanning electron micrograph of longitudinal section of tensile bar pulled to failure. *Arrow*, tensile direction.

FIG 3.—Scanning electron micrograph of longitudinal section of tensile bar pulled to failure. *Arrow*, tensile direction.

the α phase, which is the predominant phase, was well ordered but there was no evidence of precipitate. Ordering is a well-recognized strengthening mechanism; it increases the Burger's vector of dislocations and impedes dislocation motion, particularly if antiphase boundaries are present.

At 13.8% Ta, a fine (< 50 A) coherent precipitate was found in the thicker castings (Fig 6). It is described as α-Co_3Ta, although its unit cell dimensions correspond to face-centered cubic Co rather than the slightly larger cell of α-Co_3Ta. With higher concentrations of Ta, the larger cell is found, the precipitate particles are larger, and at 16.7% some are no longer coherent. In fact, at this latter composition there also is precipitate in the hexagonal phase; it is γ-Co_2Ta, which has a hexagonal structure.

In the thinner, 0.6-mm specimens, precipitate was not observed until Ta concentrations increased to more than 13.8% (Fig 7).

HEAT-TREATED SPECIMENS.—Of course none of these structures represents the equilibrium condition for this system. When the alloys were heat-treated at 700 C for 20 hours, equilibrium was approached (but not reached). Heat-treated specimens with Ta as low as

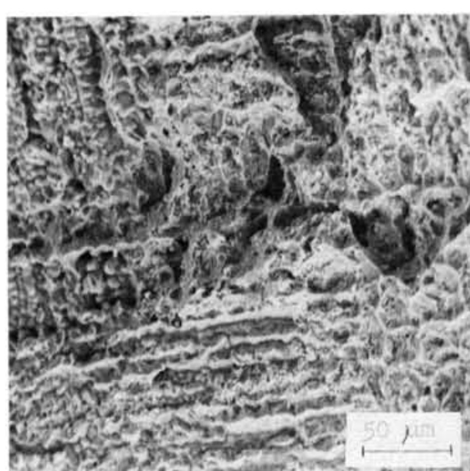

FIG 4.—Scanning electron micrograph of transverse section of 9.1% Ta tensile bar pulled to failure.

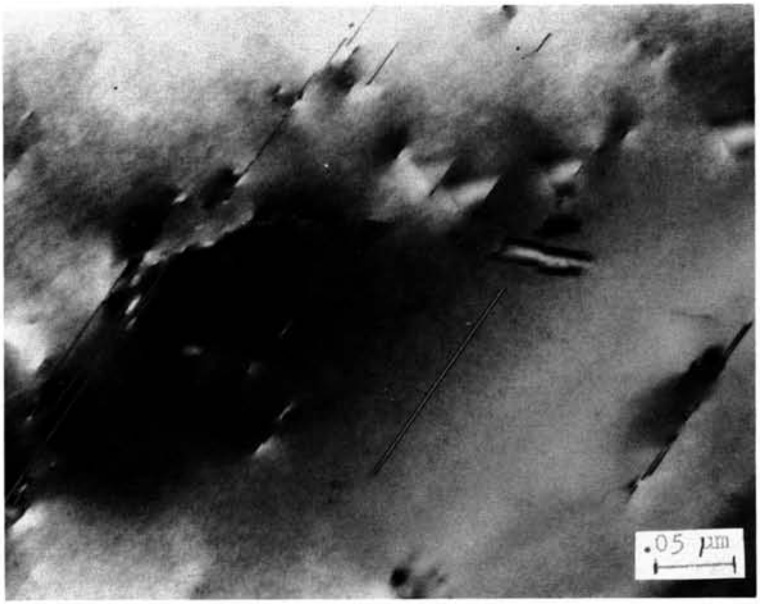

FIG 5.—Transmission electron micrograph of (110) α phase in 9.1% Ta alloy.

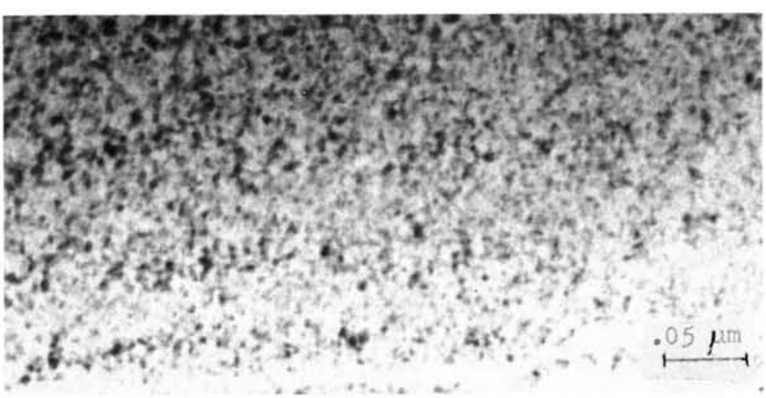

FIG 6.—Transmission electron micrograph of (110) ordered α phase in 13.8% Ta alloy.

