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Sintering of Aluminum Powder with Microwave

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Abstract: Sintering or frittage is the process of compacting and forming a solid mass of material by heat or pressure without melting it to the point of liquefaction. Sintering happens naturally in mineral deposits or as a manufacturing process used with metals, ceramics, plastics, and other materials. Sintering happens naturally in mineral deposits or as a manufacturing process used with metals, ceramics, plastics, and other materials. The atoms in the materials diffuse across the boundaries of the particles, fusing the particles together and creating one solid piece. Because the sintering temperature does not have to reach the melting point of the material, sintering is often chosen as the shaping process for materials with extremely high melting points such as tungsten and molybdenum. The study of sintering in metallurgy powder-related processes is known as powder metallurgy. An example of sintering can be observed when ice cubes in a glass of water adhere to each other, which is driven by the temperature difference between the water and the ice. Examples of pressure-driven sintering are the compacting of snowfall to a glacier, or the forming of a hard snowball by pressing loose snow together.

Keywords: Sintering, Aluminium, Silicone Carbide, Microwave Sintering

I. INTRODUCTION

Most, if not all, metals can be sintered. This applies especially to pure metals produced in vacuum which suffer no surface contamination. Sintering under atmospheric pressure requires the use of a protective gas, quite often endothermic gas. Sintering, with subsequent reworking, can produce a great range of material properties. Changes in density, alloying, and heat treatments can alter the physical characteristics of various products. For instance, the Young's modulus E_n of sintered iron powders remains somewhat insensitive to sintering time, alloying, or particle size in the original powder for lower sintering temperatures, but depends upon the density of the final product:
Sintering is static when a metal powder under certain external conditions may exhibit coalescence, and yet reverts to its normal behavior when such conditions are removed. In most cases, the density of a collection of grains increases as material flows into voids, causing a decrease in overall volume. Mass movements that occur during sintering consist of the reduction of total porosity by repacking, followed by material transport due to evaporation and condensation from diffusion. In the final stages, metal atoms move along crystal boundaries to the walls of internal pores, redistributing mass from the internal bulk of the object and smoothing pore walls. Surface tension is the driving force for this movement.

A special form of sintering (which is still considered part of powder metallurgy) is liquid-state sintering in which at least one but not all elements are in a liquid state. Liquid-state sintering is required for making cemented carbide and tungsten carbide. Sintered bronze in particular is frequently used as a material for bearings, since its porosity allows lubricants to flow through it or remain captured within it. Sintered copper may be used as a wicking structure in certain types of heat pipe construction, where the porosity allows a liquid agent to move through the porous material via capillary action. For materials that have high melting points such as molybdenum, tungsten, rhenium, tantalum, osmium and carbon, sintering is one of the few viable manufacturing processes.

In these cases, very low porosity is desirable and can often be achieved. Sintered metal powder is used to make frangible shotgun shells called breaching rounds, as used by military and SWAT teams to quickly force entry into a locked room. These shotgun shells are designed to destroy door deadbolts, locks and hinges without risking lives by ricocheting or by flying on at lethal speed through the door. They work by destroying the object they hit and then dispersing into a relatively harmless powder. Sintered bronze and stainless steel are used as filter materials in applications requiring high temperature resistance while retaining the ability to regenerate the filter element. For example, sintered stainless steel elements are employed for filtering steam in food and pharmaceutical applications, and sintered bronze in aircraft hydraulic systems. Sintering of powders containing precious metals such as silver and gold is used to make small jewelry items.

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II. ALUMINIUM

Aluminium is remarkable for its low density and its ability to resist corrosion through the phenomenon of passivation. Aluminium and its alloys are vital to the aerospace industry and important in transportation and building industries, such as building facades and window frames. The oxides and sulfates are the most useful compounds of aluminium. Despite its prevalence in the environment, no known form of life uses aluminium salts metabolically, but aluminium is well tolerated by plants and animals. Because of these salts' abundance, the potential for a biological role for them is of continuing interest, and studies continue.

