TITANIUM ALLOY HEARTH MELT TECHNOLOGY

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Abstract

HM (Hearth Melt) refining of titanium alloys for premium quality gas turbine engine rotating components is now a demonstrated production process. Production of rotating components using the EBM+VAR (Electron Beam Cold Hearth Melt plus Vacuum Arc Remelt) process has been in progress since 1988; the PAM (Plasma Arc Cold Hearth Melt) + VAR process was qualified as having acceptable refining capability in 1991. The need for these Ti alloy HM processes was fully described in a prior publication; it is only summarized here that the necessity is to minimize the probability of premature gas turbine engine component failures caused by melt related inclusions. The refining advantage that the HM processes offer over the prior premium quality triple VAR process is their enhanced capability to eliminate the melt related HID's (high interstitial defects) and HDI's (high density inclusions). This paper considers the initial production introduction of the EBM+VAR process and the qualification of the PAM+VAR process as background technology for the more advanced EBM "only" and PAM "only" processes. These more advanced processes, which involve elimination of the VAR step after hearth melting, are being demonstrated under a USAF ManTech Program (F33615-88-C-5418). The current status of the EBM "only" and PAM "only" process demonstrations is described.

Introduction and Background

Since GEAE's (GE Aircraft Engine's) initial 1989 publication(1) on the development of HM (Hearth Melt) processes for refining Ti alloys, continuous progress has been made toward the introduction and further development of these processes as described herein.

The initial production HM material as indicated in Figure 1 was EBM+VAR Ti-6-4 (Ti-6Al-4V) bar produced using a single hearth process(1). That material demonstrated production capability using the first AJMI (Axel Johnson Metals, Inc.) EBM furnace. Subsequent bar production heats were produced using the first generation dual hearth process; that process was developed to enhance the ability to eliminate melt related inclusions. Advanced dual hearth designs include two major features: a longer hearth length for increased inclusion-elimination residence time, and a shield to prevent ballistic particle transport directly to the ingot mold. The issue

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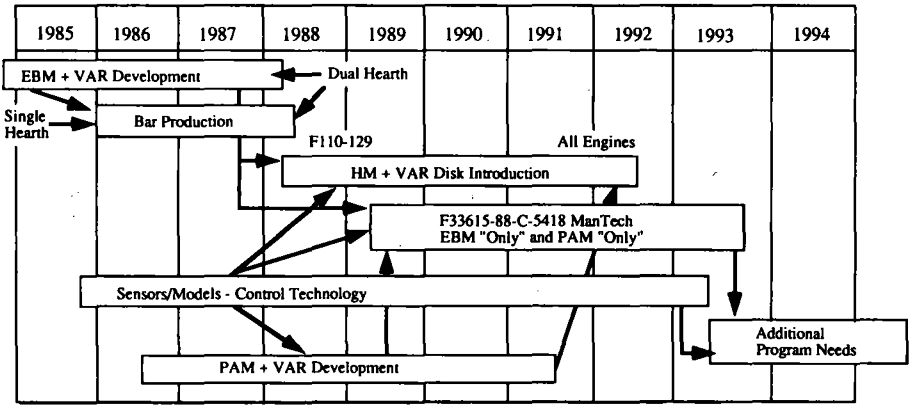


Figure 1 - GEAE Titanium Alloy Hearth Melt Development Strategy: Hearth Melt + VAR → Hearth Melt Only

of the three remaining possible HID sources in the final VAR process was also addressed in the bar program; added requirements were placed on the VAR process to minimize these possible sources.

PAM+VAR process development was initiated at W-G (the Wyman-Gordon Company) in 1986 and at T-A (Teledyne Allvac) about a year later. T-A's facility has recently been qualified for PAM+VAR production; W-G's qualification efforts have been delayed because of the multiple goals for that facility. Based on T-A's qualification, PAM+VAR entered HM+VAR introduction in 1992.

Concurrent with the HM process development efforts, programs were initiated to develop sensors and models for improved EBM and PAM process control. Significant progress has been made in establishing sensors to monitor the molten pool surface temperature, a critical parameter for the inclusion elimination mechanisms. Development of the advanced molten hearth models for assessment of parameter changes on the inclusion removal mechanisms has been more challenging, but recent progress has been achieved.

All of these combined technologies led to GEAE's decision to introduce the HM+VAR process for production of rotating disk, spool and shaft Ti alloy components in 1988. Typical of any new production process, a few early learning curve issues were encountered, but the process capability has subsequently been established to allow reasonably uneventful HM+VAR production. Production introduction has now expanded to include all military and commercial engines (mid 1992). Approximately two million kg of HM+VAR ingot have been evaluated through the end of 1991; no HID's or HDI's have been found in any of that product produced by qualified sources.

