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Microwave Sintering of Pure Metal Powders – A Review

Radha Raman Mishra[1], Rajesha S[2] and A.K. Sharma[3]

[1, 2] *Department of Mechanical Engineering, JSS Academy of Technical Education, C-20/1, Sec-62, Noida, 201301, India.*
[3]*Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee, Rookee, 247667, India.*

Abstract

The use of microwave for sintering of green compacts during powder metallurgy process is emerging as a novel and innovative technology with many advantages over conventional sintering. This review paper provides the theory of neck formation and growth that associated with diffusion mechanisms during sintering for pure metal powder and the dynamics of stable neck-growth summarized in the form of mathematical equation. The effect of microwave sintering on different pure metal powders has been mentioned to realize the potential advantages of the microwaves sintering over conventional sintering for better mechanical properties in the components manufactured by powder metallurgy process.

Keywords: Microwave, sintering, metal powder processing, neck growth.

1. Introduction

Use of microwave for heating, has been started from heating food and later applied for the processing of a wide variety of materials, like ceramics, polymers and composites. Now it is being used in the area of metallic material processing too for sintering, joining and coating/cladding but due to reflection of electromagnetic waves by most of the metals at ordinary conditions application of microwaves for metallic material processing is a challenging area of research. Some limited researches in the area of metallic material processing in the form of sintering under certain conditions were reported [Roy et al., 1999; Chillar et al., 2008; Mondal et al., 2009 and Rodiger el al., 1998]. Further, brazing of selected metals under specific conditions was reported

[Budinger, 2008 and Barmatz et al., 2000]. The Joining of bulk metallic materials in different forms in a home microwave system was reported [Siores el al., 1995 and Sharma et al., 2009]. However, the paten of cladding/coating of metallic and non-metallic powders on metallic substrates was reported [Sharma et al., 2010]. The finer microstructures and near theoretical densities achievement in the processing of metal powders in industry for diversity of products and applications always demands for new and improved processes and materials of high integrity with innovation and newer technologies. So, microwave processing can meet these demands of producing better microstructures and properties in the powder metal products [Agrawal, 2006].The earliest work of microwave interaction with metallic powders was reported for the heating rates of the refractory ceramics by adding a few percent of electrically conducting powders such as aluminum [Nishitani, 1979]. Modest heating (but not sintering) in the range from 120°C (Mg) to 768°C (Fe) was observed when a range of materials including six metals were simply exposed, to a 2.4 GHz field [Walkiewicz et al., 1988]. The microwave induced synthesis of metal sulphides by high exothermic reaction rates of metal powders with sulfur was reported [Whittaker et al., 1995]. Heated Cu powders got coated with CuO up to 650°C but did not report any sintering of them [Sheinberg et al., 1990]. The heating of Fe alloys in a microwave oven only up to 370°C were reported in 30 minutes [Narsimhan et al., 1995]. But no sintering of pure metal or alloy powders was reported in the previous studies. In 1999, it was reported that a porous, powder metal compact could be heated and sintered in a microwave field and since then many other researchers have reported successful sintering of many metallic materials [Takayama et al., 2003; Sethi et al., 2003 and Anklekar et al., 2001]. Later on other researchers also demonstrated that all powder metals at room temperature absorb microwaves and only bulk metals reflect the microwaves allowing only surface penetration as no internal electrical field is induced in metals. For powder metals the particle sizes are much smaller than the wavelength of microwave radiation in the microwave regime so the uniform field across the particle generate and causes volumetric heating [Takayama et al., 2006]. The conductivity and frequency [Ma et al., 2007], effect of E and H field [Rybakov et al., 2006], the role of particle size and also the role of initial porosity upon thermal profile which actually affects the microwave absorption by pure powdered metals was reported [Mishra et al., 2006 and Vaidhyanathan et al., 1997].The enhancement in sintering may be seen by the presence of plasma discharge in a compacted body [Veltl et al., 2004] or local over heating in a particle's contact zone [Birnboim et al.,2005]. The modeling of the heating profile, and hence the sintering process, of metal like compounds was done [Mishra et al., 2006]. The initial stage of conventional sintering and the data for microwave sintering was compared on the basis of the classic flat-ball model [Hao et al., 2009]. Sintering of ceramic powder occurs in three sequential stages referred to as the initial stage, the intermediate stage, and the final stage. In initial stage of sintering, the rapid inter particle neck growth by diffusion, vapor transport, plastic flow or viscous flow occurs [Kang, 2005]. The large initial differences in surface curvature are removed and shrinkage (or densification) accompanies neck growth during the densification mechanisms of microwave sintering in case of ceramic powders [Rahaman, 2003]. It is reported that copper steel (MPIF FC-0208 composition) and nickel steel powder (FN-0208) sintered by microwave technique have exhibited higher sintered density, better hardness and flexural strength than the conventionally sintered samples [Anklekar et al., 2005]. It has been found in literature that microwaves may be effectively used in sintering of pure metals than conventional sintering. This paper summarizes the theoretical and mathematical aspect of neck growth mechanism of microwave sintering of pure metals. The behavior of aluminum, tungsten and copper powders has been discussed when exposed to microwave.

