RECENT DESIGN AND OPERATIONAL DEVELOPMENTS OF COLD WALL INDUCTION MELTING CRUCIBLES FOR REACTIVE METALS PROCESSING

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ABSTRACT Retech Systems, LLC has been involved with the design, fabrication, and sales of cold wall induction melting systems for about 30 years. Over the past four years, Retech Systems, LLC together with Fluxtrol, Inc., has been evaluating the use of magnetic flux controllers to enhance electrical efficiency, power factor, and overall performance of the cold wall melting crucible. An open bottom, ten segment, water-cooled copper crucible was designed and built to include magnetic flux controllers. 55 mm diameter titanium alloy ingots were cast using either a 12 turn or a 14 turn induction coil with and without the use of magnetic flux controllers. Relevant tank circuit measurements were made to assess the electrical performance of each configuration. A 31% increase in casting rate was measured using magnetic flux controllers located in between the segments of the crucible and around the outer periphery of the induction coil. The increased power input available to the melt also resulted in a significant improvement in ingot surface finish, as determined by a qualitative examination.

INTRODUCTION

The induction melting process which uses a segmented, water-cooled copper crucible has been used for many years. This process is commonly referred to as Induction Skull Melting; however, it is also known as Cold Wall Induction Melting. Siemens and Halske Akt.-Ges. applied for a patent on the concept in November 1926 in Germany [1]. Official German publication and issue dates were in January and February 1931, respectively. This patent primarily applied to difficult to melt metals such as tantalum, tungsten, thorium, and their alloys. Tir and Gubchenko [2] published (in Russian) an excellent book of induction melting of reactive metals. As described by Mühlbauer, et al. [3], recent developments of the process have been primarily for reactive metals such as titanium alloys, zirconium alloys, and silicon. Most, if not all, of the development work related to the process has occurred after the Second World War and has been largely driven by the need for high performance materials in the nuclear and aerospace industries. Within the last 15-20 years, applications have emerged related to silicon processing for photovoltaic applications as well as newer titanium alloy applications for the commercial automotive markets. Both of these markets are strongly driven by material and processing costs. As such, over the past four years Retech has been more fully investigating the design and operational characteristics of its cold wall induction melting systems.

One of the primary drawbacks to the cold wall induction melting process is the high energy usage – primarily thermal, due to the lack of insulating material between the molten charge and the water cooled crucible. Theoretical calculations by Delage, Ernst, and Driole reported maximum electrical efficiency of 58-72% for a stainless steel charge with a molten slag cover, depending upon the crucible diameter and the number of segments [4]. Pericleous, et al. [5] reported results for a molten aluminum charge where the percentage of input power lost in the cooling circuits of their cold wall induction crucible ranged from about 50 to 54%. Their results were based on measuring temperatures and flows for the crucible cooling circuits only (i.e. wall and bottom). Cooling losses in the coil were not reported in this work. Their empirical results agreed quite well with their computational model. More recently, Umbrasko, et al. [6] performed theoretical computational analyses of melting an aluminum charge and a TiAl charge in crucibles of various sizes over the 5-20 kHz frequency range. Their work predicted that the power delivered to the melt for an aluminum sample ranged from 18 to 36% of the input power for height to diameter (H/D) ratios from 0.84 to 1.67. Furthermore, they predicted power delivered to the melt for the TiAl sample ranging from 21 to 24% of the input power for H/D ratios from 0.96 to 0.74. These results were a good starting point for a study presented in this paper.

The amount of published operating data relating to cold wall induction melting efficiencies (for titanium melting) is not extensive. With regards to electrical efficiency, one should understand that this type of information is difficult to obtain experimentally. Computational methods may be of great help in this area. With regard to thermal efficiency, calorimetric methods are rather easy to implement through the use of temperature and flow sensors. The key aspect in establishing the thermal efficiency while melting titanium alloys is the amount of energy that the charge actually absorbs. This is not easy to obtain. The most commonly available option is to use an optical pyrometer. But how does one calibrate an optical pyrometer at the melting point of a titanium alloy? Typically, an optical pyrometer is calibrated against an immersion type thermocouple, but molten titanium dissolves all known thermocouples. Unfortunately, most of the current research still has not thoroughly addressed this issue. The computational solutions cited above and others [7] are very useful; however, the empirical validation of these models in the molten state is still lacking.

