Experimental and theoretical investigation on Microwave melting of metals

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Abstract:

Experiments were conducted for microwave heating and melting of lead, tin, aluminium and copper with the aid of susceptors and the detailed results were presented for various microwave power levels and sample loading. Aluminium and copper samples were heated in presence of inert gas to minimize oxidation. Compared to conventional melting, microwave melting was twice as fast and more energy efficient. Lumped parameter model of the heating process showed that the conversion of microwave to thermal energy was enhanced at higher temperatures, justifying this a favourable process for metal melting applications.

Keywords: Microwave heating, melting, temperature dependence, lumped parameter model, metals
1. Introduction:

Melting metals in conventional furnaces such as electric arc furnace, cupola furnace, blast furnace, induction furnace, crucible furnace etc., consumes significant amount of energy. Additionally there are possibilities of material and energy losses and some safety risks (Moore et al., 2003). In order to overcome the inherent disadvantages of conventional melting, one or more of the advanced melting technologies such as electron beam melting, infra red melting, plasma melting, microwave melting, solar melting etc. are preferred according to the specific requirements and applications. Microwave heating receives considerable attention due to its major advantages such as high heating rates, reduced processing time, low power consumption and less environmental hazards (Jones et al., 2002). During microwave heating, large amount of heat may be generated for a lossy material throughout the volume, whereas for conventional heating, the material is heated via an external heat source and subsequent radiative transfer. Microwave finds an important application in various non-conventional heating methods. In food processing, microwave finds application in drying of foodstuffs, (Khraisheh et al., 1997), preparation of activated carbons having the properties of high surface area and pore volume (Ji et al., 2007), processing of high melting temperature glasses at high heating rates (Almeida et al., 2007), curing of polymers in order to improve their strength (Yarlagadda and Hsu, 2004) and treatment of wastes which were more energy efficient than conventional methods (Appleton et al., 2005). One of the largest application areas of microwaves is in ceramics processing, which includes sintering and quality improvement of certain ceramic materials (Menezes and Kiminami, 2008) and also joining of ceramics where materials processed with microwave exhibited better joint and flexural strength (Yarlagadda and Soon, 1998).

Although microwave can heat many materials, certain difficulties are encountered in heating metals and alloys. Microwaves cause sparking of metallic materials and most
metals are known to reflect microwaves, as their skin depth is of the order of few microns (Gupta and Wong, 2007). Skin depth is a measure of depth of microwave penetration in which the field is attenuated by 1/e of its value at the surface (Metaxas and Meredith, 1983). It was reported that microwave sintering of metal powders can be achieved, and that microwave sintering yielded fast heating rates, uniform microstructure and shape retention (Leonelli et al., 2008), increased sintered density, higher flexural strength and uniform distribution of pores (Anklekar et al., 2001). Saitou (2006) demonstrated that the rate of microwave sintering was higher than that of electric furnace sintering for iron, nickel, copper and stainless steel powders and reported that microwave radiation did not change the sintering mechanism. Microwave heating of metal particles was modeled using finite difference time domain (FDTD) technique (Mishra et al., 2006). Microwave sintering of metal-matrix composites such as copper-graphite composites was performed and the resulting finer microstructure enhanced the performance of the composites (Rajkumar and Aravindan, 2009). Sintering of other metal-matrix composites such as Al/SiC, Ti/C were achieved at high temperatures (>933 K) with low input power (<1 kW) with microwaves (Leparoux et al., 2003). Successful microwave brazing of nickel-titanium alloy has also been reported (Eijk et al., 2008). Microwave heating of metals was extended to melting process by researchers of Oak Ridge Y-12 National Security Complex (Tenn, USA) for melting and casting of steels, titanium, zirconium, uranium, copper, brass, bronze, aluminium of varying masses, from few kg to 350 kg (Ripley and Oberhaus, 2005). Agrawal (2006) reported that bulk metals such as aluminium, copper and stainless steel can be melted. While the published reports demonstrate that it is possible to melt metals, the detailed heating characteristics have not been reported so far.

Hybrid microwave melting of lead, tin, aluminium and copper was experimentally investigated by varying microwave power level and the load and the results are reported
here. The experimental results were successfully modelled by lumped parameter model. The results showed that the heat absorption was a strong function of temperature.

