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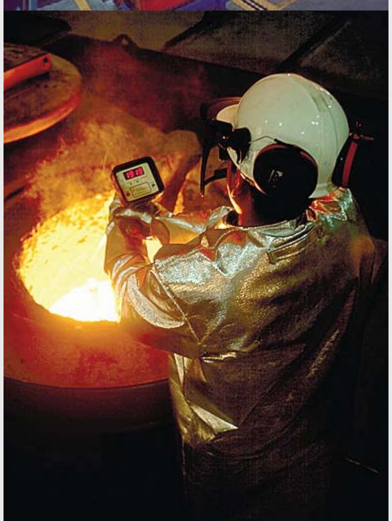

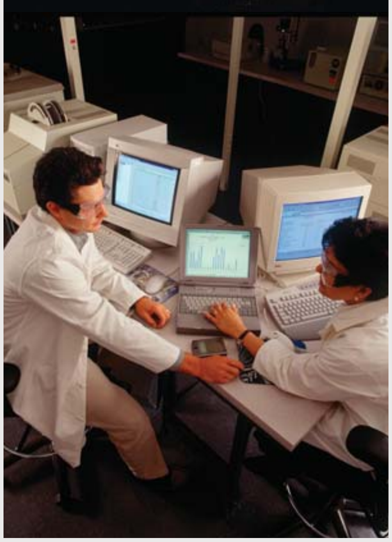

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Energy Efficiency of Microwave Melting

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Energy Efficiency of Microwave Melting

1412-555 NA

This report has been reviewed for completeness and accuracy and approved for release by the following:

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EXECUTIVE SUMMARY

This report contains the results of an engineering study on the efficiency of a Microwave Furnace for melting metal as compared to conventional melting furnaces. Technikon has installed a 6 KW research Microwave Furnace and additionally has been doing testing utilizing a similar sized unit at MS Technology, Inc. of Oakridge, TN. Under the FY2003 and FY2004 Tasks testing demonstrated that microwave melting for metal casting has the potential to redefine the applications of titanium castings, use less energy than any current melting technology used in production today, and improve the quality of the castings by providing a cleaner melt.

Initial results show that microwave melting does improve energy efficiency for melting high temperature metals like titanium over current melting processes such vacuum arc re-melting (VAR) and induction skull remelting (ISR). However for low melting metal like aluminum, microwave melting is both comparable to induction melting and one third less efficient compared to natural gas melting furnaces.

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1.0 INTRODUCTION

1.1. CERP BACKGROUND

The Casting Emission Reduction Program (CERP) is a cooperative initiative between the Department of Defense (US Army) and the United States Council for Automotive Research (USCAR), a partnership of DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation. The signers of the CERP Cooperative Research and Development Agreement (CRADA) include: the USCAR Environmental Leadership Council; the U.S. Army Research, Development, and Engineering Command (RDECOM-ARDEC); the American Foundry Society (AFS); and the Casting Industry Suppliers Association (CISA). The US Environmental Protection Agency (US EPA) and the California Air Resources Board (CARB) also have been participants in the CERP program and rely on CERP published reports for regulatory compliance data. All published reports are available on the CERP web site at www.cerp-us.org.

CERP has been expanding on the DOE/BWXT Y-12 National Security Complex developments on microwave processing to melt metal. Y-12 has demonstrated melting of various metals by microwaves including copper, stainless steel bolts, carbon steel bolts (grade 8), aluminum alloys, platinum, boron, nickel alloys, braze alloys and other DOE relevant materials. Up to 300 lb. of aluminum alloy has been melted in a single melt cycle. The good coupling of the microwaves to the susceptor and melt, as well as the low heat loss of the ceramic casketing system, enables significant improvements in energy efficiency of microwave melting. See Appendix A for more details on microwave melting. This is particularly evident in dealing with the melting of discontinuous scrap pieces such as steel bolts, and powdered metals. In fact, it has been demonstrated that microwave heating of fine powdered metals can be quite efficient, thus enhancing sintering processes.

The technical viability of microwave melting and casting of metals has been demonstrated for several metals at both Technikon and DOE/BWXT Y-12 National Security Complex.

1.2. CERP OBJECTIVES

CERP's primary purpose is to evaluate materials, equipment, and processes, quality and energy usage in the production of metal castings. Technikon's facility was designed to evaluate alternate materials and production processes designed to achieve significant air emission reductions, energy savings or process improvements. For all new processes, energy comparison to conventional processes is an important factor. The facility's principal testing arena is designed to measure airborne emissions from individually poured molds. This testing arena facilitates the repeatable collection and evaluation of airborne emissions and associated process data.

1.3. REPORT ORGANIZATION

This report has been designed to document the results of the energy usage data collected during melting testing completed at Technikon and MS Technology during FY2005 Tasks.

A general discussion on the mechanism of microwave heating is presented followed by analysis of energy consumption as compared to conventional melting technologies.

2.0 DESCRIPTION OF MICROWAVE PROCESS AND TESTING

CERP has demonstrated that microwave melting of titanium has the potential to redefine the applications of titanium castings, use less energy than any current melting technology used in production today, and improve the quality of the castings by providing a cleaner melt. The potential has been demonstrated but there are critical issues that need to be addressed prior to transition to pilot scale phase. In addition, this new melting technology for titanium can be leveraged to other alloy systems that are less reactive than titanium and have lower melting temperatures.

Melting and casting metals using microwave energy has been performed at the DOE/BWXT Y-12 National Security Complex (NSC) for over a decade. The technology has emerged from a lab-scale curiosity to a production scale process, and recently was licensed to several companies for commercial use. Metals that have been melted include steels, titanium, zirconium, uranium, copper, brass, bronze, aluminum, and many other metals and alloy systems.

