Microwave Heating of Metals
Additive manufacturing, or 3D printing, has come quite a distance since its beginnings in the 1970’s and 80’s. There are a multitude of printing techniques and material systems, but the home user is still confined to plastic filament. While plastic has many exceptional qualities, it lacks the strength to be used in many applications and thus places a firm limit on what is achievable in terms of part strength and durability. Due to the high cost of printers that print directly in metal, the vast majority of the 3D printing community that produces parts in metal, only use 3D printers for the production of patterns which are later cast. This added need for metal casting equipment and knowhow locks out many of those who are interested in the production of metal parts via 3D printing. A more direct and inexpensive solution for moving from 3d printer to metal part is needed. The intent of this paper is to gain an understanding microwave furnaces, which are potential candidates for moving from 3d printed part to metal part with a minimum investment of money, time and the development of new skills.

The mechanism by which microwaves heat up food is well understood. Many of the molecules present in food, especially water, have separations of charge called dipole moments. Microwave radiation like all electromagnetic radiation is composed of oscillating electric and magnetic fields. As microwave radiation passes through the food, the dipole moments are forced into alignment with the electric field component of the radiation. Because the field oscillates, the dipoles are forced to rapidly change their alignment, which causes a considerable amount of friction. It is this friction that then heats the food. Metal powders are heated by microwave radiation through an entirely different mechanism that is not yet fully understood.¹

First consider what happens when bulk metal parts are placed in a microwave. Most people that own microwaves know that it is a bad idea to run them while there is metal inside. The reason is because metals are good reflectors of microwaves (this is also why radar is so successful at detecting metal aircraft). The microwaves just bounce around inside of the machine until they are reabsorbed by the magnetron which then over heats and finally breaks. Sparks are also seen, which are due to the fact that metals are good electric conductors. Charge separation caused by the microwaves is confined to the
surface of the metal. When the charge becomes sufficient, the air is ionized and a spark is seen. This key observation led to the discovery of a method that would allow for metal powder sintering using microwaves.

If the particle size is small enough, the surface area to volume ratio increases dramatically. As the size of the particle decreases the energy can be transferred into the heating of the particle rather than electric discharge. The most widely accepted theory for the heating mechanism was reported by Cheng.\(^2\) His group reported that the heating mechanism is mainly due to the magnetic field component of the microwave radiation. Just as with electric generators, the oscillating magnetic field induces electric currents in the metal particles. These currents encounter resistance, which causes the metal to heat up. This helps to explain why ferromagnetic materials such as iron are heated more strongly in a microwave furnace than non-ferromagnetic materials.

Not only are metal powders heated by microwaves, they are heated quickly and evenly. In conventional sintering, metals are heated from the outside, which limits the maximum temperature of the metal to its surface temperature. This situation creates potential problems with oxidation and limits the rate at which a metal component can be sintered, as the heat must diffuse into the core. Elevating the temperature can help increase the processing time, but every metal has a maximum temperature at which it can be processed. By contrast, when metal powders are heated in a microwave the heating is volumetric, not just confined to the surface. This is due to the microwave radiation’s ability to penetrate the metal. As happens with bulk metal parts described above, microwave radiation can be reflected by the powder grains, but the reflected energy tends to be scattered throughout the powder instead of away from the metal. The scattering helps to heat the powder more evenly. Microwave heating can even be controlled to the point where the components are heated “from the inside out.”\(^3\)

In terms of heating rate, microwave sintering has outstanding performance. Compared to conventional sintering methods, microwave furnaces can do the same work with a 60% to 90% reduction in processing time and energy consumption. It has been estimated that the
energy and processing time reductions could save the US metal processing industry 3 billion dollars per year. Scaled world wide, this represents an astronomical saving.

The heating rate of metal powders is closely tied to two factors, particle size and packing density. As might be expected, when the average grain size of the metal powder is reduced, the sintering time also decreases. Mondal et al. found that for CU powders, reducing the average grain size from 383 µm to 6 µm cut the heating time from 30 minutes to 10 minutes and resulted in a higher maximum temperature. They also found that packing the green part more loosely increased the heating rate but also decreased the resulting sintered density.

