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Metallurgical Characteristics of Titanium-Alloy Foil Prepared by Electron-Beam Evaporation

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The supersonic titanium aircraft has requirements for high-strength titanium-alloy foil for honeycomb structures. In conventional rolling of such alloys as titanium–6% aluminum–4% vanadium, multiple high-vacuum anneals are required to reach the thin-foil gages, from 0.001–0.004 in., used for honeycomb cores. The advantages of electron-beam evaporation and deposition in the desired thicknesses, and without rolling and multiple vacuum annealing, are studied. The present research program is designed to prove that foils of such alloys, produced by EB evaporation on a moving substrate, are equivalent to the rolled products. EB foils easily meet the chemical and mechanical property requirements of aerospace specifications. Bend tests are superior to the rolled foil. The metallurgical characteristics have been evaluated using optical micrography and electron micrography with replica, transmission, and scanning techniques. The deposits are fully dense and of grain sizes from 0.2–0.8 μ. Microprobe analyses indicate that the chemical composition is uniform and contains alpha and beta phases. All metallurgical characteristics of EB evaporated foils appear to be suitable for the intended end uses. Evaluations in the form of actual honeycomb structures are underway.

Introduction

The advent of the "Mach-2-Plus" aircraft has made the "all-titanium" vehicle a present day reality. At more than twice the speed of sound, large areas of the vehicle skins will operate at temperatures above 500°F, the upper limit for current aluminum-base alloys. Design engineers are using ever greater quantities of titanium alloys for vehicle structures and skins in the temperature range of 400°–500°F. Honeycomb structures of high-strength titanium alloys, such as Ti–6Al–4V, would be very desirable if the cost were not excessive. However, the cost of producing the honeycomb foil thicknesses [0.001–0.004 in. (0.003–0.01 cm)] of this alloy by conventional rolling methods is prohibitive because of the many vacuum anneals required, as described by Sauvageot.[1]

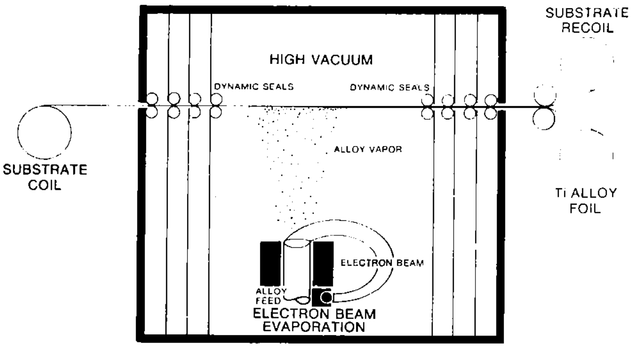


FIGURE 1. Continuous strip line using electron-beam vapor deposition.

Bunshah and Juntz[2] described the use of electron-beam evaporation and condensation to prepare experimental quantities of thin-gage titanium deposits. Smith [3] described vacuum evaporation at high rates, using electron-beam technology; and Smith and Hunt[4] outlined various methods for continuous high-vacuum strip processing.

The evaporation and condensation of metal and alloys into solid, fully dense deposits, therefore, is not novel. The unique feature of the present research program is the ability to deposit an alloy on a moving substrate strip in such a way that the deposit can be separated readily from the strip and wound into a continuous coil of uncontaminated foil.

Description of the Electron-Beam Vapor Deposition Process

In a continuous electron-beam evaporation unit, the substrate strip would be uncoiled from unwinding gear at ambient pressure at one end of the equipment, would pass through a series of vacuum roll-seals into a high-vacuum chamber (10^{-4}–10^{-6} Torr). The substrate strip preheating, and the EB evaporation and condensation all would take place within the high-vacuum chamber. The strip, coated with a uniform thickness of deposited alloy, would pass through a cooling chamber and out to atmospheric pressure through another series of vacuum roll-seals, where the foil and the substrate strips would be separated and recoiled, as shown in Fig. 1.

Table I. Typical chemical analysis of Ti-6Al-4V foils.