Bulk metals do not readily couple directly with microwave energy at room temperature because they are electrically conductive, and therefore readily reflect the incident energy. However, the electromagnetic field generated by the microwave field does allow for the loosely bound electrons to move and concentrate at surfaces, edges and points. This results in discharge of the energy in the form of arcing or plasma formation. In the case of powder metals, microwaves couple very efficiently at room temperatures and it has been demonstrated that melting of titanium powder can be achieved very rapidly.

The microwave units used for this work are relatively standard 2.45-GHz multimode unit connected to a sealed chamber equipped with vacuum capability, as well as complete control for argon, air, nitrogen and other atmospheres. The Technikon chamber is equipped with a mode stirrer to break up any standing waves and create a multimode, 2.45-GHz field within the cavity. A six (6) kW industrial microwave generator was used to provide the microwaves to the chamber through a waveguide equipped with quarter-wave tuning stubs in the waveguide to help tune the chamber and reduce the reflected power.

Figure 2-1 Technikon 6 kW Microwave Melt Furnace

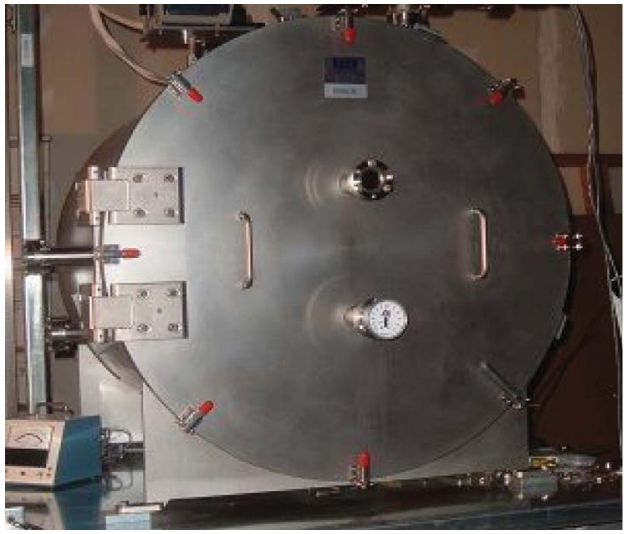


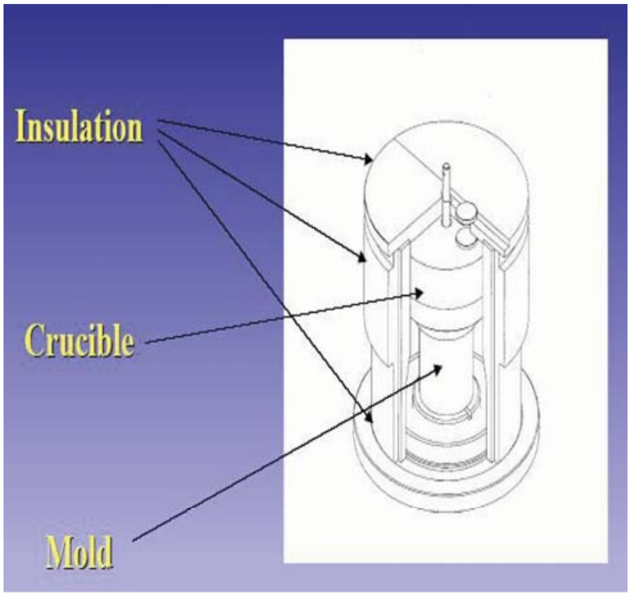
Figure 2-2 32" Diameter Chamber

Microwave metal melting does seem feasible given the common misconceptions about the behavior of metals in microwave fields. The principle that makes metal melting in the microwave possible is based on the fact that certain materials are receptors of microwave energy.

Figure 2-3 Microwave Crucible & Insulating package Shown Outside of Chamber

Three basic elements required to heat and melt bulk metals using microwaves are: a microwave chamber, a microwave recepting ceramic crucible, and a thermally insulating casket that is microwave-transparent. The metal charge is placed in a ceramic crucible, and the insulating casket is positioned to completely cover the crucible. Microwave energy applied to the cavity is strongly absorbed by the crucible. The metal charge in the crucible is quickly heated by means of radiation, conduction and convection with the heated crucible walls. The thermally insulating casket increases the energy efficiency of the microwave system by trapping the heat generated in the crucible (Figure 2-3). This method allows metal objects that cannot be directly heated by microwave energy to be melted easily and efficiently. A mold can be placed directly below the crucible with a stopper rod pouring configuration. (Figure 2-4).

Figure 2-4 Microwave Crucible, Mold and Insulation Package



To heat and melt powder metals using microwaves also require three basic elements: a microwave chamber, a microwave-transparent ceramic crucible, and a thermally insulating casket that is microwave-transparent. The metal powder is placed in a ceramic crucible, and the insulating casket is positioned to completely cover the crucible. Microwave energy applied to the cavity is absorbed by the metal powder. The thermally insulating casket increases the energy efficiency of the microwave system by trapping the heat generated in the crucible (Figure 2-3).

Several operational issues need to be addressed prior to demonstrating pilot scale capability. The issue of durability of the ceramic crucible is still an issue. Testing is ongoing to determine the maximum number of melts before crucible needs replacing, time at maximum temperature, and melt at higher temperatures (e.g. 1800ºC for superheat of 140ºC/284ºF) capability. In order to cast a part, bottom pour, tilt pour or integral crucible/mold capability needs to be demonstrated. Associated cost factors need to be determined and other cost-effective ceramic crucible systems sought and evaluated. All these issues need to be addressed at a 5 lb capability so ½ inch diameter bars can be cast for mechanical properties evaluation. At the same time testing needs to continue to refine energy savings, superheat capability, and capital cost differences using microwave melted Ti6Al4V as compared to VAR (vacuum arc remelting) and ISR (induction skull remelting).

Limits on the simple power/time scaling assume thermal stress and heating uniformity can be maintained within acceptable limits of the crucible material, which has not been yet determined. It may be necessary on the basis of present status to extend the processing time until a reliable reproducible configuration has been proven. Thus, if 1.5 hours of processing ramp time is acceptable, then actual maximum MW power may be reduced to about 40-45 kW (vs.75 kW capability of power supply).