2. Materials and methods:

![Schematic diagram of microwave melting of metals](image)

1. Microwave power unit or furnace
2. Thermocouple
3. SiC susceptor
4. Metal in clay graphite crucible
5. Refractory insulation box
6. Spacers
7. Glass tray turn table
8. Power controller
9. Water for cooling
10. Pump
11. Computer to record temperature data
12. Gas inlet

Figure 1: Schematic diagram of microwave melting of metals

A 1.3 kW water cooled Thermwave microwave oven (Research Microwave Systems, New York, U.S.A) consisting of the following components was used.

i. Microwave power unit (furnace)

ii. Microwave power controller

iii. Thermocouple assemble (Type S; temperature range 1800 K) with a gas inlet. The gas inlet was needed so that the metals that would normally oxidize on heating can be heated in presence of an inert gas such as nitrogen or argon. The thermocouple was shielded with platinum foil to prevent arcing and microwave interference with temperature measurement.
iv. Refractory insulation box or thermal pod, which can withstand temperature up to 1700 K, was used to contain the heat. Since it has a very low dielectric loss, microwaves pass through it with very little interaction.

v. Squat shaped thermcepts (50 g silicon carbide susceptor)

The schematic of the microwave setup was shown in figure 1. The operating frequency of microwaves was 2.45 GHz which is normally used in household microwaves. The metal sample in clay graphite crucible (Morganite crucibles, India) of 70 ml capacity was kept in the thermal pod insulator inside the microwave oven. At room temperatures, clay graphite crucibles do not couple well with microwaves and also they do not absorb microwaves beyond 300 K. Hence SiC susceptors, which can heat up to 1400 K, were used to provide initial heating. The power controller was used to vary output power from 40 % to 100 % of its total power. The temperature reading was directly recorded in a computer. The experiments were repeated at least twice to ensure that the data was reproducible.

Microwave melting of metals were carried out at three different power levels 100% (1300 W), 70 % (910 W) and 40 % (520 W) and at various sample loads (25 g to 150 g).

3. Results and Discussion:

3.1 Microwave melting of tin (Melting point 505 K):

Figure 2 shows the temperature profile vs time for tin samples at different loads and power levels. Tin granules of average diameter 3 mm were used for melting. It was known that some of the submicron and nanosized metal powders undergo volumetric heating when subjected to microwaves. For relatively coarse powders (>100µm), the heating may be conductive from the outside (skin) to the interior of the powder (Mishra et al., 2006). Hence, for metal particles of size in the range of 3 mm, melting was accomplished with the aid of high dielectric susceptors or crucibles.
Figure 2: Microwave melting of tin at various power levels for weights a) 50 g, b) 100 g and c) 150 g.

The melting point of tin (505 K) was represented by the horizontal line. It is seen that the initial rate of rise in temperature was lower which was due to the fact that the clay graphite
crucible does not couple with microwaves at ambient temperature. Since the power absorption by the SiC materials was relatively large compared to many other dielectric materials (Basak, 2007), the initial heating was provided by SiC susceptors and the radiant heat was supplied to the crucible which in turn heats the metal charge by conduction. Mishra et al. (2006) also reported that SiC is a good absorber of microwaves and that can be heated up to 1300 K in 5 minutes with a power output of 1.1 kW. They were also able to heat tin powder (< 75µm) close to the melting point within 4 minutes. As seen from the results, melting of tin was achieved in 5 minutes for 100 % and 70 % power, whereas melting was achieved within 7 minutes at 40 % power. At the melting point, the temperature was expected to remain constant for some time, since the latent heat of melting would have to be supplied. Thus, a small horizontal section is expected in Figure 2, near the melting point. However, the latent heat of melting for tin is very low and the heating rate was very high such that the horizontal section was not seen in the results. Only in cases where the heat supply is low relative to the thermal load, the horizontal section can be observed. The average rate of rise in temperature attained for melting tin was 42 K/min at 100 % power and 30 K/min at 40 % power. As the power level decreases, the heating rate decreases and hence an increase in melting time was observed. The time required for melting tin was the same for all loads up to 150 g at a given power level. This indicates that the contribution of the metal sample to the total thermal load was relatively less and most of the thermal energy was used in heating the susceptor and crucible.
3.2 Microwave melting of lead (Melting point 600 K):

![Temperature profile vs time for lead sample at different loads and power levels.](image)