HM "Only" Technical Approach

The major objective of the USAF ManTech Program is to establish new processes that will produce Ti alloy materials which are significantly free of HID's and HDI's while retaining freedom from type II (Al) segregation and beta flecks. Achievement of that objective is being demonstrated using two HM "only" processes, EBM and PAM, to produce two alloy types: Ti-6-4 and an advanced alloy such as Ti-6246 (Ti-6Al-2Sn-4Zr-6Mo) or Ti-17 (Ti-5Al-2Sn-2Zr-4Mo-4Cr).

The potential advantages of the HM "only" processes compared to the triple

VAR and HM+VAR processes are: (1) further cleanliness improvement, (2) finer ingot structure, and (3) reduced costs. The further cleanliness improvement comes from eliminating the three HID sources in the final VAR step of the HM+VAR process. The finer ingot structure produced by the shallower HM ingot pool offers promise to: (1) minimize solidification segregtion, (2) enhance non-destructive (ultrasonic) test capability, and (3) enhance low-cycle fatigue properties. The cost reduction comes from eliminating the final VAR step in the HM+VAR process.

The recently completed Phase I efforts involved producing and evaluating fifteen subscale heats as shown in Table I. While these are designated subscale heats, they ranged in size from 1260 to 4430 kg (432 to 660 mm diameter) and were produced using full scale HM practices. Ti-6-4 and Ti-6246 EBM heats were produced; AJMI already had demonstrated Ti-17 alloy production capability. The PAM heats involved predominantly producing the Ti-6-4 and Ti-17 alloys; T-A preferred gaining experience on Ti-17 since it was the selected Phase II advanced alloy.

Objectives were designated for each heat series as shown in Table I. The 1st and 2nd series heats were used to establish the melt process for each alloy in each melt practice. The major evaluations for these heats involved: (1) monitoring the HM parameters such as heat input, molten pool temperatures, casting rate, etc., (2) evaluating the hearth skull and ingot mold pool profiles, and (3) establishing billet quality and yield. The 3rd series of heats were directed at a proof-of-concept seed-elimination experiment for each alloy in each melt process. Seeds were added to these heats at the industry established seeding level(2) using inclusions known to form either HID's or HDI's. The entire ingot was processed to billet and bar to inspect ultrasonically for any surviving seeds for these heats. The 4th series of heats were directed at the economic issue of using lower cost revert input materials.

EBM "Only" Technical Progress

Numerous capability and producibility issues were investigated using the seven EBM "only" heats listed in Table I. All seven heats were produced at AJMI in their first EBM furnace using standard hearth configurations for EBM+VAR production. The ingots were converted to billet or bar for evaluation by the RMI Titanium Company. The major emphases of the evaluations were placed on composition control, billet integrity, and process yield. While EBM refining capability was addressed during EBM+VAR development work, further investigations were needed for better definition of the process limits. EBM process parameters, some requiring special sensor systems or evaluation procedures were monitored for comparison between heats, to assess improved control needs, and for application in advanced process models.

Table I Phase I Subscale Heats

Heat Series/Objective	EBM "Only"		PAM "Only"		
	Ti-6-4	Ti-6246	Ti-6-4	Ti-6246	Ti-17
1st/Process Evaluation	E4-1	E6-1	P4-1W	P6-1W	P7-1T
2nd/Process Evaluation	E4-2	E6-2	P4-2W	--	P7-2T
3rd/Proof-of-concept	E4-3	E6-3	P4-3T	--	P7-3T
4th/Revert Material	E4-4	--	P4-4T	--	--

Composition Control

Based on the EBM+VAR development work(1), it was known that EBM "only" ingot composition control would be challenging. The high vacuum required for EBM operation protects the molten metal from atmospheric contamination and reduces the hydrogen content, but it also causes the selective vaporization of high vapor pressure alloy elements, such as Al. As demonstrated by AJMI in commercial EBM+VAR production, achieving composition aims for a given set of EBM process parameters is an empirical process. Although it is difficult to meet composition aims for experimental heats with unusual operating procedures, the "steady-state" portion of each subscale heat was within the specified compositional ranges as shown in Figure 2. Furthermore, the compositional variations were acceptable from center to edge across the billet slices.