Another factor which strongly impacts the total required power is the production schedule. Rapid recurring 24/7 processing in which the metal load is preheated, and the temperature loss of the crucible is minimized during material transfer would reduce the process time and/or the peak power requirement. This, however, also needs to be proven in actual circumstances, but it has the potential to reduce the power-time product by 25 to 50%.

Another assumption is the microwave absorption rate. This factor is very material and size dependent. If the crucible and load is not sufficiently absorbent, then the buildup of microwave energy can create plasma or arcs. This must be examined later when a final crucible configuration is selected from a variety of possibilities.

In a September 1999 study by U.S. Department of Energy, Office of Industrial Technologies titled “Energy and Environmental Profiles of the U.S. Metal Casting Industry,” it was reported that melting was the most energy intensive process in metal casting, representing 55% of the total energy use as shown in Table 2-1.

Table 2-1 Energy Distribution for Metal Casting Process Areas

Metal Casting Processes	Energy Usage (%)
Coremaking	8
Moldmaking	12
Melting	55
Post Cast	7
Heat Treatment	6
Other	12
Total	100

Conventional melting methods for most metals are very diverse and are represented by Table 2-2.

Table 2-2 Efficiency and Metal Loss for Different Furnaces (conventional metals)

Melting Furnace		Typical Capacities*	Common Use	Melt Loss (%)	Thermal Efficiency (%)
Crucible (Gas)		15 lbs - 1.5 tns	Aluminum	4-6	7-19
			Magnesium	4-6	7-19
			Copper-base	2-3	7-15
Cupola		100 lb/hr - 20 tns/hr	Iron	3-12	40-50
Direct Arc†		1.5 tns - 100 tns	Steel	5-8	35-45
Immersion (low temperature melting)		1,600 lbs/hr	Zinc	N/A	63-67
Induction†		2 lbs - 50 tns	Aluminum	0.75-1.25	59-76
			Magnesium	2-3	59-76
			Copper-base	2-3	50-70
			Iron	1-2	50-70
			Steel	2-3	50-70
Reverberatory	Electric†	0.5 tns - 125 tns	Aluminum	1-2	59-76
			Zinc	2-3	59-76
	Gas	0.5 tns - 125 tns	Aluminum	3-5	30-45
			Zinc	4-7	32-40
Rotary		N/A	Aluminum	N/A	35
Stack Melter (Gas)		1 tn/hr - 10 tns/hr	Aluminum	1-2	40-45

Source: DOE/CMC http://cmc.aticorp.org/datafactors.html

**Information received from communication with AFS*

†The primary energy efficiencies of these furnaces are much lower (about one-third) than the listed efficiencies due to the use of electricity, which involves sizeable energy losses during generation and transmission.

When one looks at the annual castings shipped by alloy and the amount of energy used by each alloy (i.e. ratio of energy used/annual output as shown in Table 2-3) a ratio of 1 indicates equal percentage for energy used vs. annual output and a ratio greater than one indicates higher percentage of energy used vs. annual output.

Table 2-3 ***Annual Output vs. Energy Usage for Metal Castings by Alloy***

Alloy	Annual Output %	Energy Usage %	Energy/ Output
Cast Iron	68	49.5	0.73
Steel	9	9.8	1.09
Aluminum	16	33.9	2.12
Copper	2	2.5	1.25
Zinc	3	1.7	0.57
Magnesium	1	1.6	1.60
Others	1	1	1.00
Total	100	100	

Titanium and superalloys fall under the "other" category and use investment casting process to produce parts. Since titanium and superalloys represent such a small annual output, these alloys are usually not included in metal casting industry studies shown in Table 2-2. However, from a DOD perspective, these alloy systems are critical to many of the weapon systems, especially lightweight armament systems and vehicles for the Army.

Titanium is not represented in Table 2-2 because of its unique requirement to be melted in a controled atmosphere (either argon or a vacuum). The method of melting is called skull melting and there are two common melt furnaces designs: Vacuum Arc Remelt (VAR) and Induction Skull Remelting (ISR). They both require water cooled copper crucibles that chill a layer of melted titanium and form a skull in which the molten titanium is contained. This copper crucible is then tilted to pour the complete content of the melt into a mold. The total process occurs in a vacuum chamber. These titanium melt processes are considerably less efficient than the more common melting technologies, because of the amount of melt energy required to overcome the water cooling of the copper crucible that creates the skull. Typical energy requirements are shown in Table 2-4 for a 50 lb Ti64 melt, assuming 1 hour to melt the alloy.

Table 2-4 ***Melting Energies and Superheat capability of Titanium Furnaces.***

Melting Process	Power Supply (KW)	Limit of Superheat Capability (°F)	Increased Power Usage (%)
Microwaves	~75	up to 300+	baseline
ISR	600	Up to 50	87.5
VAR	200	Up to 25	62.5
VIM (superalloys)	120	up to 300+	37.5 (if possible)

Multiple tests were completed by Technikon utilizing the MS Technology 6 kW microwave furnace located at Oakridge, TN. Both titanium powder obtained from International Titanium Powder (ITP) and bulk aluminum melt tests were completed. The data from these tests were utilized to compare energy efficiency as compared to conventional melting methods as shown in Table 2-5.

Table 2-5 Melting Efficiencies of Aluminum and Titanium (Baselines vs. Microwave)

Melting Process	Melt Temp (°F)	Aluminum (%)	Melt Temp (°F)	Powder Titanium (%)
Natural Gas	1400	33	NA	NA
VIM	1400	20	NA	NA
VAR	NA	NA	3059	15
ISR	NA	NA	3084	5
Microwave	~1400	22	~3060	37.5

NA: Not Applicable

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3.0 CONCLUSION

The results of the microwave melted aluminum indicate that the melting efficiency is comparable to vacuum induction melting and almost a third less efficient than natural gas melting of aluminum. Even though electricity (3412 Btu/kWh) has 3.4 times more energy (Btu) than natural gas (1000 Btu/scf), 60% of the total energy used in Aluminum metal castings is with natural gas while electricity represents 27%. This decision has been an economical decision since historically cost of natural gas has been cheaper than electricity.