As can be gathered from the literature, the main thrust of recent research in academia on cold wall induction crucibles has been with the closed bottom type. These are typically used for tilt-pour or bottom pour casting. Open bottom cold wall induction crucibles are used to make relatively long ingots. One of the early inventors was Philip Clites at the U.S. Bureau of Mines in Albany, OR [8]. The technique was first put into industrial practice by Cezus in France primarily for consolidating titanium scrap in the late-1980's [9]. Typically, the ingots of consolidated material are not 100% dense. This is acceptable because more often than not, the ingots formed are used as feedstock in a Vacuum Arc Remelt (VAR) furnace. More recently, companies such as Sumco in Japan and eMix in France have developed open bottom cold wall induction crucibles for 100% consolidation of small, high purity, silicon pieces. The ingots are cut into bricks which are then sliced into thin wafers to form a standard size poly-crystalline Si photovoltaic cell. However, despite these recent applications, very few papers (if any) have been published about empirically determined melting efficiencies (whether electrical or thermal) for the titanium alloys or silicon. Consequently, Retech and the Centre for Induction Technology at Fluxtrol, Inc. have been working collaboratively over the past three years to understand the relationship between cold wall induction crucible design and optimum melting efficiency. This work uses a combination of computer simulations validated by actual measurements during production. The goal has been to enhance the electrical efficiency for optimum throughput.

EXPERIMENTAL APPARATUS & PROCEDURE

Melting crucible and chamber

Soft magnetic composite (SMC) material provided by Fluxtrol, Inc. was designed into select locations of an open bottom cold wall induction crucible and the induction coil. Figure 1 shows the details of the 55 mm inside diameter open bottom cold wall induction crucible. Three configurations were tested: 10 segment crucible and 12 turn coil; 10 segment crucible with SMC inserts in between each segment at the top and bottom of each slot and 12 turn coil; 10 segment crucible with SMC inserts in between each segment at the top and bottom of each slot and a 14 turn coil with external SMC shunts attached to the coil. The dimensions of the crucible and coil are shown in Table 1. Thermocouples and flow meters were installed in the cooling circuits of the crucible and coil for calorimetric measurements during melting.

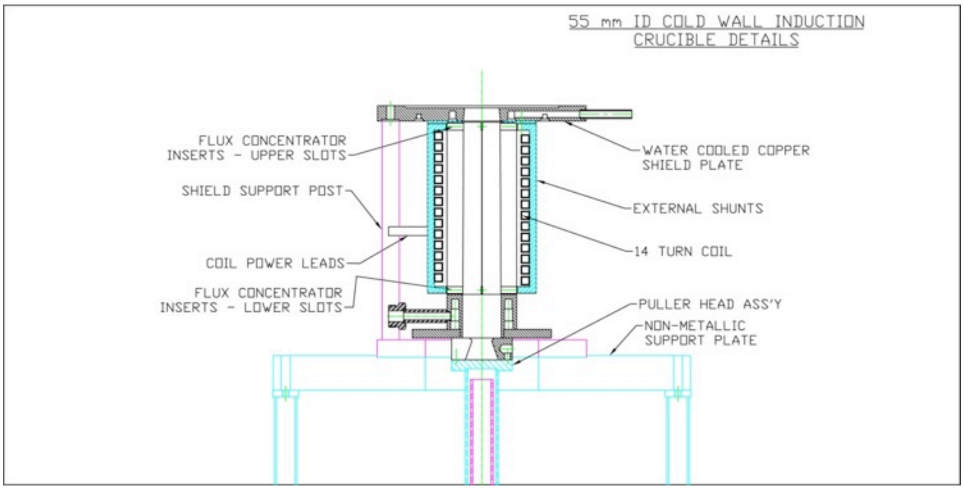


Figure 1. Schematic layout of 55 mm ID cold wall induction crucible

Table 1. Details of 10 segment crucible and coil (mm)

Crucible ID	Crucible OD	Slot Width	Slot Length	Overall Length	Mounting Flange OD	Mounting Flange Thickness
55	102	0.51	251	314	203	12.7

SMC Insert Width	SMC Insert Length		Top of Slot to Centerline of Top Insert	Bottom of Slot to Centerline of Bottom Insert	
2.0	10.2		6.4	6.4	

Coil Turns	Coil ID	Coil Length	External SMC Shunts
12	114	152	No
14	114	248	Yes

To prevent hot material from damaging the coil, a water-cooled copper shield plate was installed at the upper end of the crucible. It has a single radial slot from the outside diameter to the inside diameter. In between the bottom of this shield and the top of the crucible, a thin SMC disc was installed to limit the interaction of the magnetic field with the shield plate.