2. Mechanism of Microwave Sintering of Pure Metal Powder

The synchrotron radiation X-ray computed tomography technique was introduced for the in-situ investigation of microstructure evolution of aluminum powder and kinetics mechanisms of microwave sintering was carried out and compared with conventional sintering. The investigations of sintering neck growth kinetic mechanisms clearly indicate that in the early stage, the surface diffusion for the conventional sintering and the grain-boundary with volume diffusion for the microwave sintering was dominant. In the next stage, oxidation on grains surface reduce or nearly stop the neck growth in the conventional sintering but the microwave sintering was influenced slightly because of the non-thermal effects such as the micro-focusing, interfacial polarization etc. The sintering with microwave has two types of effects: one similar to conventional and other different from it. In the similar effect, the sintering necks form and grow. In the different effect, after a short sintering time the contact breaks off because of the tensile and pressure force from other particles and the large initial differences in surface curvature of particles removed, so the rough surface becomes smooth in a short time [Kuczynski, 1949]. The two sphere model was developed for the powder system which consists of two equalized spheres with two slightly different geometries according to different possible particle situations, depending on whether the mechanisms are densifying or non-densifying [Demirskyi et al., 2010]. This model for the densifying mechanisms interprets the spheres (i.e. shrinkage) as well as neck growth. The neck formed between particles (of radius a) is assumed to be circular with a radius of x. The assumption for end of transition of particles is that the radius of the neck between the particles must reach a value of 0.4–0.5 of the particle radius [Rahaman, 2003]. However, the basic assumption in the models of a single dominant mass transport mechanism is not valid for most powder systems. The dynamics of stable neck-growth at initial stage of sintering can be represented in terms of mathematical equations. It was summarized by Kucsynski and can be expressed as below [Kuczynski, 1949]-

$$\left\{ \frac{x}{a} \right\} \tag{1}$$

Where x/a represents the ratio of the inter-particle neck radius to the particle radius, F (T)/am is a constant that involve particle size, temperature, geometric and materials terms, t is the sintering time that corresponds with mass transport process. The log (x/a) and log (t) have a linear relationship with a slope equals to 1/n where different n represents different main diffusion mechanism [Feng et al., 2012]. Both the conventional and microwave sintering processes on aluminum are following linear relationship but microwave sintering which was hardly influenced by oxidation, has different diffusion mechanisms from conventional sintering.

3. Application of Microwave for Sintering of Metal Powders

The sintering of pure metal powder by microwave was reported in literature [Demirskyi et al., 2010; Prabhu et al., 2009; Mondal et al., 2009; and Ghosh et al., 2011]. The pure metal powders were sintered in different situations and effects of parameters on mechanical properties were reported.