The preliminary results of the microwave melted titanium indicate that the melting efficiency is greater than the two baseline production melting processes (VAR and ISR). The key to the increased melting efficiency is that microwave melting of titanium powder did not require a water cooled crucible. Another factor that is the melting temperature of titanium powder (3034ºF) is considerably higher than aluminum (1220ºF), requiring more heat to melt. This gives microwave melting an advantage for higher temperature melting metals, especially using powder, which will suscept the microwaves directly rather than heating a suscepting crucible for bulk metal melting. This also explains why microwave melting of aluminum does not provide any advantage over existing production melting processes such as natural gas or induction melting.

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APPENDIX A BACKGROUND ON MICROWAVE PROCESS

MICROWAVE INTERACTIONS IN THE MELTING OF METALS

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ABSTRACT

The microwave oven in your home is a highly efficient appliance for cooking. But place a fork or aluminum foil in the oven and sparks fly. Doesn't metal reflect microwaves? Yet, microwaves are the higher frequency cousin of radio waves. It is well known that an induction furnace is commonly used for the heat treatment/melting of metals. At higher electromagnetic frequencies, lasers and incoherent infrared also melt metals, so why not microwaves? Actually, you do heat metals with your microwave. That fork or aluminum foil can get very hot.

Recent developments in the processing of ceramics have provided a new paradigm in the processing of metals[1,2]. The use of non-wetting ceramic crucibles has reduced the chemical interactions. This reduces slag as well as inclusions. The process is environmentally green and cost effective for a number of high value metals. A companion poster paper will address the chemical cleanliness of microwave cast metals.[3] Microwaves heat via: 1) dipole rotation, 2) ionic current, 3) electronic current and 4) other nonlinear processes. By controlling the form of microwave heating along with appropriate thermal insulation, very high temperatures can be achieved with relatively low microwave power. The heat treatment, sintering, melting and casting of solid and powdered metals such as aluminum, various steels, copper, and numerous other metals have been demonstrated[1-4].

One aspect of the new paradigm for microwave melting of metals is the heating efficiency[5,6]. But skin depth of microwaves in metals is small, how can it be efficient? Certainly heating a susceptor in the central region is thermally efficient. But how does a metal heat at low temperatures (< 600^{o}C)? At high temperatures (> 1200^{o}C), blackbody heating is significant, but the gray body coefficient for most metals is low, typically less than 0.35. Mechanisms involved in the heating processes will be discussed. This includes indirect heating of dielectrics (hybrid heating), direct heating, plasmas, and a few secondary phenomena.

INTRODUCTION

Metals have been heated and melted by a wide range of frequencies in the electromagnetic spectrum. Traditionally infrared and visible light are used. High power radio frequencies (20 kHz-300 MHz), and now low frequency power (300 Hz- 20 kHz) commonly heat metals by induction.

In many cases with microwaves, the heating of metals have been ignored or assumed to be negligible. Metals largely reflect microwaves, and the skin depth of penetration is very thin. So there is little expectation to utilize MW for melting metals. But the specific heats of metals are low compared to ceramics, so if heat can be transferred to the metal and thermal losses are minimized, we would be able to approach metal melting in a different way. Figure 1 shows a sample of 30 lbs of Cu molten by MW and cast in place.

Waveguides and cavities carrying high power microwaves have often been too hot to touch. In the very high power microwave tube industry, it is well known that waveguide and cavity walls must be actively cooled,[7] to avoid overheating and melting! But such high power and frequency is not needed to heat metals. Microwave absorbing ceramics or susceptors have been used in the microwave tube industry for over 50 years to reduce unwanted MW heating, improve efficiency of MW generation or as 'dummy' loads.[8]

The advantage found in rapid heating of a variety of ceramics by MW can be used in the hybrid heating of metals. Induction, gas fired and radiant heat are not able to heat ceramics as rapidly as MW. Highly overloaded systems can be used to uniformly heat the surfaces and volumes of ceramic crucibles for metal melting and casting.

Figure1: MW melted and cast Cu, 30 lbs.

Plasmas (ionized gas) are not generally aimed to heat metals either. Surface processing with plasmas are well known[9]. In fusion energy research, magnetically confined plasmas still leak to the wall or dirty plasmas are removed by divertors[10,11]. The sheath criterion and neoclassical Bohm diffusion are well known in plasma physics concerning plasma loss to the walls. One specific application is the arc plasma which is used to vacuum arc melt aluminum or titanium[12]. An MW generated plasma has melted small samples of metal. Scaling to large metal loads is possible under controlled circumstances. Uniform heating to melt a large load is usually not a requirement. However, ceramic insulation or crucibles would require fairly uniform heating. Metal crucibles may be possible for some cases.

In this paper, we will discuss some of the microwave interactions involved in the melting of metals. It is useful to keep track of potential interactions when trying to predict the ultimate size and fast heating rates needed for industrial usage. This will also help clarify some possible misconceptions of the process.

