PLASMA COLD HEARTH MELTING OF TITANIUM IN A PRODUCTION FURNACE

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In response to increasing demand from the aerospace industry for defect-free titanium, Teledyne Allvac completed installation of a plasma cold hearth furnace in late 1989. This equipment was designed to remove high density inclusions by entrapment in the skull and Type I alpha defects by dissolution in the molten metal or by entrapment in the skull.

That this concept works has been demonstrated in cold hearth furnaces with electron beam but not plasma as the heat source. Several plasma heats were seeded with thousands of defects including titanium nitrides, tungsten carbide, tungsten, tantalum, and molybdenum. These ingots were then converted directly (no VAR) to bar, immersion ultrasonic and x-ray inspected to confirm defect removal.

INTRODUCTION

A significant problem of titanium alloys used in critical applications is the occasional occurrence of high density and hard alpha inclusions. Catastrophic jet engine failures, some resulting in loss of life, have been directly attributed to the undetected presence of such defects in titanium components.

Cold hearth melting is a technique designed to produce the highest quality titanium alloys completely free of these inclusions. This capability has already been demonstrated in a production cold hearth furnace using electron beam as the heat source and in pilot scale plasma cold hearth furnaces.

In mid-1986, Teledyne Allvac decided to add cold hearth melting to its existing titanium melting capabilities. This decision was primarily driven by the aerospace industry's need for defect-free titanium, and also reflected Teledyne's desire for additional melting capacity. A plasma cold hearth furnace was installed in late 1989 and production began in February of 1990.

This report describes the furnace design and capabilities, melting experience gained to date, and evaluation of the material produced in the furnace.

DEFECTS AND COLD HEARTH MELTING

Two types of inclusions occur in titanium alloys: high density inclusions (HDIs) and Type I hard alpha defects. HDIs are particles of significantly higher density than titanium and are introduced through contamination of raw materials used for ingot production. These defects are commonly molybdenum, tantalum, tungsten, and tungsten carbide. Hard alpha defects are titanium particles or regions with high concentrations of the interstitial alpha stabilizers nitrogen, oxygen, or carbon. The most troublesome defects are high in nitrogen and typically result from titanium burning in air during raw material manufacture, handling, or melting. Due to the nature of conventional melting processes and limitations in inspection techniques, both types of defects can find their way into finished titanium components.

Cold hearth melting offers the ability to eliminate these inclusions. In this method, the raw materials are fed into one end of a water cooled copper hearth where they are melted. The molten metal is heated further as it flows across the hearth and is deposited in an ingot mold at the other end. A solid titanium skull forms between the liquid pool and the copper hearth. Any HDI fed in with the raw materials will sink to the bottom of the pool and become trapped in the skull. If a Type I alpha defect fed in is denser than the liquid, it will be removed in a similar manner. If the defect is less dense, it will be carried along with the flow and must be dissolved before reaching the ingot. Pool superheat, pool volume, and melt rate are critical, therefore, as they directly affect this dissolution.

TELEDYNE ALLVAC'S PLASMA COLD HEARTH FURNACE

One of the first design decisions made was to use plasma rather than electron beam as the heat source. A fair comparison of the two methods is complex and not within the scope of this report. The major factor influencing the choice of plasma, however, was the high vacuum conditions required for electron beam melting. The significant evaporation of alloying elements that occurs under these conditions makes ingot chemistry control very difficult and also results in a significant yield loss. Both of these concerns are eliminated with plasma.

Teledyne Allvac's plasma furnace, supplied by Retech Inc, uses four 750 kilowatt transferred arc plasma torches. One torch heats each of three hearth pools and the fourth heats the ingot top (Fig. 1). Metal flow from the melting area is carried through two right angles and three shallow lips before reaching the ingot. A steel wall provides a barrier between the initial melting pool and the ingot mold. This turning of the flow through a 180 degree angle with an intervening barrier wall is an important feature as it prevents unmelted material from moving directly into the ingot and short circuiting the defect removal process. Plasma torch movement is controlled through easily programmed patterns. The same microcomputer that controls torch movement also provides ingot withdrawal control.