	Al	V	Fe	C	N	O	H	Other elements	Ti
AMS 4911B	5.50 6.75	3.5 4.5	0.30 max	0.08 max	0.05 max	0.20 max	0.015 max	max 0.40	Bal.
	5.62	3.99	0.07	0.02	0.0113	0.12	0.0023	0.40	in.
	5.77	4.46	0.30	0.025	0.0042	0.10	0.0056	0.40	in.
	5.73	4.13	0.07	0.020	0.0047	0.15	0.0078	0.40	in.
	5.98	4.56	0.09	0.024	0.0038	0.14	0.0078	0.40	in.
	5.55	3.92	0.13	0.017	0.0056	0.12	0.0046	0.40	in.
	5.71	4.06	0.08	0.020	0.0156	0.10	0.0031	0.40	in.
	6.73	3.54	0.19	0.013	0.0077	0.12	0.0018	0.40	in.
	6.12	3.52	0.16	0.019	0.0028	0.087	0.0017	0.40	in.
	5.94	3.84	0.20	0.026	0.0059	0.14	0.0112	0.40	in.
	6.14	3.63	0.15	0.021	0.0084	0.13	0.0053	0.40	in.

In order to evaluate the titanium-alloy foils in terms of aerospace requirements, a laboratory unit was designed to simulate as nearly as possible the conditions which would prevail in the continuous unit. The evaporation source of vapor can be fed continuously with bar, rod, or wire of suitable composition. The substrate is preheated and passed over the source at a controlled rate to obtain various thicknesses of foil. Samples of thicknesses from 0.001 to 0.009 in. (0.003–0.02 cm) have been made in Ti–6Al–4V alloy.

Properties of Titanium-Alloy Foils

Visual and Dimensional Characteristic

The foil samples, when deposited on polished substrate, have a bright finish on the substrate side and an appearance slightly less bright on the condensate side. Under proper deposition conditions, samples have been made with dimensional tolerances of plus or minus 10% of nominal thickness when measured from side to side and end to end. The maximum size of sample on present equipment is approximately 8×30 in. On production equipment, coils of 12-in. (30.5-cm)-wide foil by 500–1000 ft (150–300-m) lengths should be possible, with thickness tolerances approaching plus or minus 5% of nominal gage.

Chemical Composition

The chemical analysis conforms to Aerospace Material Specification No. 4911 B, as shown in Table I. In fact, the impurity level is somewhat lower than the starting feed stock, as a result of removal of small amounts of interstitial impurities by EB refining.

Mechanical Properties

The mechanical properties of foils deposited on properly preheated substrates consistently exceed the strength requirements of AMS 4911 B specification for annealed Ti–6Al–4V: 134 000 psi minimum ultimate tensile strength, and 126 000 psi minimum yield strength. This specification requires a minimum tensile elongation of 6% for nominal thicknesses between 0.008 and 0.025 in. (0.02 and 0.06 cm), but does not specify a minimum elongation for nominal thicknesses below 0.008 in. (0.02 cm). Even though a number of foil specimens, in the "as-deposited" condition, show elongations below 2%, they readily pass the specified bend test around a diameter equal to nine times the thickness (9*T*). Samples can be bent 180° around a diameter equal to less than five times thickness; and many have a bend factor less than one times thickness.

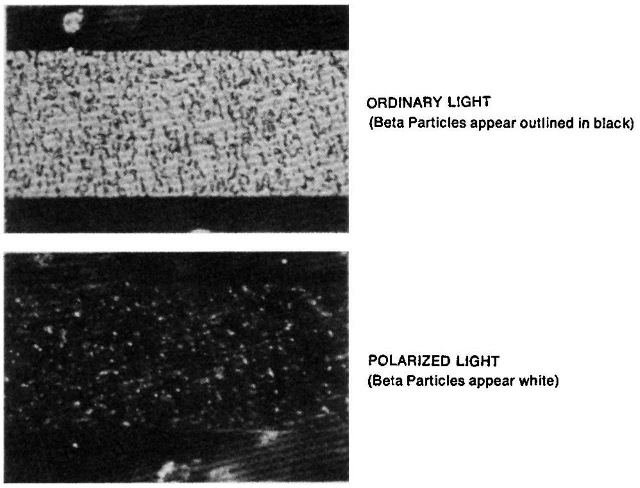
Tensile strengths, elongations, modulus of elasticity (*E*), and bend test data of typical as-deposited foil samples are shown in Table II. It will be noted that yield strengths in the 140–170 KSI range are not uncommon (10%–35% higher than the minimum specified). Higher tensile yield and ultimate strengths have been obtained, but with corresponding lower values for tensile elongation.