CURRENT GENERATION

Most people are familiar with electrical current and resistivity in the form of Ohm's law. Microwaves are limited in the penetration depth in metals, semiconductors and unmagnetized dense plasmas by the familiar skin depth:

$$\delta = (1/ \pi f \mu \sigma).5 \tag{1}$$

Where f = frequency in Hz; μ = permeability (hy/m) ($\mu o = 4 \pi \times 10^{-7}$); σ = conductivity (mhos/m) (for Cu: $\sigma = 5.8 \times 10^{7}$ at room temperature) = $1/\rho$ resistivity ρ is inversely proportional to conductivity. At 2.45 GHz, for Cu, T=20°C, δ = 1.3 micron, pretty shallow. Surface resistivity is related to skin depth by:

$$R_s = 1/\sigma \delta \tag{2}$$

R_s = .013 ohms again, not much. The metal's resistivity ρ is temperature dependent and generally increases with temperature. The increase in resistivity with temperature is nearly linear, even for many alloys to the melting point T_m or other phase transition. At phase transitions, there is a small quantum jump. For most metals at T_m, the resistivity increase[13,14] is generally only about a factor of 2. Resistivity is generally affected by the Fermi surface, impurities, electron or hole mobility as in semiconductors, and lattice effects.[15] Claims of significant enhancement of resistivity near or beyond the melting temperature[16], when MW heated, have not been substantiated. Anomalous resistivity is often associated with surface finish, porosity, impurities and possible magnetic effects.

Induction heating with microwaves is generally avoided, although small regions or instances of induction can be found. Some cases include scrap metal where loops are formed. Some cases with poor conductors may be found.

The magnetic field components of microwaves, at power levels of interest, are negligible. Despite the apparent low magnetic fields, researchers at Penn. State Univ.[17] have demonstrated that processing of ferromagnetic material is different in a primarily H field region of microwaves than in a primarily E field. More ferromagnetic domains were observed in the H field processed region. The electric field polarization is different from the magnetic field polarization. It is suspected that magnetic dipole alignments should favor chemical kinetics that also preserves magnetic dipole alignment. Electric field heating, in such cases may be small, but significant. It is assumed that the electric field in ferrites at the appropriate region of a waveguide can be kept small enough to not disrupt the magnetic dipole alignment. Such activity in paramagnetic or diamagnetic material would be harder to demonstrate.

BASIC SUSCEPTOR HEATING OF METALS

Consider the simple configuration of a cylindrical block of metal contained in a susceptor ceramic crucible, surrounded by a thermal insulation, all contained in a metal chamber. The simple geometry would be a set of concentric surfaces. Basic MW heating would preferentially heat the susceptor ceramic, with small amounts of direct heating to the metal load, insulating fiber board and chamber. The chamber is expected to support at least a single MW mode. For large industrially relevant configurations, the chamber would support multiple modes. Frequencies of 915 MHz and 2.45 GHz are generally considered, primarily for ISM frequency allocation, power availability and cost economy. All calculations presented here are based on 2.45 GHz.

Simple steady state thermal calculations assuming multiple surface temperature profiles in the susceptor provide good estimates of temperatures distributions and power requirements[5,6]. Heating of a solid block of metal directly by MW is usually small. Heat is transferred from the hot crucible to the metal by conduction, convection and blackbody. By summing the energy requirements, good estimates of time to heat and maximum required MW power are made. For example, one ton of Cu can be heated to 1260°C in one hr, average MW power: 238 kW. This is achievable at plug efficiencies of 50%. This projection is supported by numerous experiments up to 500 lbs of metal. The power nevertheless, is considerable and a furnace designer must be aware of a multitude of potential problems.

A fine grid transient temperature is still in progress, however, estimates by a series of steady state calculations is instructive. The metal is set inside the crucible, making contact at the bottom surface. Contact conduction is assumed to be limited by the MW heating rate and thermal conductivity of the crucible. Results of such calculations are shown in Table 1 for 1 ton of Cu starting from room temperature 20^{o}C. S1, S2, etc. represent flux surfaces. S1 is the metal outer surface, S2 crucible inner surface, S3 crucible outer surface, S4in insulation inner surface, S5out insulation outer surface and S6ch chamber inner surface. A heating schedule to melt in 1 hour is assumed.

At the very start of MW heating, direct MW heating of the metal load dominates for a short time. Conduction then rapidly increases and dominates as soon as a few degrees difference is achieved between the crucible and metal, as in Table 1 (A). Convection rarely exceeds direct MW heating if rapid heating scenarios are assumed. Blackbody heating is small, as expected, in the first phase of heating. Blackbody starts to exceed convection at about 300-400^{o}C. Compare with direct MW metal heating at about 1% of the applied MW power. As the crucible temperature reaches 600- 700^{o}C, blackbody starts to get significant and surpasses direct microwave heating, Table 1 (B). Convection is the smallest factor but approaches the direct heating near the melting point, especially as the MW is ramped down to hold the crucible temperature. As the metal melts, a larger contact surface forms, which increases conduction and severely reduces blackbody and convection. The increase of direct MW due to higher metal resistivity is small by comparison.

It is conceivable with some tinkering of parameters, to get a condition where the initial heating can be greater for the metal than the ceramic due to size and relative specific heats. The metal would be hotter than the ceramic and transfers heat to the ceramic. At higher temperatures, the larger dielectric loss of the ceramic would dominate. The optimum set of conditions would be to transfer heat from the ceramic, with the appropriate heat transfer, ceramic strength (minimal stress) and heating profiles, while maximizing direct heating.

TABLE 1: Calculations flux surfaces S1-metal, S2-cruc. ID, S3-cruc. OD, S4in-insul. ID, S5out-insul. OD, S6ch-chamber ID;   A) 10 kW, S3=50^{o}C, B) 250 kW, 600^{o}C, C) 250 kW, 1200^{o}C.