Figure 3 shows the temperature profile vs time for lead samples at different loads and power levels. Lead shots of average diameter 3 mm were used for the melting investigation. The melting point of lead (600 K) is represented by the horizontal line. It is seen that melting of lead was achieved in 5.5 minutes for 100 % power, 6 minutes for 70 % power and 9 minutes at 40 % power. The average rate of rise in temperature attained for melting lead was 51 K/min at 100 % power and 33 K/min at 40% power. As expected, a decrease in the power level to very low values led to an increase in the time needed to reach a given temperature. For loads up to 100 g, there was no significant difference in melting characteristics between 100 % and 70 % power as the heating load was not high. Also at a given power level, the time required for melting was the same for loads up to 150 g. The latent heat of melting for lead and tin were 22.5 kJ/kg and 58 kJ/kg respectively. Due to low latent heat of melting and rapid heating by microwave, the latent heat signature which was expected at the melting point, was not seen.
3.3 Microwave melting of aluminium (Melting point 933 K):

![Graph showing temperature profile vs time for aluminium at different power levels]

*Figure 4: Microwave melting of aluminium (25 g) at various power levels.*

Agrawal (2006) showed that bulk aluminium metal can be melted in a microwave field with susceptors, but the detailed heating characteristic was not reported. Figure 4 shows the temperature profile vs time for aluminium (25 g) at different power levels. Bulk aluminium metal of diameter 14 mm and thickness 12 mm were used for the melting investigation. The melting point of aluminium (933 K) is represented by the horizontal line. The experiments were carried out in presence of argon in order to minimize aluminium oxidation. It is to be noted that an air-tight setup could not be maintained and hence presence of small quantities of oxygen could not be excluded. The entire setup was enclosed in a wooden box and argon was allowed to flow at 6 lpm for 10 minutes. The flow was stopped and microwave heating was started. If the argon was allowed to flow through the thermocouple tip during the experiments, it led to cooling of the thermocouple, resulting in underestimation of the sample temperature. The time required for melting were 9 minutes at 70 - 100% power and 14 minutes at 40% power level. The average rate of rise in temperature required to melt aluminium was 82 K/min at 100 % power and 48 K/min at 40% power.
3.4 Microwave melting of copper (Melting point 1356 K):

![Temperature profile vs time for microwave melting of copper turnings (25 g) at various power levels.]

Figure 5: Microwave melting of copper turnings (25 g) at various power levels

Demonstration of melting of bulk copper has been reported earlier (Ripley and Oberhaus, 2005). Figure 5 shows the temperature profile vs time for microwave melting of copper turning (25 g) at various power levels. Copper turnings of average thickness 2 mm were used for melting studies. The melting point of copper (1356 K) is represented by the horizontal line. Copper has a tendency to oxidize at high temperatures in ambient air and hence argon atmosphere was maintained to minimise oxidation. The time required for melting was 20 minutes at 70 – 100% power and 29 minutes at 40% power level. The average rate of rise in temperature of melting copper at 100% power level was 84 K/min till 1023 K. Thereafter, average rate of rise in temperature reduced to 26 K/min due to the temperature dependent dielectric loss of the SiC susceptors (Baeraky, 2002).
3.5 Comparison of Microwave melting with Conventional melting:

Figure 6: Comparison of microwave melting with conventional melting for a) tin, b) lead and c) aluminium
Figure 6 shows the melting characteristics of metals using the microwave of 1300 W capacity and a muffle furnace (conventional) of 2500 W capacity. For all the metal used, conventional oven heats much slower than microwave oven. It has been reported that temperatures of 1673-2073 K can be reached using low power (2 to 6 kW) microwave oven as compared to induction heating which required 10 – 150 kW (Moore et al., 2003).

Table 1: Comparison of melting time and heating rate for microwave and conventional melting of metals

<table>
<thead>
<tr>
<th>Metal used</th>
<th>Microwave (1300 W)</th>
<th>Conventional (2500 W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Melting time (min)</td>
<td>Rate of rise in temperature (°C/min)</td>
</tr>
<tr>
<td>Tin</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Lead</td>
<td>6</td>
<td>51</td>
</tr>
<tr>
<td>Aluminium</td>
<td>9</td>
<td>82</td>
</tr>
</tbody>
</table>

Table 1 shows the melting time and heating rate for both microwave and conventional mode of melting. The time required to melt metals was halved by using microwave, instead of conventional furnace. The energy required was also half for microwave when compared to the energy requirement for the conventional furnace. Since the muffle furnace used has limitation of operating only up to 1100 K, comparative studies on copper could not performed.