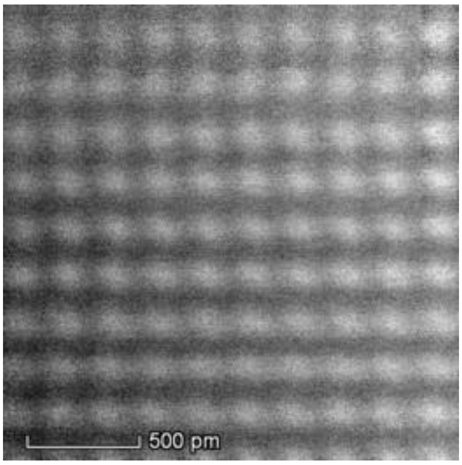
Physical Characteristics.

A. Nuclie and Isotopes

Of aluminium isotopes, only 27Al is stable. This is consistent with aluminium having an odd atomic number. It is the only aluminium isotope that has existed on Earth in its current form since the creation of the planet. Very nearly all the element on Earth is present as this isotope, which makes aluminium a mononuclidic element and means that its standard atomic weight practically equates to that of the isotope. The standard atomic weight of aluminium is low in comparison with many other metals, which has consequences for the element's properties. All other isotopes of aluminium are radioactive. The most stable of these is ^{26}Al (half-life 720,000 years) and therefore could not have survived since the formation of the planet. However, minute traces of ^{26}Al are produced from argon in the atmosphere by spallation caused by cosmic ray protons. The ratio of ^{26}Al to ^{10}Be has been used for radiodating of geological processes over 10^5 to 10^6 year time scales, in particular transport, deposition, sediment storage, burial times, and erosion. Most meteorite scientists believe that the energy released by the decay of ^{26}Al was responsible for the melting and differentiation of some asteroids after their formation 4.55 billion years ago. The remaining isotopes of aluminium, with mass numbers ranging from 22 to 43, all have half-lives well under an hour. Three metastable states are known, all with half-lives under a minute.

B. Electron Shell

An aluminium atom has 13 electrons, arranged in an electron configuration of $[Ne]3s^2 3p^1$, with three electrons beyond a stable noble gas configuration. Accordingly, the combined first three ionization energies of aluminium are far lower than the fourth ionization energy alone. Such an electron configuration is shared with the other well-characterized members of its group, boron, gallium, indium, and thallium; it is also expected for nihonium. Aluminium can relatively easily surrender its three outermost electrons in many chemical reactions. The electronegativity of aluminium is 1.61 (Pauling scale).



High resolution STEM-HAADF micrograph of Al atoms

A free aluminium atom has a radius of 143 pm. With the three outermost electrons removed, the radius shrinks to 39 pm for a 4-coordinated atom or 53.5 pm for a 6-coordinated atom. At standard temperature and pressure, aluminium atoms (when not affected by atoms of other elements) form a face-centered cubic crystal system bound by metallic bonding provided by atoms' outermost electrons; hence aluminium (at these conditions) is a metal. This crystal system is shared by many other metals, such as lead and copper; the size of a unit cell of aluminium is comparable to that of those other metals. It is however not shared by the other members of its group; boron has ionization energies too high to allow metallization, thallium has a face-centered cubic structure, and gallium and indium have unusual structures that are not close-packed like those of aluminium and thallium. Since few electrons are available for metallic bonding, aluminium metal is soft with a low melting point and low electrical resistivity, as is common for post-transition metals.