A (10kW)	S1	S2	S3	S4in	S5out	S6ch
T(C)	45.4	48.5	50	47	23	20
Qbb(W)	-5	0	25	0	17	
Qcv(W)	-9	0	14	0	26	
Qcd(W)	-4911	-5025	0	40	0	
Qtot (W)	-4925	-5025	40	40	42	

C (250 kW)	S1	S2	S3	S4in	S5out	S6ch
T(C)	1039	1140	1200	1192	206	35
Qbb(W)	-12210	0	7042	0	2792	
Qcv(W)	-735	0	55	0	5016	
Qcd(W)	-85054	-100498	0	7098	0	
Qtot (W)	-97998	-100498	7098	7098	7808	

B (250 kW)						
T(C)	464	555	600	587	100	22
Qbb(W)	-1961	0	2355	0	752	
Qcv(W)	-604	0	102	0	1877	
Qcd(W)	-115533	-120598	0	2457	0	
Qtot (W)	-118098	-120598	2457	2457	2629	

Moisture or trapped gases in ceramics and ceramic insulation are always a concern when placed in a MW furnace cold. It is also a problem with cold metals in metal foundries[12]. Consequently the process simulated by Table 1, assumes relatively slow initial heating until 200^{o}C. Bound water, may exist at temperatures as high as 600°C. Sufficient inert gas flow is assumed to remove water vapor and other gases. Such “forced” convection can also be included in the model. Vacuum can also be modeled by shutting off convection and using the appropriate thermal conductivity of the insulation.

The scaling of this type of heating for large quantities of metal, and rapid heating has lead to questions such as: what can we achieve, what are the limitations, what kind of problems may we expect, etc. In the above scenario, a solid metal block was assumed. Metal scrap or even metal powder would change the heating profile significantly. Of course, electric field strength and ceramic stresses should be determined. This paper raises some of these issues.

MICROWAVE MODES

Waveguide and cavity modes for microwaves are well known in their simple forms as rectangular or cylindrical configurations. In the hollow waveguide or cavity with perfectly conducting walls, we have the transverse electric (TE or H-mode), transverse magnetic (TM or E-mode) modes and the transverse electromagnetic (TEM) mode when multiple conductors exist. Complex shapes, finite wall resistivity, dielectrics, etc. can result in a hybridization of modes. In a highly oversized chamber, there is a spectrum of overlapping modes, each with different cavity Q (Qnmp). One goal is to excite the modes that efficiently and uniformly heat the crucible.

The simple case of a lossless cylindrical dielectric coaxial to a larger metal casing can be calculated analytically[18] and has been approximated by finite element or finite difference time domain calculations[19]. An analytical calculation for the coaxial dielectric problem has been extended to multiple dielectrics by one author (Huey) for lossless dielectrics and perfectly conducting metals[18]. Loss is then included as first order estimates in each region. Several aspects of the multimode calculation can be given. Comparisons of the analytical calculations versus the FEM & FDTD calculations will be presented in a future paper. Figure 2 is an example of the calculated fields for a coax configuration at 2.45 GHz, with a metal load in the center, contained within a crucible and surrounded by insulation. The mode is a hybrid TE/TM, dominant TM. Similar calculations were performed for ceramic loads also. Note the increase of the Ez field in region 1 and the Hphi field in region 2 (crucible). Such calculations provide power deposition profiles on the metal load, crucible, insulation and chamber wall.

When all regions in the coax model support a propagating mode, the distribution of heating is mode dependent. In most cases, the distribution is not considerably different. In cases where the mode is primarily resonant in the 1st region, then heating of the load metal can be significantly greater than in other cases. This type of phenomenon has been observed in the design of coaxial cavities for very high power millimeter wave tubes known as gyrotrons[20]. Whereas such phenomena are avoided in gyrotrons, possible enhancements to the processing of metals may be desirable.

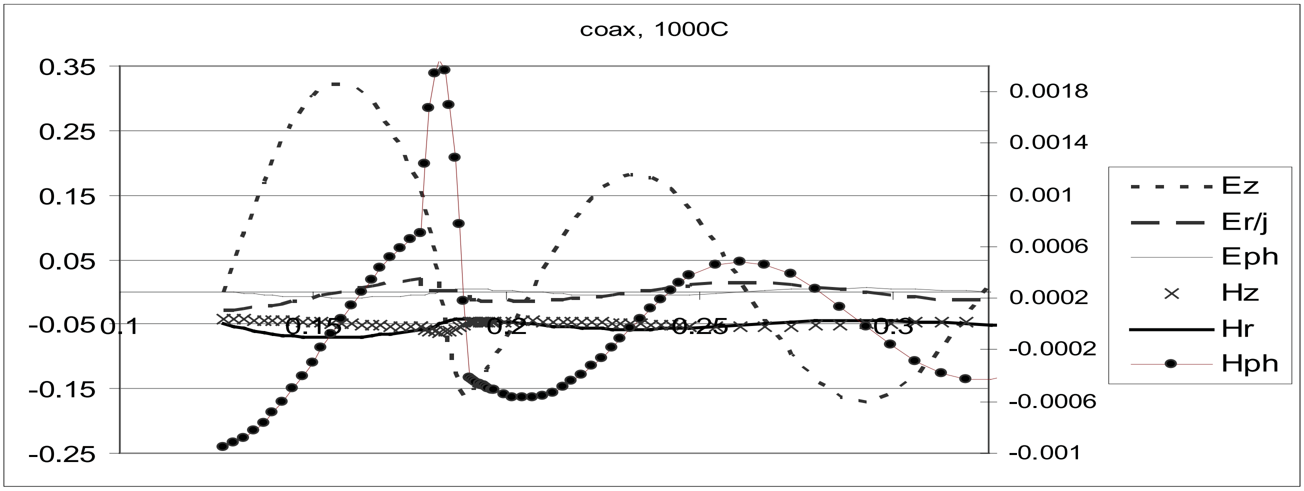

Figure 2: Example of analytical calculation of MW fields: coax, metal center, crucible, insulation. Left axis electric fields, right axis magnetic fields. Note zero offsets of vertical scales and radial axes to facilitate viewing.

Akin to single mode optical fibers, a non-radiating mode may exist in the crucible itself.[18] Power coupling for this mode can only be introduced at the entrance of the crucible. No MW power from this mode would couple with the insulation or the chamber wall, except to enter the crucible. If the dimensions are right then a crucible resonance mode may be set up. If the attenuation is severe enough, then the Q may be inconsequential. If not, then the field in the crucible may quickly build up to levels where gas breakdown may occur and plasma is generated within the crucible. This phenomenon has been observed by the authors. It can lead to plasma heating of the metal. This has potential application, but large plasmas are difficult to control and maintain. Damage to the crucible due to non-uniform heating is one problem.