3.6 Modelling Approach:

The energy balance equation for microwave melting of metal can be given by

\[
\rho C_p \frac{dT}{dt} = p
\]

where \( \rho C_p \) is the specific heat per unit volume and \( p \) is the heat source due to microwave propagation within the material (Basak and Kumaran, 2005). The assumptions involved in the model are as follows: i) the heat loss to the surroundings by convection and radiation is negligible, due to the presence of thermal pod arrangement. ii) All of the microwave
energy was absorbed by the SiC susceptor due to very little interaction by the microwaves with bulk metals and clay graphite crucible. iii) The temperature of metal and crucible were the same throughout the experiments.

Dimensionless parameters $\theta$ (dimensionless temperature) and $\tau$ (dimensionless time) are introduced in order to non-dimensionlize the energy balance equation. The variables which affect the melting of metal are i) density ($\rho$), ii) diameter/thickness ($L$), iii) specific heat ($C_p$), iv) input microwave power ($I$) and v) temperature ($T - T_\infty$) where $T$ is the sample temperature and $T_\infty$ is the ambient temperature. The dimensionless temperature and dimensionless time are defined as follows

$$\theta = \frac{\rho_e C_p_e (T - T_\infty)}{(I / L^3_e) t_f} \quad \text{and} \quad \tau = \frac{t}{t_f}$$

(2)

where $t_f$ is the time required for melting metal, suffix ‘e’ represents the effective or weighted average property of metal, clay graphite crucible and SiC susceptor. Table 2 gives the physical and thermal properties of tin (Gaver, 2004), lead (King et al., 2004), aluminium (Sanders, 2004), copper (Kundig and Drescher, 2004), clay graphite crucible and SiC susceptor (Chen et al., 2007).

**Table 2: Properties of metals, clay graphite crucible and silicon carbide susceptor**

<table>
<thead>
<tr>
<th>Metal / Material</th>
<th>Density kg/m$^3$</th>
<th>Specific heat J/kg.K</th>
<th>Latent heat of fusion (kJ / kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tin</td>
<td>7310</td>
<td>222</td>
<td>58</td>
</tr>
<tr>
<td>Lead</td>
<td>11350</td>
<td>130</td>
<td>25</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2700</td>
<td>741.56+(0.5071*T)</td>
<td>395</td>
</tr>
<tr>
<td>Copper</td>
<td>8960</td>
<td>355.9+(0.092*T)</td>
<td>212</td>
</tr>
<tr>
<td>Clay Graphite crucible</td>
<td>1800</td>
<td>-242+(2.07<em>T)-(0.000572</em>T$^2$)</td>
<td></td>
</tr>
<tr>
<td>SiC susceptor</td>
<td>3100</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

The detailed calculations in evaluating the effective properties are given as follows,

Effective density is given as, $\rho_e = \frac{\sum m}{\sum V}$

(3)
where, \( \Sigma m \) and \( \Sigma V \) is the total mass and volume of metal, crucible and susceptor respectively.

Effective Diameter/Thickness is given as, \( L_e = (\Sigma V)^{1/3} \) \hspace{1cm} (4)

Effective heat capacity is given as, \( C_{pe} = \frac{\sum (mC_p)}{\Sigma m} \) \hspace{1cm} (5)

Differentiating \( \theta \) and \( \tau \) in equation (2) and comparing with equation (1), the following dimensionless energy equation is obtained.

\[
\frac{d\theta}{d\tau} = \overline{Q}(\theta) \tag{6}
\]

where \( \overline{Q} = \frac{p(T)}{1/\ell^3} \) which is a function of \( \theta \).

For various types of dependence of \( \overline{Q} \) on \( \theta \), as a linear \( (\overline{Q} = a + b\theta) \), quadratic \( (\overline{Q} = a + b\theta + c\theta^2) \) and cubic \( (\overline{Q} = a + b\theta + c\theta^2 + d\theta^3) \) function of \( \theta \), the relationship between the dimensionless temperature and time can be shown to be as follows:

for linear dependence as, \( \theta = \frac{a}{b}(e^{b\tau} - 1) \) \hspace{1cm} (7)

for quadratic dependence as, \( \theta = \left[ \frac{s}{2c} \tan \left( \frac{s \tau}{2} + \tan^{-1} \left( \frac{b}{s} \right) \right) - \left( \frac{b}{2c} \right) \right] \) \hspace{1cm} (8)