The 55 mm cold wall induction crucible was installed in a research and development vacuum chamber at Retech called the PAM-5. See Figure 2. This is a 1524 mm ID water cooled chamber. The inner wall of the chamber is stainless steel. Beneath the melt chamber is a mold chamber with a separate access door for material removal. A hydraulic cylinder is mounted in the bottom of the mold chamber. Ingots up to 1270 mm long can be produced for research and development applications. A small pusher type feeder can feed up to 100 mm diameter pieces into the process.

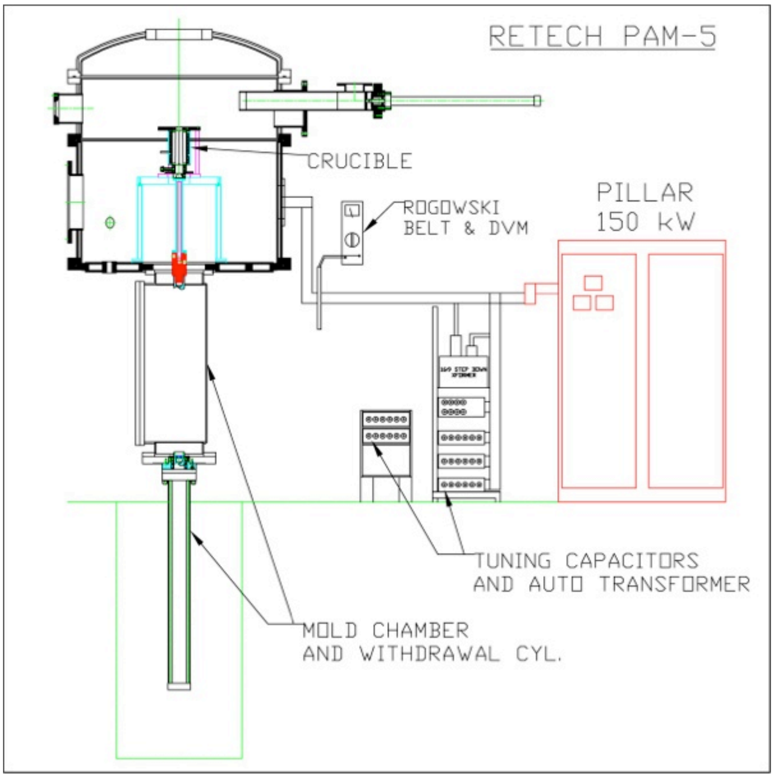


Figure 2. Schematic layout of Retech's PAM-5

Induction Power Supply

The Retech PAM-5 has two induction power supplies available, but only a Pillar Induction 150 kW Mark 5 unit was used for these tests. Due to the nature of the power supply design, it is worthwhile to briefly describe how it interacts with the load. The power supply has a fixed voltage, variable frequency AC source coupled to the output terminals through a reactor. These older Pillar Induction power supplies were designed to automatically maintain power factor near unity over the range of power settings. They were also designed to operate at a 3rd harmonic. They were particularly useful for steel heat treating as they can automatically adjust frequency once the Curie point was exceeded. It is important to note that the Mark 5 power supply was not operated in fixed power output nor fixed voltage output as is capable with most modern induction power supplies. Although this type of power supply may not be necessarily ideal for production melting applications, it was very useful to characterize the interaction between the load (i.e. the coil, crucible, and capacitors – the tank circuit) and the supply. This interaction was primarily monitored using a Rogowski current waveform transducer (Type CWT 30B – 1 mv/A) from PEM in the United Kingdom. A Fluke 87V True RMS Multimeter was connected to the Rogowski transducer to read the tank circuit current and frequency. The transducer was located approximately half-way between the tuning capacitor station and the crucible/coil. See Figure 2 for the approximate location of the transducer.

As received, the Mark 5 power supply output voltage was too high to correctly match to the 55 mm ID cold wall induction crucible and coil load requirements. An autotransformer was installed where the turns-ratio was set at 16:9. A total of 87.51 microfarad of tuning capacitors was connected in parallel with the coil. The power leads to the coil are 12.7 mm x 76.2 mm water cooled copper buss spaced approximately 3 mm apart. The total length of buss run from the tuning capacitor station to the coil is approximately 3.6 m. There is a short 254 mm buss run from the output of the Mark 5 to the tuning capacitor station. Given the relatively long distance from the power supply to the coil, the power leads to the coil were designed to minimize losses as much as possible.