Before ingot casting begins, vaporization can excessively deplete Al from the pools as they are being established in the hearths. This material can produce an ingot bottom with a below specification Al content, as shown in Figure 2, resulting in a significant process yield loss. In heats outside the program, and in later program heats, AJMI demonstrated pool formation procedures that prevent this Al depleted region.

After ingot casting stops, beam power is reduced gradually in the ingot mold. Evaluations in this program have shown that this "hot top" practice minimizes voids and segregation in the billet due to shrinkage cavities near the ingot top. Without a hot top practice, the cavities can extend about 200 mm from the ingot top as shown in Figure 3. While the cavities have been essentially eliminated by long duration hot top practices, the resulting Al depletion was unacceptable as shown in Figure 2 for Heat E4-3. A balance between minimizing cavity formation and Al depletion appeared to be achieved in some heats. This practice would minimize the ingot top yield loss. The full scale heats of Phase II will be used to demonstrate whether this balance can be maintained with larger ingot diameters.

Because melt rate is inversely proportional to pool residence time, it directly affects both selective vaporization and inclusion elimination capability. Rough measurements of casting rate, which approximates melt rate, indicated typical process variations of about ±30%. While experience has indicated that this is an adequate level of control, improved melt rate monitoring and control practices are being developed.

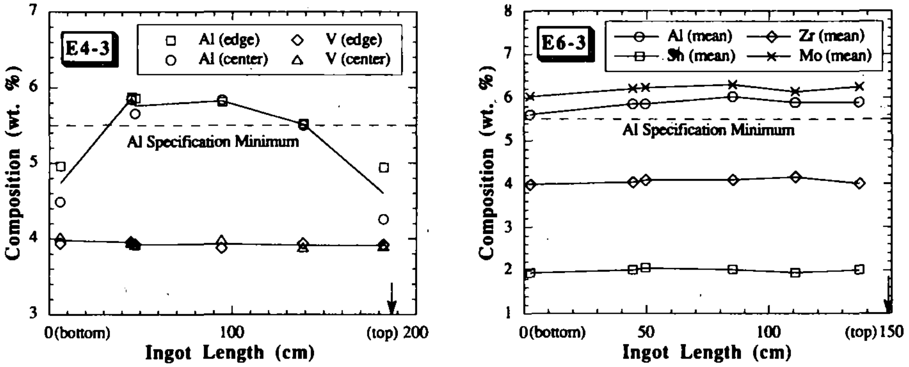


Figure 2. EBM billet compositions. Only the central portion of Heat E4-3 has acceptable billet homogeneity; modified procedures in Heat E6-3 achieved acceptable top to bottom homogeneity.

Billet Integrity

No inclusions or segregation were found in the 1st and 2nd series unseeded heats for both alloys. Likewise, no surviving seeds or segregation were found in Heat E4-3 billet and bar, demonstrating full inclusion elimination capability for Ti-6-4. HID's attributed to ten surviving nitrided sponge seeds were found in Heat E6-3. No inclusions were found in similar seeded heats conducted outside of the ManTech program with Ti-17(1), an alloy with similar thermophysical properties to Ti-6246. Investigations indicate that the survival mechanism is related to the solid electrode feedstock preparation used for Heat E6-3; this mechanism did not exist for the compacted particulate feedstock used in the Ti-17 heats. Although this is a much lower seed survival rate (about 0.4%) than that for the triple VAR process of about 8%(1), work to eliminate this mechanism continues.

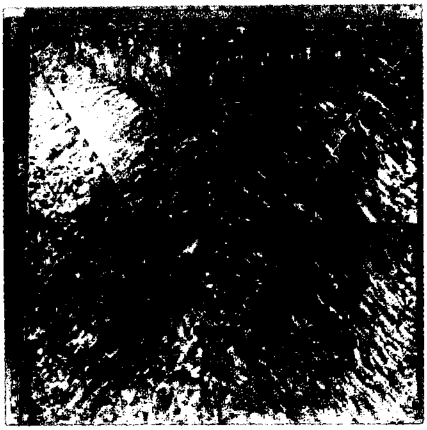


Figure 3. Macroetched axial slice of the E4-4 EBM ingot top. The 470 mm deep pool (outlined) helps to produce a fine billet macrostructure.

Six HID's also were found in Heat E4-4; they were associated with flame-cut VAR crown revert feedstock that is not allowed for current premium quality applications. This is again a much lower incidence than expected for triple VAR, but proves that current restrictions against using such feedstock cannot be relaxed without further development. The HID survival also was associated with HM pour interruptions. As a result, limits and precautionary procedures are being developed for process interruptions.