The resulting material properties are another area where microwave sintering excels. In conventional sintering, the finished grain structure is difficult to control because the metal is heated from the outside. Microwave sintering produces metal parts with a smaller more even grain structure. Roy et al. report that microwave sintered parts are frequently stronger than conventionally produced parts, sometimes dramatically stronger. It is also note worthy that the parts produced can approach theoretical density (or the density of the pure metal without voids). Even when there are voids, the sintered metal is usually tougher than conventionally produced metal with the same void content. This is because the voids tend to be rounded rather than angular resulting in lower stress concentrations.

At this point it should be clear that microwave sintering is capable of producing high quality parts using a fraction of the time and energy required by other methods. Focus will now be shifted to how microwave furnaces are setup and whether or not it is feasible at the DIY level.

The general microwave furnace is setup with a 2.45 GHz, 1-6 Mw microwave source (magnetron), circulator, tuner, furnace cavity, and inert environment gas lines. Surprisingly, 2.45 GHz is the same frequency used in home microwaves, which operate at the low end of the power range used in microwave furnaces. The circulator is a device
that basically protects the magnetron from reflected microwaves. If magnetron reabsorbs too much energy, it can easily overheat. The tuner helps to tune the frequency of the microwaves to enhance the oscillation in the furnace cavity. The furnace cavity is a metal container sized such that the microwaves are reflected around the chamber until they are absorbed. Inside the furnace cavity is a ceramic insulator such as mullite and inside the ceramic insulator is an alumina crucible. The green powdered metal part is placed inside of the crucible. One interesting quality of ceramic insulators is that they are typically transparent to microwaves, so microwave energy can enter the area inside the insulation where the powdered metal is, but the heat is retained. This is true especially at lower temperatures. As the furnace heats up however the ceramic lining begins to absorb some of the microwave energy. The furnace cavity is sealed and flooded with flowing inert gas. The inert gas is often mixed with a small amount of hydrogen gas to help pull of any oxidation on the metal. Professional equipment, such as that described above, is be capable of reaching temperatures of up to 2000 °C.

For the DIY 3D printer, there is the conventional microwave oven, which operates at a frequency of 2.45Ghz and power output of 0.8 to 1 Mw. While lower power and lacking some of the special controls, it has been shown that it is possible to achieve high temperatures. David Reid has posted online about his attempts to use a conventional microwave oven to melt metal. He has successfully achieved temperatures of 1000 °C sufficient for many nonferrous metals. Without the proper protection, the magnetron may not last as long, but Craig’s List has a free microwave to offer on a daily basis. It should also be fairly easy to retrofit a microwave oven with a flowing gas setup in order to help prevent oxidation. Lacking tanks and regulators, a charcoal cover may also be feasible.

David Reid followed the method outlined by those at Oak Ridge Y-12 National Security Complex. In addition to heating metal as described above, the crucible is lined with a material called a susector. Powdered graphite and magnetite are both suseptors, which means that they strongly absorb microwave radiation and convert it to heat. With suseptors, a microwave furnace can be turned into something more similar to a conventional furnace. The microwave energy is used to heat the susector, which in turn
heats the metal. With this setup, the metal can be fully melted because the fine grain size is not being depended upon for heating. Furthermore, bulk metal pieces can be melted. This is excellent in terms of the versatility that it offers but it must be noted that many of the benefits of melting powdered metals may be lost due to the strong absorption of the suseptors located outside of the powder.

What is lacking at this point is more experimentation with potential methods for producing metal parts via 3D printing and then microwave sintering in a conventional microwave oven. It may be possible to print molds with FDM machines like a Rep-Rap and then ram them with a metal powder mixed with an organic binder such as sugar. The green part may then be placed into a granular insulator for support and sintered in the microwave. Possibly mixing small amounts of suseptor materials in with the metal powder could help bring the part up to sintering temperature faster. There is still much to be learned in this area.