Ingot Casting

Feed material enters the top of the 55 mm ID crucible. With induction power on, the material is allowed to melt and form a relatively stable molten pool on top of the ingot. A titanium alloy starting stub may be used to initiate the melt. The bottom of the stub has an attachment which matches the configuration of the puller head assembly. The attachment may be the frustum of a cone – commonly called a dovetail. The puller head assembly is controlled by a closed loop servo-hydraulic valve. The operator at the control console sets a specified puller head speed which determines the casting rate of the ingot. More material is added to the top of the crucible to form the ingot. Ideally, the input feed rate is matched to the puller head withdrawal rate to maintain a consistent casting rate as well as a constant pool height location within the crucible. As can be imagined, pool height variations can affect the load impedance seen by the induction power supply.

RESULTS AND DISCUSSION

A summary of the titanium alloy ingot casting data is presented in Table 2. Ten ingots were made using the same 10 segment 55 mm ID, 314 mm tall crucible. A magnetic shield between the water cooled copper shield plate and the top of the crucible was used for all tests. Four ingots were made using the 12 turn coil without any SMC inserts. The average casting rate was 0.962 kg/min. Four ingots were made using the 12 turn coil with SMC inserts. The average casting rate was 1.209 kg/min. Two ingots were made using a 14 turn coil with external flux concentrating shunts and SMC inserts. The average casting rate was 1.259 kg/min. The casting rate increase using the 12 turn coil with SMC inserts over the 12 turn coil without was 26%. The casting rate increase using the 14 turn coil with SMC inserts over the 12 turn coil without was 31%.

Table 2. Titanium Alloy Ingot Casting Data

Ingot Number	Ave. Crucible Power	Ingot Mass	Casting Time	Puller Head Speed	Casting Rate	Coil Turns - Slot Inserts
	(kW)	(kg)	(min)	(mm/min)	(kg/min)	
1-18-13	128	5.836	5.75	85.7	1.015	12-none
1-24-13-1	128	5.644	6.50	75.8	0.868	12-none

1-24-13-2	128	5.370	5.50	87.7	0.976	12-none
1-25-13	129	5.442	5.50	89.6	0.989	12-none
2-5-13-1	128	5.850	5.00	103	1.170	12-SMC
2-5-13-2	128	5.864	4.50	109	1.303	12-SMC
2-7-13	128	5.618	4.63	104	1.213	12-SMC
2-13-13	129	5.406	4.70	98.0	1.150	12-SMC
2-21-13-1	129	5.406	4.50	113	1.201	14-SMC
2-21-13-2	127	5.928	4.50	117	1.317	14-SMC

Computer simulations were performed on each coil and crucible configuration by Fluxtrol, Inc. Simulation results were compared to the average casting rates obtained during the ingot casting. The results are presented in Table 3. The power into the melt was not experimentally determined. A suitable thermocouple was not available to calibrate an optical pyrometer. And the PAM-5 is not ideally set up with the correct line of sight needed for optical pyrometry. Instead, the accuracy of the power into the melt estimated by the computer simulations was based on a comparison of the total resistance (calculated by $R=P/I^2$) – from simulation to the experimentally determined value. The error between the two was calculated and corrected for frequency. As shown in Table 3, the error values were less than 10%. It can be assumed that the power into the melt (determined by the computer simulation) has a similar amount of error. The most important result of the simulation is that the power into the melt is predicted to increase through the use of flux concentrators in between the crucible segments and also with the use of external shunts around the coil. The computer simulation predicted an 85% increase in the power to the melt. The corresponding experimental results measured a 31% increase in the casting rate. It is not known how much of the predicted increased power to the melt should be reflected in a corresponding increase in the casting rate. This should be an area of future study.