Ingots from 14 inches to 30 inches in diameter can be cast in lengths up to 250 inches. Two rotary drum feeders can deliver raw materials with maximum dimensions of six inches. A bulk feeder is also installed which can feed pieces up to 24 inches in diameter and 15 feet long. The melt chamber and withdrawal chamber are equipped with isolation valves so that multiple ingots can be cast and removed without opening the furnace.

The plasma furnace is operated with an inert gas atmosphere at a one to 3 psi positive pressure. Argon, helium, or a mixture can be used. Typically, a 100 percent helium atmosphere ia used which gives the highest energy efficiency. Each of the plasma torches uses up to 110 standard cubic feet per minute of helium. Economics require, therefore, an efficient gas recycling system. Such a system, provided by Air products and Chemicals, is utilized with the Teledyne Allvac furnace.
This system provides particulate separation, compression, and removal of hydrocarbons, hydrogen, and moisture. Oxygen and moisture are typically maintained at less than l0 ppm.

MELTING EXPERIENCE

Between February and July of 1990, 32 ingots totaling approximately 250,000 lbs. were produced in the furnace. The majority of the ingots were Ti-6Al-4V. Melt rates and yields anticipated for the furnace have been achieved. Raw materials ranging from 100 percent revert to 100 percent virgin were melted with no problems. Both vacuum distilled and acid leached sponge were used. Melting acid leached sponge in large percentages presented no problems except for some difficulty viewing through the clouds of dust generated. No significant difference in yield is noted with raw material types.

During the initial melting, standard practices were developed and a number of operational problems were solved. Raw material feeding was one of the most difficult tasks tackled. Several generations of hydraulic pushers and feed chutes for the rotary feeders were tried before the present arrangement was assembled. The bulk feeder has not been used extensively due to time constraints. Feeding and melting large revert is difficult because of arc length limitations. Routine use of this type of material should be possible, however, with further process development.

Plasma torch water leaks were common before enough experience was gained to avoid damage. The primary danger is what is referred to as a double arc. Normally, the arc is transferred from an internal electrode past an electrically isolated nozzle to the titanium at ground potential. If the nozzle comes close to or touches ground, the arc immediately transfers to the nozzle and water soon appears. The best way to avoid damage is to monitor for low nozzle voltage. With sufficient automation, a number of actions can be taken in response to this signal.

Automatic ingot withdrawal control has been incorporated. The electrode voltage from the ingot plasma torch is used to indicate arc length. With appropriate mathematical processing of this signal, regulating withdrawal to maintain a constant pool level ia relatively simple.

PRODUCT EVALUATION

Chemical Uniformity

The chemical uniformity of the plasma cold hearth melted ingots is of great interest because this property should be one of the major advantages over electron beam melting. The chemistry of five typical plasma plus VAR ingots is given in Table 1. These ingots, approximately 10,000 pounds each, were converted to billet and sampled at surface and center from five equally spaced locations along their length. The average given in the table is that of the ten samples; the variability given ie the difference between the highest and lowest values.

Measurements from a conventionally produced ingot are given for comparison, as well as the specification aims. No measurable evaporation loss is observed, which if present would appear most strongly in lowered and variable aluminum content. Overall chemical uniformity is comparable to that of conventionally produced ingots. Nitrogen and copper analysis showed no significant air or hearth copper contamination.

Billet and Bar Inspection

Twenty-One plasma plus single or double VAR ingots have been processed to four or five inch diameter billet and contact ultrasonic inspected. No inclusions or other defects were found. Billet macrostructure evaluation of these heats yielded results typical of conventionally processed ingots. Several of these heats have been processed to small bar (less than 2 inch diameter) and evaluated for macrostructure and microstructure. Again, results typical of conventional product were obtained.