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C. Chemistry

Aluminium combines characteristics of pre- and post-transition metals. Since it has few available electrons for metallic bonding, like its heavier group 13 congeners, it has the characteristic physical properties of a post-transition metal, with longer-than-expected interatomic distances. Furthermore, as Al^{3+} is a small and highly charged cation, it is strongly polarizing and aluminium compounds tend towards covalency. However, unlike all other post-transition metals, the underlying core under aluminium's valence shell is that of the preceding noble gas, whereas for gallium and indium it is that of the preceding noble gas plus a filled d-subshell, and for thallium and nihonium it is that of the preceding noble gas plus filled d- and f-subshells. Hence, aluminium does not suffer the effects of incomplete shielding of valence electrons by inner electrons from the nucleus that its heavier congeners do. Aluminium's electropositive behavior, high affinity for oxygen, and highly negative standard electrode potential are all more similar to those of scandium, yttrium, lanthanum, and actinium, which have ds^2 configurations of three valence electrons outside a noble gas core: aluminium is the most electropositive metal in its group. Aluminium also bears minor similarities to the metalloid boron in the same group; AlX_3 compounds are valence isoelectronic to BX_3 compounds (they have the same valence electronic structure), and both behave as Lewis acids and readily from adducts. Additionally, one of the main motifs of boron chemistry is regular icosahedral structures, and aluminium forms an important part of many icosahedral quasicrystal alloys, including the Al–Zn–Mg class. Aluminium's corrosion resistance can be excellent due to a thin surface layer of aluminium oxide that forms when the bare metal is exposed to air, effectively preventing further oxidation, in a process termed passivation. The strongest aluminium alloys are less corrosion-resistant due to galvanic reactions with alloyed copper. This corrosion resistance is greatly reduced by aqueous salts, particularly in the presence of dissimilar metals. In highly acidic solutions, aluminium reacts with water to form hydrogen, and in highly alkaline ones to form aluminates—protective passivation under these conditions is negligible. Primarily because it is corroded by dissolved chlorides, such as common sodium chloride, household plumbing is never made from aluminium.

III. SILICON CARBIDE

Silicon carbide (SiC), also known as carborundum is a semiconductor containing silicon and carbon. It occurs in nature as the extremely rare mineral moissanite. Synthetic SiC powder has been mass-produced since 1893 for use as an abrasive. Grains of silicon carbide can be bonded together by sintering to form very hard ceramics that are widely used in applications requiring high endurance, such as car brakes, car clutches and ceramic plates in bulletproof vests. Electronic applications of silicon carbide such as light-emitting diodes (LEDs) and detectors in early radios were first demonstrated around 1907. SiC is used in semiconductor electronics devices that operate at high temperatures or high voltages, or both. Large single crystals of silicon carbide can be grown by the Lely method and they can be cut into gems known as synthetic moissanite. Silicon carbide exists in about 250 crystalline forms. Through the inert atmosphere pyrolysis of preceramic polymers, silicon carbide in a glassy amorphous form is also produced. The polymorphism of SiC is characterized by a large family of similar crystalline structures called polytypes. They are variations of the same chemical compound that are identical in two dimensions and differ in the third. Thus, they can be viewed as layers stacked in a certain sequence. Alpha silicon carbide (α-SiC) is the most commonly encountered polymorph, and is formed at temperatures greater than 1700 °C and has a hexagonal crystal structure (similar to Wurtzite). The beta modification (β-SiC), with a zinc blende crystal structure (similar to diamond), is formed at temperatures below 1700 °C. Until recently, the beta form has had relatively few commercial uses, although there is now increasing interest in its use as a support for heterogeneous catalysts, owing to its higher surface area compared to the alpha form. Pure SiC is colorless. The brown to black color of the industrial product results from iron impurities. The rainbow-like luster of the crystals is caused by a passivation layer of silicon dioxide that forms on the surface. The high sublimation temperature of SiC (approximately 2700 °C) makes it useful for bearings and furnace parts. Silicon carbide does not melt at any known temperature. It is also highly inert chemically. There is currently much interest in its use as a semiconductor material in electronics, where its high thermal conductivity, high electric field breakdown strength and high maximum current density make it more promising than silicon for high-powered devices. SiC also has a very low coefficient of thermal expansion (4.0×10^{-6}/K) and experiences no phase transitions that would cause discontinuities in thermal expansion.

IV. MICROWAVE SINTERING

Microwave heating and sintering is fundamentally different from the conventional sintering, which involves radiant/resistance heating followed by transfer of thermal energy via conduction to the inside of the body being processed. Microwave heating is a volumetric heating involving conversion of electromagnetic energy into thermal energy, which is instantaneous, rapid and highly efficient.