Table 3. Comparison of Simulated and Experimental Results

Parameter	12 turn coil without inserts		12 turn coil with inserts		14 turn coil without inserts		14 turn coil with inserts		Inf. Long 14 Turn
	Sim.*	Exp.	Sim.*	Exp.	Sim.*	Exp.	Sim.*	Exp.	Analytical
Current (Amp)	1000	1599	1000	1628	1000	1431	1000	1504	1000
Voltage (Volt)	192	377	192	385	186	296	195	331	214
Imped. (Ohm)	0.192	0.236	0.192	0.236	0.186	0.207	0.195	0.220	0.214
Freq. (kHz)	6.45	6.58	6.45	6.55	6.45	6.39	6.45	6.88	6.45
Tot. Pow. (kW)	49.3	128	49.3	128	56.5	110	59.8	128	49.7
Melt Pow.(kW)	12.82	N/A	16.5	N/A	16.75	N/A	20.5	N/A	23.7
Rmelt (mOhm)	12.82	N/A	16.5	N/A	16.75	N/A	20.5	N/A	23.7
Rtotal (mOhm)	49.3	50.1	49.3	48.3	56.5	53.7	59.8	56.6	49.7
Error - Rtotal	0.5%		-2.9%		-4.7%		-9.1%		N/A

A calorimetric measurement was made on the amount of power removed by the crucible using the 14 turn coil during ingot casting. The data is presented graphically in Figure 3.

Power removed by the crucible cooling circuit was on average 72% of the input power. Power removed by the coil cooling circuit was on average 12% of the input power. The power removed from the buss leads to the coil and from the autotransformer was not measured during these tests. It is anticipated that a significant portion of the 16% unaccounted power can be attributed to these cooling circuits. Future work should confirm this assumption.

Optical photographs were taken of some of the ingots made using each coil and crucible configuration studied. These qualitative observations are presented in Figure 4. The ingots produced using the 14 turn coil had much less laps, folds and ripple than those produced using the 12 turn coil without SMC inserts. The 12 turn coil with SMC inserts was also better than the 12 turn without, but not quite as good as the 14 turn coil. Future work should quantify the surface finish improvement. A suggested means to do this is to machine the outside diameter of the ingots until smooth. The finish diameter to the starting diameter will be the key metric.

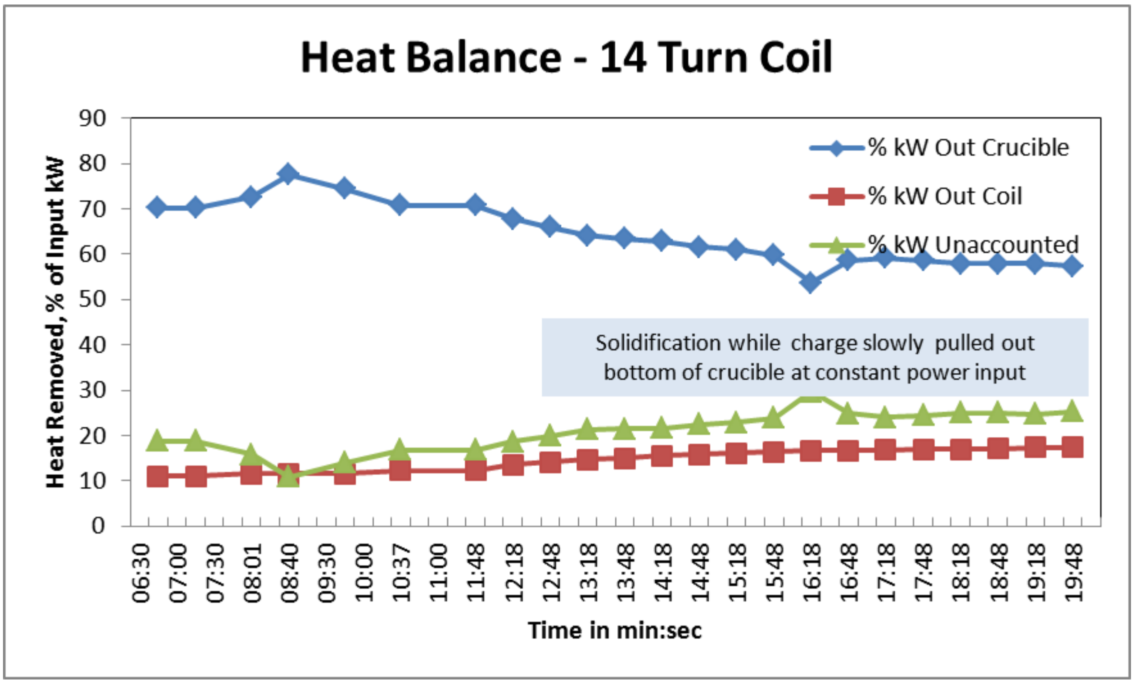
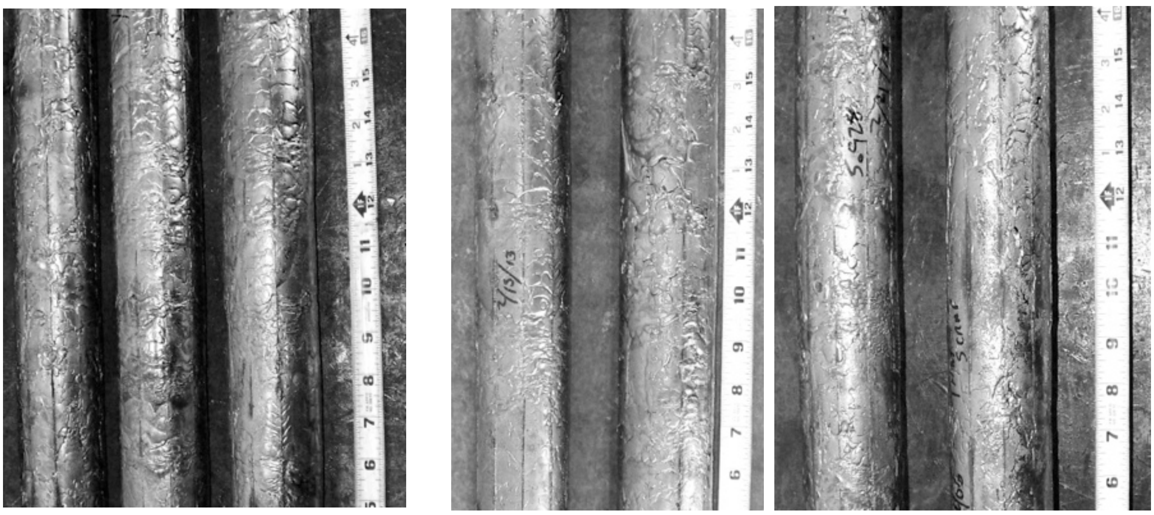