3.1 Tungsten Powder

The study of microwave sintering of pure tungsten powder of as-received grade and tungsten powder activated by high-energy milling (HEM) was carried out for sinterability comparison and analysis for process optimization when both the powder compacts are sintered under identical conditions [Prabhu et al., 2009]. Densification in sintered compact made of as received powder is around 85% and activated powder around 93% of theoretical density (19.3 g/cm3 for tungsten). High-energy milling has reduced the particle size, increased surface area and thereby a higher energy state of the powder due to significant strain of the particles from high impact forces during milling which facilitates atomic mobility during the sintering process resulting in rapid densification. The unetched microwave sintered (at 2073 K with 1 hour soaking) samples reveal that the porosity is higher in as-received powder as compared to activated powder. In etched condition, the sintered sample (with 93% density, at 2073 K with 1 hour soaking, Etched with 60% H_2O_2 solution) of activated tungsten reveals considerable sintering with the presence of grain boundaries.

3.2 Copper Powder

The investigation of the neck growth kinetics during microwave sintering of free-packed copper powder was carried out by application of the classical sphere-to-sphere approach which shows similarities between microwave and conventional sintering processes for long soaking times [Demirskyi et al., 2010]. Surface diffusion was the predominant diffusion mechanism during microwave sintering at other cases for low temperatures. At higher sintering temperatures, volume diffusion is the main sintering mechanism. The study of thermal profile of copper metal powder was done when the material is exposed to 2.45 GHz microwave radiation in a multimode microwave furnace [Mondal et al., 2009]. The temperature variation with time of exposure of the copper powder compacts when sintered in multimode microwave furnace depends upon the particle size and initial porosity for a specific particle size of Cu powder while keeping the power setting and total exposure time constant. As particle size increases the heating rate decreases and after certain time heating rate becomes constant at a particular power setting. The heating rate increases as the green density decreases (porosity increases). Higher is the porosity higher is the heating rate and for a fixed particle size and fixed power setting the final temperature become saturated which is 1037°C.

3.3 Aluminum Powder

The microwave sintering of aluminum was studied by characterizing the sintered powder. When Commercial Al powder was exposed to microwave radiation for 45 min and characterization were carried out the microwave treated Al powder confirmed the formation of Al–α-Al_2O_3. The temperature measured was 1000±10°C after 45 min microwave heating of the Al powder. Al phase was only identified in the as received Al powder while α-Al_2O_3 and Al phases were detected in the microwave treated Al powder. The formation of Al–α-Al_2O_3 is due to the oxidation of Al particle which absorbs the microwave power that results in heating in ambient atmosphere. So, it may be assumed that finely divided Al metal powder was heated due to some kind of energy loss mechanisms in the microwave field. Thus, an oxide shell was formed around the Al core particle [Ghosh et al., 2011].

4. Conclusions

Application of microwaves for sintering of the pure metal powder in powder metallurgy process has been emerged as a potential process. The microwave sintering has significant advantages over conventional sintering because of different diffusion mechanism involved in it. The following facts of microwave sintering can be summarized as:

1. The diffusion mechanisms in conventional and microwave sintering are quite different because of non thermal effects of microwave.
2. The smoother surface of powder compact is developed in short time by microwave sintering than conventional sintering.
3. The log (x/a) and log (t) have a linear relationship with a slope equals to 1/n where values of n different for conventional and microwave sintering which interprets existence of the different diffusion mechanisms.
4. The mechanical properties of microwave sintered compacted metal power can be improved by pre working on metal powder as in the case of tungsten powder.
5. During microwave sintering, at lower temperatures surface diffusion and at higher temperatures volume diffusion are dominant diffusion mechanisms as in the case of pure copper powder.
6. Thermal profile during microwave sintering in multimode microwave furnace depends upon particle size and porosity present in compacted powder metal.
7. The effect of oxidation on sintering of metal powder by microwave is less effective phenomenon in comparison to conventional sintering

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