العنوان:	MULTIPHYSICS MODELING OF THE SPARK PLASMA SINTERING -SPS- PROCESS
المؤلف الرئيسي:	Luqman, Muhammad
مؤلفين آخرين:	Nouari, Saheb(super.)
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ABSTRACT

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objective of the computational work done in this study is to develop a coupled electrical–thermal–mechanical Finite Element Model of the SPS process. This model has been used to study two different classes of materials – aluminum (an electrical conductor), and alumina (an electrical insulator), where a range of aspect ratios has been considered for each disk-shaped sample. In order to validate the results obtained via computational analysis, a small-scale experimental study is also conducted to determine the relationship between SPS process-parameters and the mechanical properties of sintered sample. Comparison of the results obtained from the computational model with those achieved from the experimental study, indicate that almost all the process parameters as well as mechanical properties are characterized by inhomogeneity within the sintered samples.

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التخصص : الهندسة الميكانيكية

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n	Material constant
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t	Time
V	Electric potential
V_o	Applied voltage
W	Equivalent strain rate
α	Surface energy
λ	Electrical conductivity
μ	Shear modulus
ρ	Mass density
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BY

MUHAMMAD LUQMAN

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DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
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MASTER OF SCIENCE

In

MECHANICAL ENGINEERING

MARCH 2014

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DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Mr. MUHAMMAD LUQMAN** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN MECHANICAL ENGINEERING.**

Dr. NOUARI SAHEB

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Dr. SALAM A. ZUMMO
Dean of Graduate Studies

30/1/14

Date

Dedicated to my beloved parents, sisters and brothers.

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All praise belongs to ALLAH, the Almighty, who created the universe and sustains it; and Durud and Salam be on the last of all the prophets (صلي الله عليه وسلم) who made the truth prevail over falsehood and provided humanity with guidance for all times.

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CHAPTER 1

INTRODUCTION

Spark Plasma Sintering (SPS) is a sintering technique which incorporates both uniaxial pressure and application of electric current to accelerate the sintering process. This technique offers various advantages over conventional sintering methods, e.g., faster heating rate, shorter sintering time, higher rate of powder densification, achievement of grain size in the nanocrystalline regime and near-theoretical density, cleanliness of near-surface particles by plasma ions, and avoidance of abnormal grain growth. The foremost advantage of SPS is achievement of near-theoretical density during sintering of ceramic powders characterized by high melting point and lower self-diffusion rate due to the existence of covalent bonding. However, the major disadvantage of this technique is the existence of thermal and mechanical gradient along the sample cross-section due to high heating rates, especially in case of ceramic and polymeric powders which are characterized by low values of electrical and thermal conductivity.

The fundamental mechanism of SPS is not well known. However, it is hypothesized that the interaction of electric current with the particles results in micro-sparks, which eventually leads to the removal of surface impurities and accelerates the surface and grain-boundary diffusion kinetics. A number of mathematical models, simulating the effect of SPS process parameters on the density evolution of the sample, have been proposed and implemented in Finite Element-based softwares including ABAQUS, ANSYS, CFD and COMSOL Multiphysics. In the present work, COMSOL Multiphysics has been used to simulate the electrical, thermal and mechanical

gradients along the cross-section of aluminum and alumina powders, sintered using the SPS process under a variety of heating rates.

1.1 SPARK PLASMA SINTERING (SPS)

1.1.1 Instrumentation

The SPS machine is composed of a uniaxial press, vacuum chamber (or controlled atmosphere), two punch electrodes, a die, a DC pulse generator, a controller/computing unit, and sensors to monitor the temperature, pressure and punch position. A generalized schematic highlighting the primary SPS instrumentation is shown in Figure 1.

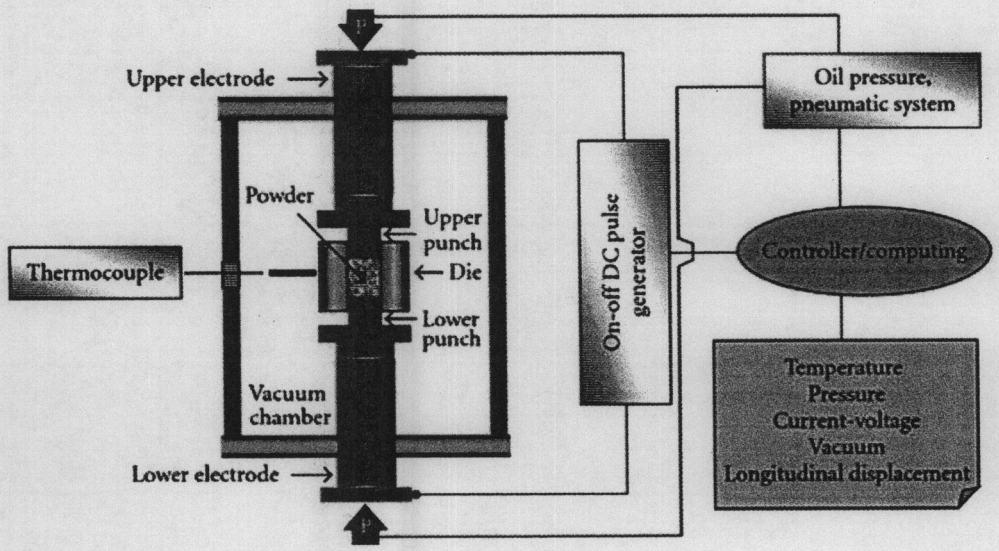

Figure 1: Schematic of SPS Process [1]