Vaporized metals in the furnace condense on the cold chamber surfaces to form dense deposits enriched in high vapor pressure elements, in some cases exceeding 50 wt % Al. There is a concern that, without the subsequent VAR process, deposit pieces that fall into the ingot mold pool could survive to form a segregated region in the EBM "only" ingot. Many such fall-in occurrences were observed, particularly during Heat E4-1, without any associated segregated regions being found in the billet inspections. One cracked segregated region found in billet ultrasonic inspection of Heat E6-3 may have been caused by an unusual deposit from a viewport used only in experimental trials; that possible source has been eliminated. AJMI has demonstrated, and continues developing, practices that greatly reduce occurrences of deposits falling into the ingot mold.

The 152 mm diameter billet macrostructure and microstructure of the subscale heats were equivalent to, or finer than, commercial triple VAR or HM+VAR billet. This is attributed to having less ingot mold pool volume for EBM as shown in Figure 3 than for VAR. Billet structures produced by various conversion practices indicate that additional refinement of billet structure and reduced noise for ultrasonic inspection might be possible.

Process Yield

Based on the subscale results, full scale EBM "only" melting and conversion yields should be at least equivalent to current commercial experience. Ingot sidewall improvements noted with increasing ingot diameter indicate that full scale ingots can be made with standard EBM "only" procedures that will not require significant sidewall conditioning losses.

PAM "Only" Technical Progress

The PAM approach to melting of Ti alloys is being pursued by several primary titanium suppliers. T-A and W-G have been involved in the USAF ManTech Program and have each melted heats that were planned as a part of the Phase I effort. Eight heats have been melted that ranged in weight from 1475 to 3810 kg. The three heats melted at W-G were 610 mm in diameter and are coded by the letter W in Table I; the five heats melted in T-A were 660 mm diameter and are similarly coded by the letter T. All of the planned Phase I heats have been melted and evaluated. Much has been learned about PAM of Ti alloys. Key capabilities of the process have been identified and key technical issues that are the focus for further efforts toward the implementation of PAM "only" product are being resolved. Space does not allow a full description of all of the pertinent Phase I information; thus, the option was taken to summarize the capabilities and issues identified in the work to date. These capabilities and issues are grouped into the same three broad categories previously discussed in the EBM section: composition control, billet integrity and process yield.

Composition Control

The PAM process evaluations conducted to date under the ManTech Program have shown excellent reproducibility of the raw material composition in the ingot and billet. Chemical analysis of Heat P7-1T was performed at five locations along the billet length, and at the center and surface at each location. The results indicated that all the metallic elements averaged within 0.1 wt% of the target chemistry with a standard deviation of generally less than 0.05 wt%. Earlier program heats that did not achieve the same target accuracy were determined to be the result of the physical characteristics and deblending of the input material blend. In an effort to expand the confidence for reproducibility of composition, a short melt was conducted using billet produced from Heat P6-1W. The short ingot stub produced in this effort was analyzed for chemistry and determined to be within 0.1 wt% of the values previously measured in the billet.

Hydrogen content measured at the billet stage for the early PAM heats have been between 100 and 350 ppm. It has been determined that the PAM furnace atmosphere has a significant influence on the hydrogen content of the ingot produced, and that billet conversion can be expected to add as much as 40 to 50 ppm hydrogen to the product. Significant progress has been achieved in controlling the hydrogen content of PAM "only" material in this program. Heat P7-1T, which was the first PAM Ti-17 heat in the industry, contained approximately 225 ppm hydrogen after billet conversion. This heat and the second PAM Ti-17 heat, P7-2T, were both melted using just sponge and master alloy. Heat P7-2T contained only 60 ppm hydrogen at the ingot stage, and averaged 85 ppm hydrogen as 152 mm diameter billet. The significant change to the PAM process to reduce the heat hydrogen level was to scrub hydrogen from the helium gas atmosphere as it passed through the recirculation system. The subsystem used to scrub hydrogen was operated in a manual mode for Heat P7-2T, and has since been automated.

In summary, efforts conducted under the ManTech program have shown that PAM reproduces input material composition very effectively. With some additional control development and possibly some fine tuning of the conversion processes, PAM "only" billet will also be capable of meeting the specified hydrogen content.