Often mode stirrers are used to help achieve uniform fields. This concept, is simplistic, and can lead to the significant excitation of modes that do not heat as desired. The actual aim is to control MW heating and insulation to achieve the desired temperature profile, achieve efficient heating while maintaining reproducibility and safety. Combinations of multi- or distributed MW sources and stirrers are expected. Modes may exist within a solid dielectric cylinder, sphere, cube, etc or within a portion of a larger object. Depending upon the physical size and shape, the dielectric constant, temperature dependencies, and coupling by the microwaves, a local hot spot may build up. Modal analyses help identify such possibilities[21].

Finally, analytic modal calculations are limited in scope due to the treatment of loss as a perturbation. Finite element steady state and finite difference for transient calculations fill much of the gap, limited often by memory, time or lack of physical properties data.

MW & METAL PARTICLES

In the presence of a MW field, the free electrons in a metal surface would oscillate as a current and generate a scattered wave pattern. In the case of a long thin wire, the scattered or reflected wave is cylindrical in shape, for a large flat plate the scattered wave is often a direct reflection like a mirror. As mentioned above, the penetration depth of the MW is typically characterized by the skin depth. The skin depth at 2.45 GHz is very shallow, typically, from about 1 μm to 10 μm in metals at room temperature. The skin depth slowly increases to a factor 2 to 10 times greater as the temperature is raised to near the melting temperature. Furthermore, at melting the resistivity may increase abruptly by about a factor of 2, thereby increasing the resistivity by another square root of 2.

Consider now the small metal particles for powder metal. If the particle size is less than 3 μm, it will most likely be smaller than the skin depth sometime during the heating process. Also, due to charge buildup at the ends of the particles, currents are reduced and modified, creating different scattering patterns. Particles are not shaped as the ideal ellipsoid shape, and changes in current flux or direction may also exist. Also the intervening space between particles will allow some MW to penetrate deeper. Thus, in a non-magnetic metal powder, the MW power penetration depth is significantly deeper than the skin depth. It is estimated that MW power penetration depths can be as much as 1 to 3 cm deep depending on the particle size, bulk density percentage, conductivity, oxide coating, etc. Direct MW heating of metal powder is strong[22,23]. Thus direct MW sintering of metal powders at 2.45 GHz may be limited to thicknesses of 3 to 9 cm. Thick pre-forms may require slow MW heating to avoid sintering of the surface region before any significant heat can transport to the central region. Hybrid heating would be required to complete the volumetric sinter, once significant sintering (or percolation) occurs.

High power MW on metal powder also causes arcing along and within the surface regions of the metal powder. The flow of charge in each particle causes nearest neighboring particles to build a large electric potential between particles. By turning off the room lights, many arcs can be viewed through a view port window. This may not be a bad situation, but rather a helpful one to help deposit more MW power to heat the powdered mass. Thus, high power MW will have shorter penetration depth in metal powder than low power MW. Extremely high power MW would deliver significant power in the arcs in powder. Gas heating (or moisture evaporation) and rapid expansion could cause bursting. This certainly should be avoided and may represent one limit to very high MW power.

A solid metal surface has a surface finish, depending on the forming process. A typical machined surface finish is about 1-3 μm. Finer finishes are possible, but it is important to note that even moderately smooth machined surfaces are comparable to the skin depth. So the penetration depth really can be deeper than the skin depth due to the profile or roughness of the surface.

MW PLASMA

Gas breakdowns by MW, RF and lasers are well known and may occur at any gas pressure. Various conditions aid in the initiation of the gas breakdown. In it’s purest form, a focused MW spot can breakdown air, vapor, or ‘vacuum’ primarily initiated by the existence of free electrons as calculated by the Saha equation[11]. Other sources of electrons are discussed below. Collisions forming avalanches of electrons will then further ionize the neutral gas. Mean free paths of electrons and collision frequencies are dependent upon gas molecule (or atom) number density, energy of the electrons and cross sections for various interactions (such as elastic, ionization, excitation, recombination, etc.). Generally, the mean free path cannot be significantly larger than the focused region of the MW and the ionization collision frequency should be lower than the MW frequency. However, in extreme cases, a very high power MW (or laser) can violate those conditions. Recombination time constants are generally longer than the MW period, thus maintaining a vast supply of free electrons.

In practice, the mean free path of electrons compared to the physical dimensions of the crucible and metal play a role. If the mean free path is much less than the spatial extents, then we obtain the Paschen[24] curves. When the mean free path is large compared to spatial dimensions, then multipactor[24] effects, due to secondary emission arise. With high microwave power, electron energies in multipacting have often produced X-rays[25] from Bremsstrahlung radiation. This can produce significant local heating of metal and ceramics.

It is not always easy to create plasma with the desired properties. Uniform plasmas need to be controlled in a tight range of parameters. Initiation of the plasma often requires different conditions than maintaining controlled plasma. Often the operator would initiate plasma by a change of MW power, frequency, reflection, gas density, etc. Arcs and plasmoids may form instead of uniform plasmas. In some cases, arcs may be desirable. Usually MW power requirements to initiate the arc/plasma are greater than to maintain steady state plasma. Increasing the MW power does not necessarily increase the plasma density in the desired way. Often, a localized, arc or plasmoid may develop when MW power is increased, which may prevent access to the desired plasma condition.

Many species temperatures[10,11] are sustained in plasmas due to differences in collision frequencies. They include neutral gas temperature, electron temperature, and ion temperatures (depending on the mix of gases, different ion states, excited states, etc.). Temperatures are so high that we refer to temperature in units of kT in electron volts (1 eV ~11600°K). Low pressure plasma will have a higher electron temperature than atmospheric pressure plasma due to relative collision frequencies. Velocity distributions for each species temperature are not necessarily Maxwellian.