1.1.2 Sintering procedure

In SPS process, an electrical current is applied concurrently with a uniaxial mechanical pressure to sinter/consolidate powders for specific applications with preferred density and configuration. The applied mechanical load and electrical current can be kept

constant during the course of the sintering cycle, or can be varied during the subsequent densification stages. The powder to be sintered is placed in a die and then heated via application of electrical current. For electrically conducting powders, the following types of dies can be used:

- Electrically conducting die,
- Electrically insulating die (as the powder itself guarantees the electrical circuit closure), or
- A conducting die having non-conducting coating on the interior surface.

For insulating powders, the die material must be conducting in order to fulfill the requirement of a closed electrical circuit to initiate the sintering process. For the same reason, all the other components of the system, i.e., electrodes, blocks, spacers, and plungers etc. need to be made of an electrically conducting material, e,g. stainless steel, copper, graphite, etc.

1.1.3 Electrical transport in SPS process

The flow of electrical charge through the die-specimen system in SPS process relies primarily on the power supply characteristics, and thus can be characterized by different intensities and waveforms. However, irrespective of the waveform of the electrical current, the root mean squared value of the instantaneous intensity of the applied current can be expressed as:

$$I_{RMS} = \sqrt{\frac{1}{\tau}\int_{t}^{t+\tau} I^2(t)dt}$$

Where; "I" denotes the instantaneous current, and "t" represents the sampling time. Generally, in case of DC power supply, the applied voltage can be only a few volts (e.g. 0-10 V) and the current can be a several thousand Amperes (e.g. 1000-10,000 A). In case of pulsed DC power supply, the ON and OFF timings are usually in the range of a few milliseconds. The different types of pulse patterns that can be observed in the DC power supply are shown in Figure 2.

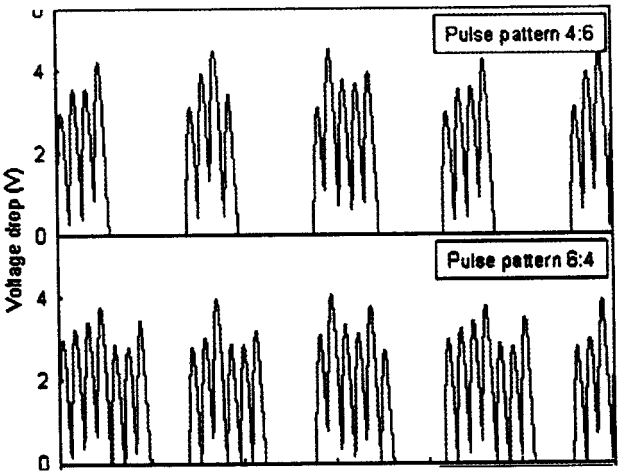

Figure 2: Different pulse patterns in pulsed DC power supply [2]

1.1.4 Heating mechanism in SPS process

The foremost difference between heating mechanism in SPS process and other sintering techniques is that internal heat generation occurs exclusively due to the Joule effect of the DC current. The total heat generation in SPS process is a combination of two components:

a. Heat generation in the die and punches, and

b. Heat generation in the sample

In case of a conducting powder sample, the sample is heated both by the heat generated in the sample itself as well as by conduction of heat from electrodes and the

die. However, insulating powders are heated only by the conduction of the heat generated in the dies and the electrodes.

Although, the true mechanism of heat generation in SPS is still unclear, the heat generated in SPS is hypothetically attributed to the micro-spark discharge (plasma heating) in the gaps between neighboring powder particles, resulting in neck formation, which establishes a path for the conduction of electrical current through the particles. It is then followed by Joule heating, originating from the resistance of the material to the electrical current flowing through it, resulting in the coarsening of the grains (see Figure 3). As this heat generation has a localized character and almost uniform distribution, it allows rapid temperature rise and drop, which prohibits coarsening (growth) of the material grains.

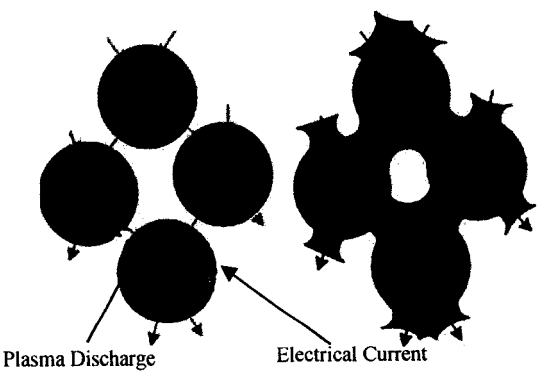

Figure 3: SPS Sintering mechanism; Plasma heating (left), & Joule heating (right) [3]

It is worth mentioning here that the only heat generation mechanism in the SPS process which is supported by experimental validation is the Joule effect. All other phenomena that are associated with the current flow – plasma formation, generation of sparks, high local temperature at the contact surfaces of the particles, etc. – may take

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BY

MUHAMMAD LUQMAN

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