Metallurgical Characteristics

Metallographic examination of the Ti–6Al–4V foil samples shows extremely fine grain size in the as-deposited condition. Beta particles in an alpha matrix are barely distinguishable at 750X magnification. The electron microscope is able to resolve the beta particles at 4000X. However, after annealing, the beta particles are clearly visible at 750X magnification, as shown in Fig. 2, using both bright-field and polarized lighting.

Table II. Typical mechanical properties of Ti 6–4 foils as deposited by electron-beam vapor deposition.

AMS 4911B Specification	U.T.S. KSI 134 min.	Y.S. KSI 126 min.	Elong. % ···	$E\times10^{-6}$ 16.4	Bend test Dia =9*T* (9 ×thickness)	Thickness
	140	140	8.0	16.5	<1*T*	0.0025 in.
	152	152	4.0	14.2	<1*T*	0.0025 in.
	145	145	1.0	17.5	2*T*	0.0045 in.
	140	140	4.9	15.6	1*T*	0.005 in.
	138	138	11.0	15.2	<1*T*	0.0052 in.
	139	138	2.0	16.0	<1*T*	0.0052 in.
	142	139	5.0	17.5	<1*T*	0.0052 in.
	142	142	1.0	16.3	2*T*	0.0020 in.
	140	140	1.0	15.3	3*T*	0.0029 in.
	170	170	1.5	15.6	1*T*	0.003 in.
	160	156	1.5	16.7	<1*T*	0.0015 in.



ORDINARY LIGHT
(Beta Particles appear outlined in black)

POLARIZED LIGHT
(Beta Particles appear white)

FIGURE 2. Photomicrographs of Ti–6Al–4V annealed electron-beam evaporated 0.0014-in. (0.04-cm) foil (750X).

As with most vapor-deposited alloys, the crystals tend to grow in a columnar manner, perpendicular to the substrate. This is clearly visible when comparing micrographs of samples taken perpendicular to the substrate (Fig. 2) with transmission electron micrographs of the equiaxed view of a plane parallel with the substrate, as seen in Fig. 3. This transmission electron micrograph at 105 000X clearly shows the beta particles in the grain boundaries of the hexagonal alpha crystals. The grain size varies from about 0.2–0.8 μ, depending upon the preheat temperature of the substrate.

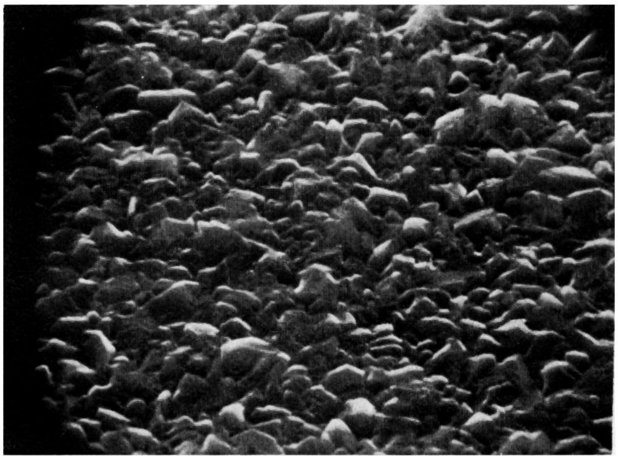


FIGURE 4. Scanning electron micrograph electron-beam Ti–6Al–4V foil "condensate side" (10 000X).

Scanning electron micrographs of the surface of the foil on the condensate side at 10 000X (Fig. 4) show the particle size of the deposited hexagonal crystals of alpha titanium.