Plasma density is dependent upon the rates of formation of electrons, ion types and recombination. Most plasmas do not achieve full ionization of the neutral gas. Ionization fractions are usually less than a few percent, unless sufficiently high MW electric fields are generated in large dimensions compared to mean free paths.

Plasmas and semiconductors behave much like metals to microwaves when the number density of 'free' electrons which yields the plasma frequency f_p (or ω_p), exceeds the microwave frequency.

$$f_p \sim 9000\ n^{1/2} \qquad [\mathrm{Hz}] \tag{3}$$

Where: n = number of electrons/cm3, m = electron mass, e = electron charge. Note $\omega_p = 2\pi f_p$ is also called the plasma frequency. Example: for $n=10^{11}$/cc, then $f_p = 2.85$ GHz, note air density is about 2.5×10^{19}/cc. Above the plasma frequency, the MW sees the plasma as a dielectric. For unmagnetized plasma, the plasma dielectric constant[10,11] is:

$$\varepsilon_p = c^2\, k^2/\omega^2 = 1 - \omega_p^{\ 2} / (\nu 2 + \omega^2) \ < \ 1 \tag{4}$$

Notice, when MW frequency $\omega > \omega_p$, there is propagation. For $\omega < \omega_p$, the wave is damped and a skin depth arises. Collisions, especially if the collision frequency ν is higher than f_p, should be included. Non-collisional damping of MW and other plasma waves exist that would transfer MW energy to the plasma[10,11].

For magnetized plasma, the situation is much richer. Magnetized plasmas are beyond the scope of this paper. However, it is important to note that the non-relativistic electron cyclotron frequency (gyro-frequency) is given by:

$$\omega_c /2\pi = f_c = 2.8\ \mathrm{GHz/kG} \tag{5}$$

Where kG is kilo-Gauss (pardon the units) of magnetic field. Nearly 1 kG of magnetic field, not likely from the microwave field magnetic component, would be required to generate a fundamental resonance. It would require a modest external magnetic field source such as electromagnets or permanent magnets. But note if there is an applied magnetic field and plasma, a high order harmonic resonance can also exist. Usually very high order resonances are damped out by collisions, etc.

Plasma bombardment of metals and dielectrics depend on the charge buildup of the object and the subsequent electric potential with respect to the plasma potential. The transition of the potential of the plasma to the object potential is known as the sheath region. Any object immersed in plasma is surrounded by a plasma potential sheath. Electrons and ions travel at different rates. Diffusion of plasma to an object is determined by ambipolar diffusion[10,11]. A bias voltage can be applied to increase the energy of bombarding electrons or ions to preferentially heat the object. Heating of the object is dependent on the diffusion rate which is based on both the plasma density and temperature. A high electron temperature (> 1 eV) at low density (~10^9/cc) would not provide significant heating.

Light from plasma usually arises from recombination. MW and RF generated plasma lights are now readily available. Recombination light represents a major energy loss for the plasma and some of it may heat the load. Blackbody light, requires significant light scattering and consequently exists mainly in very large or extremely dense plasmas. Electron bombardment of the load or other materials, especially with a bias voltage can generate Bremsstrahlung radiation (photons developed from the rapid deceleration of electrons near a heavy nucleus) such as X-rays.

Other more exotic plasma effects exist at high MW power. Microwaves, like light exert a radiation pressure. This is known as the ponderomotive force[11,26,27]. It provides coupling to low frequency, in this case, ion waves in plasmas and possibly phonons in ceramics. It has been shown to create plasma density perturbations and may enhance sintering of ceramics by microwaves[28]. With multiple MW sources, beat waves can be generated in plasmas or dielectric material that may couple to phonons. Scattering of such phonons may serve as a minor heating mechanism or as a nondestructive (or noninvasive) diagnostic.

CONCLUSIONS

MW heating of metals for melting and casting has been demonstrated. Scaling to 500 lbs of metal has been successfully demonstrated by one author. However, continued scaling to levels such as 1 ton of Cu to 1260°C in one hour and beyond, present challenges for the MW furnace designer and should not be undertaken by the novice. Analytical modeling, simulations, etc. of the electromagnetic and thermal aspects are helpful tools to calculate or design well behaved furnaces.

Nevertheless, knowledge and experience of very high power MW, power supplies, MW components, plasmas, and diagnostics are invaluable for scaling to handle industrial size applications.

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APPENDIX B ACRONYMS AND ABBREVIATIONS

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ACRONYMS AND ABBREVIATIONS

AFS	American Foundry Society
BO	Based on ( ).
BOS	Based on Sand.
CARB	California Air Resources Board
CERP	Casting Emission Reduction Program
CISA	Casting Industry Suppliers Association
DOD	Department of Defense
EEF	Established Emission Factors
GS	Greensand
HAP	Hazardous Air Pollutant defined by the 1990 Clean Air Act Amendment
HAP	Hazardous Air Pollutants
HC as Hexane	Calculated by the summation of all area between elution of hexane through the elution of hexadecane. The quantity of HC is performed against a five-point calibration curve of hexane by dividing the total area count from C_6 through C_{16} to the area of hexane from the initial calibration curve.
I	Data rejected based on data validation considerations
Lb/Lb	Pounds per pound of binder used
Lb/Tn	Pounds per ton of metal poured
LOI	Loss on ignition
MACT	Maximum Achievable Control Technology
MMS	Mixing, Making, Storage
NA	Not Applicable
ND	Non-Detect

NESHAPs	National Emission Standards for Hazardous Air Pollutants
NT	Lab testing was not done
PCS	Pouring, Cooling, Shakeout
PM	Particulate Matter
POM	Polycyclic organic matter (POM) including naphthalene and other compounds that contain more than one benzene ring and have a boiling point greater than or equal to 100 degrees Celsius.
QA/QC	Quality Assurance/Quality Control
TEA	Triethylamine