Billet Integrity

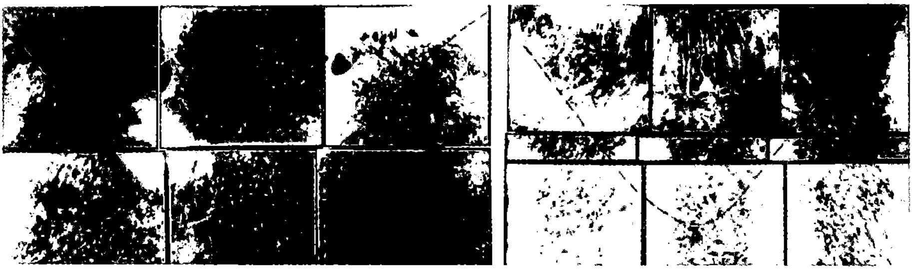
The general subject of billet integrity is broad and includes issues such as: inclusions (HID's and HDI's), voids (both evacuated and gas filled), and structure (micro and macro). T-A has effectively demonstrated total inclusion elimination from Ti-6-4 using PAM; T-A's separate paper(3) discusses the details of these demonstrations.

Clean voids have been observed in PAM billet material evaluated in this program. Their occurrence has been associated with shrink cavities resulting from an irregularly shaped molten pool pattern in the ingot. The torch pattern over the ingot for Heat P6-1W allowed the solidification of an island in the center of the pool and created shrinkage voids at the bottom left side of the molten pool as shown in Figure 4a. The torch pattern in this instance had been preferentially directed at the edge of the ingot in an attempt to enhance the ingot surface condition. Billet from this heat exhibited clean voids in the location of the shrink porosity. The torch pattern was modified for subsequent heats to yield a typical ingot molten pool as shown in Figure 4b. No clean voids were found in the billet for any other heats in Phase I. The potential for gas filled voids in PAM "only" material exists; however, none have been observed. More direct and definitive approaches to assessment of the level of risk associated with the occurrence of clean voids, both evacuated and gas filled, are being considered. Such approaches could include extensive bar production or extensive large-bar low-cycle fatigue testing.

The macrostructure of PAM "only" converted material is typically finer than that of PAM+VAR or triple VAR material given the same conversion practice. This observed macrostructural refinement is apparently a result of a smaller ingot grain size. No microstructural anomalies have been observed beyond that of the early clean void porosity for PAM "only" billet material, nor are they expected since microstructural features are generally a function of conversion and heat treatment rather than melting.

Process Yield

Process yield has not been fully assessed in the ManTech Program because of



(a) 0.14X (b) 0.12X

Figure 4. Ingot mold pool profiles for (a) Heat P6-1W and (b) Heat P4-2W. Improper PAM torch patterns (a) can cause ingot microshrink cavities that result in clean voids in the billet. Proper torch patterns (b) eliminate these clean voids.

competing objectives. Specifically, in each heat except the last two, the top of the ingot was not hot topped; it was marked with copper during the final stages of melting and removed prior to conversion for analysis of the steady state molten pool. Removal of the top of the ingot creates a relatively low aspect ratio ingot which is not optimum for yield. The Phase II full scale heats will provide the best opportunity to quantify yields.

Significant features of the process which affect yield and economics can also be identified from the work done on this program. There are almost no losses of raw material in the melting cycle. Given a constant skull weight, the ingot weight resulting from a melt cycle is generally within 1% of the raw material input weight. Present experience shows the surface finish of a PAM "only" ingot is not as good as a PAM+VAR ingot and requires significant conditioning prior to conversion. The shoe required for PAM ingot retraction is also a significant loss to PAM "only" yield. These primary yield losses for PAM "only" may be offset to some extent by a reduced molten pool depth at the top of the ingot which will require less cropping during conversion than a PAM+VAR heat. The discussion of product yield is ultimately directed to consideration of process economics. Offsetting the potentially reduced yield in an economic balance will be the avoidance of the cost associated with a subsequent VAR cycle. Further, although it is almost impossible to quantify, the increased product integrity offered by avoiding potential HID occurrence in the final VAR will also be a key economic consideration.

Conclusions

The two million kg of HM+VAR production ingot has demonstrated that hearth melting of Ti alloys is a viable production process; improved freedom from melt related HID's and HDI's has been found in that product compared to current triple VAR material. While most of the HM+VAR production to date has been made by the EBM+VAR process, very encouraging results were obtained for the PAM+VAR process during the qualification demonstrations. Ongoing development efforts directed at HM "only" technology for the EBM and PAM processes have defined issues which must be resolved before these can likewise be considered for production introduction. However, no issues have yet been defined which are not resolvable via reasonable process modifications or enhanced process definition and control.

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