Figure 3. Heat balance for 14 turn coil with external SMC shunts and SMC inserts in crucible slots – constant 129 kW power input

Finally, this study did not attempt to assess the effect of molten pool oscillations during ingot casting on the casting rate nor the ingot surface finish. This should be an area of close examination for future work. To illustrate this point, tank circuit readings were made during one test at the end of ingot casting. At this time it was visually observed that the molten pool oscillations were at a minimum, and the molten pool formed an ellipsoidal or paraboloidal shape for a brief period of time. Within a short period of time the amplitude of the molten pool oscillations increased causing portions of the pool to touch the copper wall and thereby solidify. Surface tension effects then seem to dominate and the skull grows up along the mold wall – the magnetic field must change shape somehow to exacerbate this problem. At any rate, a tank circuit frequency change of about 100 Hz was measured between the two conditions. This occurred over a 3 minute period. It is important to note that the molten pool oscillations and subsequent skull formation can sometimes cause erroneous tank circuit readings which led to some measurement error. Average tank circuit readings were reported in an attempt to minimize the experimental error.

CONCLUSIONS

For an identical input power of 129 kW, a 31% increase in casting rate of 55 mm OD ingots was measured using magnetic flux concentrators located in between the segments of the crucible and around the outer periphery of a 14 turn induction coil. It must be noted that the crucible design (number of segments, H/D ratio, wall thickness, etc.) was not optimized. Further work will yield a crucible design with higher electrical efficiency. A qualitative examination of the ingot surface finish showed significant improvement. This was attributed to the increased power input to the melt within the crucible. The amount of power removed by the crucible was 72% during ingot casting and that removed by the coil was 12% of the input power. Further experimental work is needed to clarify the exact amount of power to the melt in the cold wall induction crucible. A better understanding is needed regarding the magneto-hydrodynamic forces developed during ingot melting and casting in an open bottom cold wall induction crucible. Retech and Fluxtrol plan to investigate this aspect further in order to optimize ingot surface finish. All of these factors will improve product yield and ultimately reduce the cost of producing small diameter titanium alloy ingots.



(a) (b) (c)

Figure 4. Titanium alloy ingots surface: (a) without SMC inserts; (b) with SMC inserts; (c) 14 turn coil with external shunts and SMC inserts

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