Average room temperature tensile properties of six plasma heats processed to bar are given in Table 2 and compared to that of conventionally processed material and typical aerospace grade minimums. No significant difference with the standard material is noted. At least six heats have been immersion ultrasonic inspected at bar with no defects found.

SEEDED HEATS

Part of the qualification plan for the plasma cold hearth furnace is an evaluation of its inclusion removal capabilities. This is done by "seeding" various types of inclusion sources into the raw material for one or more heats and inspecting the resulting product for inclusions. Some preliminary evaluations of this type have already been done. A 5,000 pound heat was melted with chips machined with tungsten carbide tools. This type of chip is known to contain as many as one tungsten carbide particle per pound. After melting, the ingot was processed to small bar and ultrasonic and x-ray inspected. No defects were found.
The skull remaining in the hearth was x-rayed and found to contain many defects, obviously removed from the raw material.

Two 3,000 to 4,000 pound heats were made with Type I hard alpha sources added. 300 to 400 artificially nitrided sponge particles were added to virgin compacts to be fed in with the rest of the raw material. After melting, the ingots were processed to small bar and ultrasonic inspected (immersion to a #2 FBH). No defects were found.

Most recently, five 4,000 to 5,000 pound heats were made, the first seeded with HDI and hard alpha sources, the others with hard alpha sources only. The HDI sources consisted of various size pieces of tungsten, tungsten carbide, tantalum, and molybdenum added at a rate of more than one per 10 pounds of ingot. Nitrided sponge of various nitrogen levels, torch cut revert, and enfoliated bar ends were added as hard alpha sources at a rate of almost one per pound of ingot. These defects were put with virgin material carefully compacted to avoid crushing the brittle hard alpha seeds. Ultrasonic and x-ray inspections showed the first heat to be completely free of HDIs. Ultrasonic inspection of all five heats showed less than one percent survival of the hard alpha seeds. It should be noted that this is less than one percent survival of artificially generated seeds added in a worst case method. This is very promising, as it is a significant improvement over triple VAR, the best of the conventional processes. Additional trials are planned to further improve this performance.

SUMMARY

Plasma cold hearth melting promises to produce high quality titanium alloys free of high density and Type I hard alpha inclusions. In early 1990, Teledyne Allvac began operating a production scale furnace of this type. Initial melting has shown the furnace to be reliable and capable of melting a wide variety of raw materials. Good melt rates and high yields have been achieved. Evaluation of billet and bar product has shown good chemical uniformity, mechanical properties, and freedom from defects.

Seeding trials have demonstrated the furnace's ability to remove 100 percent of high density inclusions. The process also removed more than 99 percent of artificial worst case hard alpha seeds, which is a significant improvement over triple VAR.

TABLE 1

PLASMA + VAR CHEMICAL UNIFORMITY

HEAT	Al AVG	Al VAR	V AVG	V VAR	Fe AVG	Fe VAR	O AVG	O VAR
AK73	6.26	0.26	4.13	0.24	0.18	0.06	0.16	0.04
AK77	6.20	0.14	3.91	0.17	0.21	0.10	0.16	0.06
AK87	6.19	0.20	3.93	0.22	0.18	0.05	0.15	0.05
AK88	6.33	0.11	4.03	0.17	0.19	0.03	0.17	0.05
Std. Prod.	6.13	0.24	3.92	0.29	0.17	0.11	0.15	0.05
Spec. Aim	6.30		4.20		0.15		0.17	

AVG - Average of ten samples
VAR - Variation, difference between highest and lowest of ten samples

TABLE 2

PLASMA HEAT ROOM TEMPERATURE TENSILE

	UTS (ksi)	0.2% YS (ksi)	RA (%)	EL (%)
Plasma Avg.	144	133	43	17
Typical Std. Grade	148	136	43	17
AMS 4978 Minimums	135	125	25	10