where \( s = \sqrt{4ac - b^2} \) and \( a, b, c, d \) are the parameters. For cubic dependence of \( \theta \), the integrations were carried out using three point Gaussian quadrature. On analyzing models such as \( \overline{Q} \) being a constant or linear or quadratic function of \( \theta \) the model results do not fit with experimental data well for all the metal cases. The model results for \( \overline{Q} \) as a cubic function of \( \theta \) fits the experimental data well for all metals used. The best fit results for this model along with the experimental data in the dimensionless form are shown in Figure 7.
Figure 7: Effect of change of $\theta$ over $\tau$ for all metals at power levels a) 100%, b) 70%, and c) 40%
It is seen that the model predictions agree reasonably well with the experimental results for various loads and type of metals. Table 3 gives the best fit of coefficients obtained for various power levels. Ideally all of the results must show identical parameter values (a, b, c and d), since non dimensional variables have been used. However, some of the assumptions of the model such as no heat loss to the surroundings and uniform and identical temperatures of the sample, crucible and susceptor were not exactly implementable in the experiments and the deviations led to different values of parameters. The value of ‘a’ is consistently higher at 40% power level when compared to the value at 100% power level. This indicates that the susceptor temperature was probably higher than the sample temperature in the rapid heating conditions of 100% power level. At lower heating rates, the assumption of identical temperature of susceptor, crucible and sample was more likely to be valid. Since the temperatures of the sample and the susceptor could not be simultaneously measured in situ, the uniform temperature assumption was employed. Besides these reasons, the inability of the model to provide single parameter values for all metals at a particular power level is due to the fact that the absorption of microwave by SiC susceptor varies at high temperatures (Baeraky, 2002) and the heat losses by convection and radiation would also be significant. While the microwave heating is shown to be faster than conventional heating, further optimization is possible. The crucible itself could be made of the susceptor material thereby eliminating some of the heat losses and shorter melting time could be achieved. Similarly, the load and the microwave power level could be varied in a wider range than was possible in the current study to make this process more efficient.
Table 3: Best fit parameter values for cubic dependence modeling of microwave metal melting

<table>
<thead>
<tr>
<th>Metals</th>
<th>Power level</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead and Tin</td>
<td>100 %</td>
<td>0.0125</td>
<td>5.141</td>
<td>-103.00</td>
<td>833.27</td>
</tr>
<tr>
<td></td>
<td>70 %</td>
<td>0.0191</td>
<td>4.587</td>
<td>-64.68</td>
<td>409.02</td>
</tr>
<tr>
<td></td>
<td>40 %</td>
<td>0.0299</td>
<td>4.542</td>
<td>-49.33</td>
<td>221.36</td>
</tr>
<tr>
<td>Aluminium</td>
<td>100 %</td>
<td>0.01474</td>
<td>6.353</td>
<td>-56.55</td>
<td>161.54</td>
</tr>
<tr>
<td></td>
<td>70 %</td>
<td>0.02077</td>
<td>6.206</td>
<td>-42.88</td>
<td>97.63</td>
</tr>
<tr>
<td></td>
<td>40 %</td>
<td>0.04886</td>
<td>5.970</td>
<td>-32.07</td>
<td>48.93</td>
</tr>
<tr>
<td>Copper</td>
<td>100 %</td>
<td>0.01500</td>
<td>12.526</td>
<td>-178.64</td>
<td>654.86</td>
</tr>
<tr>
<td></td>
<td>70 %</td>
<td>0.01589</td>
<td>10.891</td>
<td>-97.14</td>
<td>216.56</td>
</tr>
<tr>
<td></td>
<td>40 %</td>
<td>0.02302</td>
<td>12.680</td>
<td>-103.76</td>
<td>218.13</td>
</tr>
</tbody>
</table>

4. Conclusion:

Microwave melting of tin, lead, aluminium and copper was accomplished at high heating rates, with clean and controlled process conditions. The melting time for lead and tin were not affected by the increase in load up to 150 g irrespective of the power level used. On comparing with a conventional furnace, microwave melting was found to be twice faster, consume less energy and safer to handle. The experimental results were modelled by lumped parameter model using a heat source which varies cubic in nature with temperature. The model predictions agree well with the experimental data at all temperatures and process conditions.

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