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The microwave part of the electromagnetic spectrum corresponds to frequencies between 300 MHz and 300 GHz. However, most research and industrial activities involve microwaves only at 2.45 GHz and 915 MHz frequencies. Based on their microwave interaction, most materials can be classified into one of three categories - opaque, transparent and absorbers. Bulk metals are opaque to microwave and are good reflectors - this property is used in radar detection. However, powdered metals are very good absorbers of microwaves and heat up effectively, with heating rates as high as 100°C min-1. Most other materials are either transparent or absorb microwaves to varying degrees at ambient temperature. The degree of microwave absorption, and consequently of heating, changes dramatically with temperature.

A. Microwave vs. Conventional Heating

The use of microwave energy for materials processing has major potential, and real advantages over conventional heating. These include:

- Time and energy savings
- Rapid heating rates
- Considerably reduced processing time and temperature
- Fine microstructures and hence improved mechanical properties and better product performance
- Lower environmental impact.

B. Which Metals can be Microwave Sintered?

Until recently, microwave heating has been applied to sinter only oxide ceramics and semi-metals like carbides and nitrides. However, our research reveals that in powdered form, virtually all metals, alloys, and intermetallics will couple and heat efficiently and effectively in a microwave field, and their green parts will produce highly sintered bodies with improved mechanical properties. For example, in our exploratory experiments we tried two common commercial steel compositions, namely Fe-Ni-C (FN208) and Fe-Cu-C (FC208). These formed highly sintered bodies in a total cycle time of about 90 min at temperature range of 1100-1300°C with a soaking time of 5-30 min in forming gas (a mixture of N2 and H2) atmosphere. Mechanical properties such as the modulus of rupture (MOR) and hardness of microwave processed samples were significantly higher than the conventional samples - in the case of FN208, the MOR was 60% higher. The densities of microwave processed samples were close to the theoretical densities, and the net shape of the green body was preserved without significant dimensional changes.

C. Which Metals have been Microwave Sintered?

Many commercial powder-metal components of various alloy compositions, including iron and steel, copper, aluminum, nickel, molybdenum, cobalt, tungsten, tungsten carbide, tin, and their alloys have been sintered using microwaves, producing essentially fully dense bodies. Figure 1 illustrates some of the metallurgical parts processed using microwave technology. The biggest commercial steel component that has been fully sintered in our system so far is an automotive gear of 10 cm in diameter and about 2.5 cm in height.

Metallic parts produced by microwave sintering such as gears cylinders, rods and discs.

D. Microwave Sintering Devices

A typical microwave sintering apparatus operates at a 2.45 GHz frequency with power output in the range of 1-6 kW. The sintering chamber consists of ceramic insulation housing (batch system) or an alumina tube insulated with ceramic insulation from outside, figure 2. The primary function of the insulation is to preserve the heat generated in the workpiece. The temperatures are monitored by optical pyrometers, IR sensors and/or sheathed thermocouples placed close to the surface of the sample. The system is equipped with appropriate equipment to provide the desired sintering atmosphere, such as H2, N2, Ar, etc, and is capable of achieving temperatures up to 1600°C.

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V. FURNACES

Microwave Sintering furnaces (lab or production scale) operate with Microwave radiation as a source of heating and offer distinct advantages to conventional furnaces. We offer a variety of Microwave furnaces for laboratory applications and production plants. We also provide solutions with hybrid furnaces where electrical heaters are combined with microwave energy for specific materials which do not absorb microwaves at lower temperatures. The furnaces we offer have controlled atmosphere with or without vacuum. They are designed to process material in batch or continuous mode.

VI. CONCLUSION

The shown picture (image 2) is the sintered Aluminuim block. The Aluminium block was kept under a Microwave Furnace and the temperature was steadily increased to reach sintering temperature of 400 degree celcius. The Aluminium green model was kept on a silicon carbide (SiC) blocks to transfer heat to the aluminium green block. Titanium fine powder

Aluminium green block in microwave furnace

Sintered aluminium block

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