FIG 7.—Transmission electron micrograph of (100) ordered α phase and α-Co_3Ta in 13.8% Ta alloy.

FIG 8.—Transmission electron micrograph of (110) α phase and α-Co_3Ta in heat-treated 9.1% Ta alloy.

9% contained fine α-Co_3Ta precipitate in some regions of the α phase (Figs 8-10).

Higher Ta compositions contained larger precipitates (Fig 11) and also precipitates (β-Co_3Ta and γ-Co_2Ta) in the hexagonal phase. In the Co-Ta system, α-Co_3Ta is described as a metastable phase and β-Co_3Ta is the equilibrium phase at 700 C.

Sigma phase.—This study has not included quantitative information on how much σ phase occurs in each composition, but it has suggested that the embrittling influence of the σ phase may have been overestimated, at least for this system.

For example, Figure 12 shows a specimen with a considerable quantity of σ phase (the needles) surrounding each island of hexagonal phase. Yet this is a section of a tensile

Fig 9.—Transmission electron micrograph of (130) α phase and α-Co_3Ta in heat-treated 9.1% Ta alloy.

FIG 10.—Transmission electron micrograph of (100) α phase and α-Co_3Ta in heat-treated 9.1% Ta alloy.

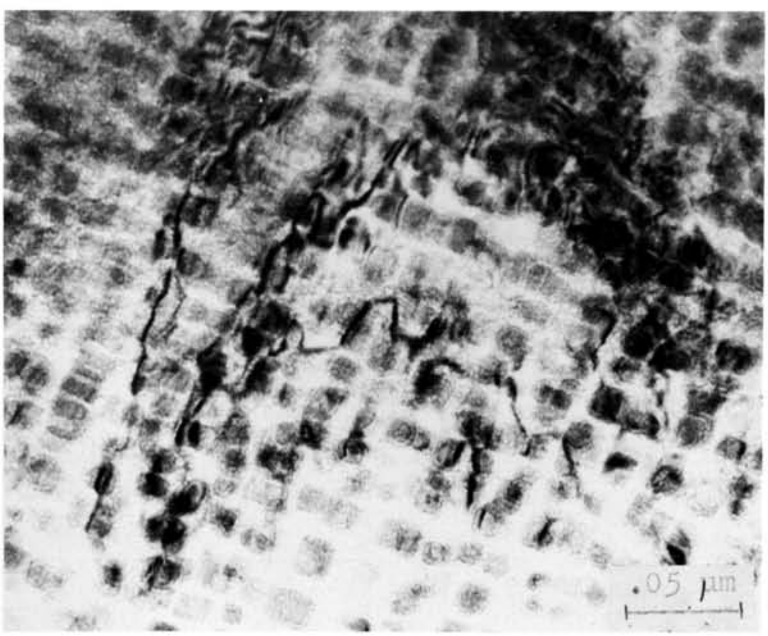

FIG 11.—Transmission electron micrograph of (120) α phase and α-Co_3Ta in heat-treated 16.7% Ta alloy.

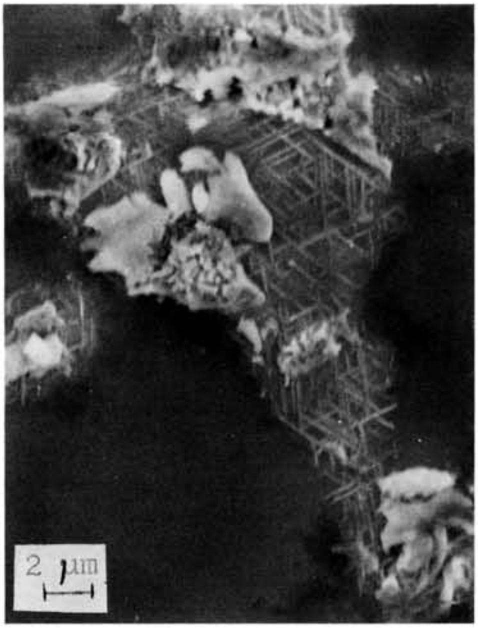

FIG 12.—Scanning electron micrograph of 9.1% Ta alloy shows α, β, and σ phases.

bar with an elongation of 14.5%; and failure has started in the β phase, not in the σ phase.

Conclusions

As the Ta concentration is increased in this alloy system, strengthening is increased first by ordering of the Ta in the face-centered cubic phase and later by formation of a fine, coherent precipitate, α-Co_3Ta. However, increasing the Ta concentration also increases the amount of the more brittle hexagonal phase and ductility decreases.

A desirable combination of these properties for dental applications was reported[1] for 13% Ta, where strengthening is by ordering and elongation is about 10% for the 2.5-mm castings. In practical situations, where the thickness of partial denture clasps, for example, may vary between 1 and 2 mm, Ta concentrations slightly less than 13% will be needed to achieve the desired properties. The thicker portion of such a casting would have a slightly different microstructure, with less hexagonal phase and more Ta in each phase; hence, it would have greater strength and greater ductility than the clasp region. The composition should be selected for optimum properties in the clasp. A slower cooling rate should improve the properties of these alloys.

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