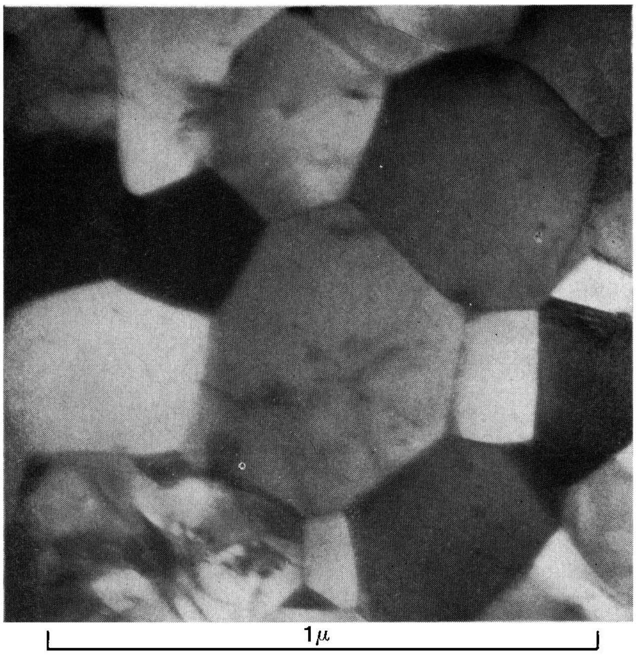


FIGURE 3. Transmission electron micrograph Ti–6Al–4V foil (105 000X).

Microprobe traces of vanadium and aluminum lines show fairly constant ratios of V:Al across the thickness of the foil sample. Examination of annealed foils by probe at high magnification shows the expected enrichment of vanadium in the beta particles.

Honeycomb cores made from electron-beam-evaporated titanium-alloy foils are being evaluated for structural usage. A typical honeycomb core is shown in Fig. 5. All metallurigcal evidence to date indicates that EB-evaporated foils have all the expected strengthening characteristics of alpha and beta phases in Ti–6Al–4V alloy. The strength levels and bend ductilities are superior to wrought foils of equal thickness.

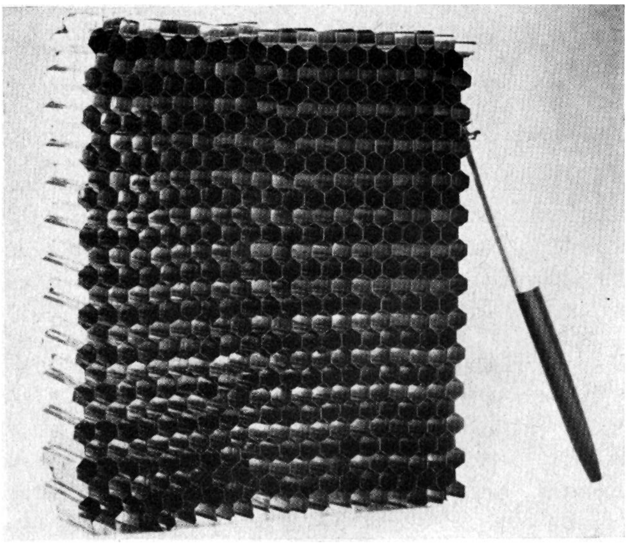


FIGURE 5. Honeycomb core made from 0.002-in. (0.005-cm)-thick elecron-beam evaporated Ti–6Al–4V foil.

Conclusion

The severe weight-saving requirements in the construction of the new and yet-to-be-designed Mach-2-Plus aircraft are legend, and are forcing detailed investigation of every mechanism and all materials. These efforts especially focus onto large and complex structural elements where a fractional saving per unit will multiply into hundreds and perhaps thousands of pounds in reduced weight. Honeycomb structures and their materials are one such design element.

The search for weight saving in honeycomb materials presumes the possibility of finding for the sandwich core a fabricable, high-strength titanium alloy in thin foil gages. The thousands of pounds of reduced weight which could result would be very desirable.

Present titanium alloy core materials have ultimate tensile strengths (UTS) of approximately 75 KSI. Electron-beam vapor-deposited titanium-6Al-4V foils in thicknesses from 0.0014–0.009 in. (0.004–0.02 cm) have tensile strengths of 140–170 KSI. Since the electron-beam vapor-deposited Ti–6Al–4V foils are formed as a deposit in the required thicknesses, the costly and contaminating multiple anneals of conventional rolling are not necessary. Properties of these foils are equal, and in many instances, superior to those conventionally produced, because they have reduced amounts of contaminants. This method on a production scale would provide a range of high-strength titanium alloys in thin gage foil form.

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