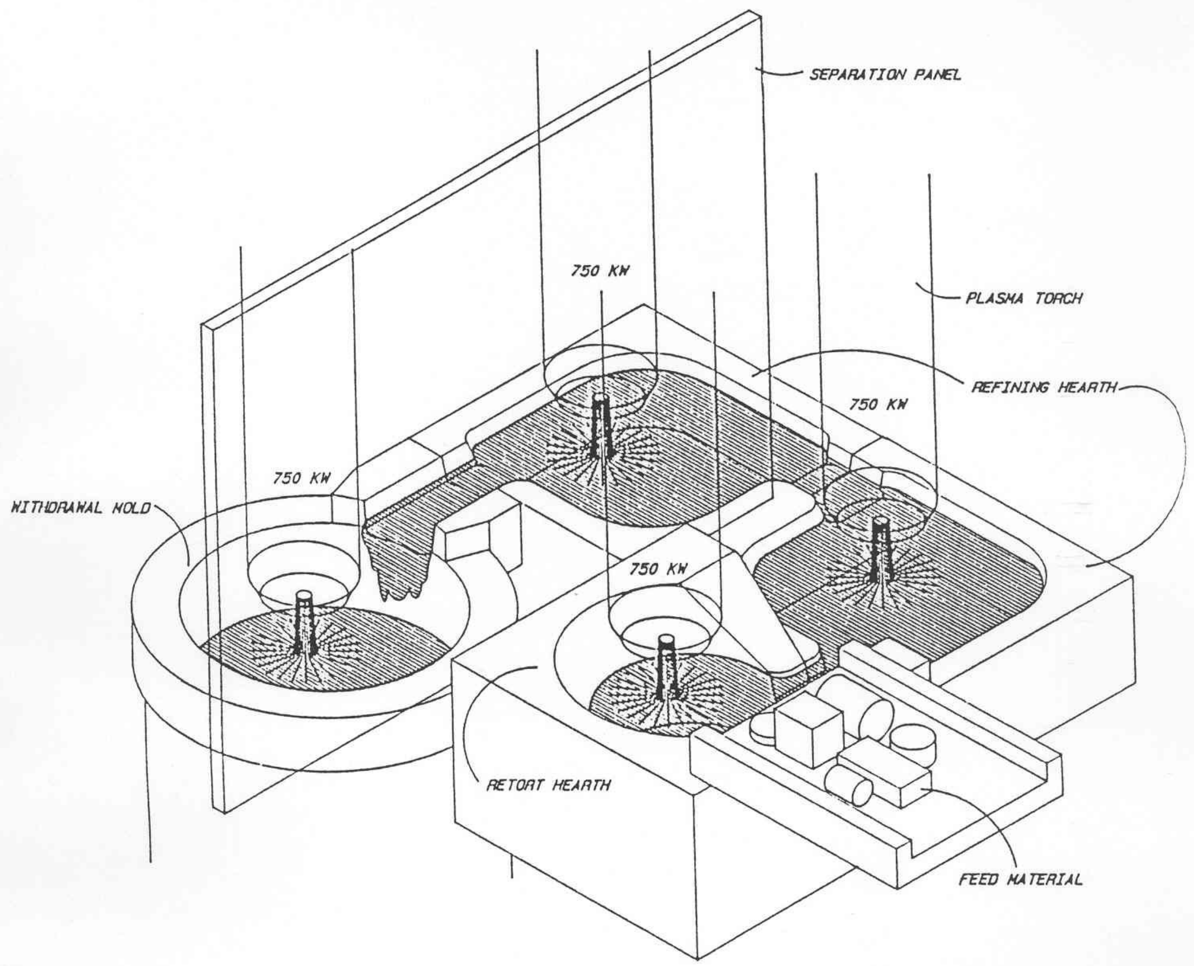

FIG. 1 - TELEDYNE ALLVAC'S PLASMA FURNACE