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Original Research Paper

An investigation into the parameters affecting the breakdown voltage and inter-particle bonding in the electrical discharge compaction of metal powders

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ABSTRACT

The aim of present investigation is to gain deeper understanding of breakdown behavior and inter-particle bonding by conducting experimental tests. This may lead to improve the state of compaction by relative arrangement of initial parameters to maintain uniform distribution of current density and producing compacts with sufficient mechanical strength. Experimental work was carried out using two different set-ups. The first arrangement was employed to provide steady-state alternating voltage. The effect of column geometry and particle size on breakdown voltage was investigated under this condition. The second set-up, capacitor discharge circuit, was used to provide impulse voltage. Under this condition, the influence of column geometry, particle size, application of axial pressure, evacuation of air, energy input, electrode material and configuration on breakdown voltage was studied. Also, scanning electron microscopy was employed to study the effect of different parameters on inter-particle bonding. The results of experiments conducted on the influence of each of the voltage and capacitance on the compaction properties are also discussed.

1. Introduction

Powder Metallurgy (PM) methods have been used increasingly as a fabrication technique in various industrial areas for many years. During last few decades, the need to increase production rates of compacts and to improve compact properties has led to an interest in dynamic compaction methods. These methods differ from conventional PM techniques in respect of the compacting pressure and the rate of compaction. Increasing the rate of compaction results in a more uniform density distribution, improved mechanical strength, and in the case of die compaction, lower ejection force [1].

Taylor [2] introduced the idea of passing electric current to consolidate metal powders. In this process, passage of direct electric current through the powder column contained in an electrically insulated tube, leads to densification and sintering of powder particles. Cremer [3] developed this method by applying alternating voltage along with external pressure. Since then, several consolidation and sintering methods have been developed by many scholars based on this simple and effective technique. These methods are categorized by the time and amount of electric current as well as axial pressure applied on powder column. A detailed classification of the methods based on using electric current has been provided by Yurlova and colleagues [4].

One of these methods is referred to as Electrical Discharge Compaction (EDC) [5] has attracted interests over the past few decades. In EDC method, a high transient current passing through the loose powder breaks down the oxide layers as well as causing heating and welding of powder particles. Simultaneously, it generates an intense magnetic field in the radial direction which exerts an intensive magnetic pressure on powder column diametrically [6].

There are many studies that have investigated different aspects of EDC and have applied this method to consolidate a wide range of powdered materials. Wu and co-workers examined microstructure as well as mechanical properties of WC-10Co carbides compacted by EDC technique and showed that finer grain size can be obtained using short sintering time [7]. Wu and Guo applied EDC to manufacture both coarse and ultrafine WC-Co cemented carbides. They realized that EDC technique is capable of producing graded materials with excellent mechanical properties and also control cobalt

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migration process during consolidation [8]. Darvizeh and Tavoli showed that an optimum thickness of oxide layer is required to produce sufficient local heat for neck formation. If the oxide layer is removed, insufficient heat is generated and this results in weak inter-particle bonding and poorer mechanical strength. On the other hand, beyond a critical thickness of oxide it is not possible to compact the column of powder, and molten channel formation occurs [9]. Grigoryev and Olevsky simulated thermal process within inter-particle contacts during EDC and also investigated the effect of electric current on the temperature distribution in both microscopic and macroscopic scales [10]. Lee and colleagues studied densification behavior and corresponding mechanical properties of zirconium nitride (ZrN) powder during high voltage EDC process. The outcomes of their study indicated that the properties of compacted ZrN is highly dependent on the magnitude of the voltage applied [11]. Aleksandrova and co-workers evaluated the relationship between electric circuit parameters and density of compacts [12]. More recently, Lagos and co-workers have showed that simultaneous use of an electric press of 15 tones and 40 V transformers can leads to produce hard metals with finer grain size and more hardness in comparison with conventional PM methods [13].

Gorza and Zavaliangos realized that inter-particle oxide layers and the gap around the contacts between particles play an important role in breakdown voltage strength [14]. Also Garina indicated that thermal oxidation of metal powder particles increase the breakdown voltage significantly [15].

Literatures do not provide experimental results related to breakdown voltage behavior of different metallic powders. Furthermore, the aim of present study is to predict the behavior of metallic powders at the compaction stage by achieving better understanding of influential parameters on breakdown behavior. If this could be fully obtained, waste of time and material can be avoided. Present work does not claim such a valuable achievement, but this approach has not been used in studies of EDC process. In fact we have laid down primary stages and the extension of this work may permit to find initial voltage and energy level for EDC compaction of different powders with different morphology and oxide content.

The present work aims to investigate experimentally the effect of various parameters on breakdown voltage behavior of metal powders during EDC process. Wide range of tests have been performed using two experimental set-ups including steady-state alternating voltage and impulse discharge voltage. The effects of column geometry, particle size, application of axial pressure, evacuation of air, energy input and electrode material and configuration on breakdown voltage behavior of metal powders have been investigated.

2. Breakdown voltage in high-voltage EDC

Commercial powder particles naturally have an adherent surface of oxide. Most metal oxides are classified into semiconductors with a high electrical resistance. In EDC process, electrical energy stored in capacitors is discharged suddenly through powder column contained in an electrically non-conductive tube between two electrodes. Any single particle between two electrodes may be considered to consist of layers of different electrical conductivity. Using this concept, makes it possible to consider each particle as a dielectric unit which has a particular equivalent electrical circuit. When the voltage applied to a dielectric is progressively increased, a breakdown of dielectric will finally take place, and the conducting current will sharply increase. The subsequent reduction in voltage is explained by a decrease in the dielectric resistance. The minimum voltage necessary to break the powder column is defined as the breakdown voltage. A strongly conductive breakdown channel formed during a breakdown, practically produces a short circuit between electrodes. Dielectric breakdown generates a spark or an electric arc which can fuse, burn and crack the dielectric. In the case of metallic powders the oxide layer surrounding the powder particle will be broken and metal-metal bonds will be formed through powder column.

3. Materials and methods

In order to prepare a powder column, as-received metal powders including steel (M84), iron (JJM), nickel (Ni) and copper (Cu) were classified into a range of mesh sizes (for this purpose, metal wire sieves were used and classification was made according to mesh sizes given in Table S1 in Supplementary data). Percentage composition of as-received powders is given in Table 1. A qualitative television microscope was employed to investigate particle size distribution of different powders. For each powder sample, 50 readings were taken on a Quantimet 720 and average particle size was calculated (typical results as obtained for Cu and M84 powders are graphically presented in Fig. S1 in Supplementary data). Experiments were carried out using two different set-ups. The circuit shown in Fig. 1(a) was employed to provide a steady-state alternating voltage. This circuit consists of a variac for controlling the input voltage from 0 to 250 V, connected to the main supply. The variac output is fed to a step-up transformer. The output of this transformer is connected to the sample via a current limiting resistance. This resistance is to limit the current drawn by the sample at breakdown and by doing so, protecting the winding of the transformer from the excessive current higher than its rating. The measuring equipments in the circuit are the ammeter and the voltmeter. By connecting the powder column across the circuit and increasing the applied voltage by manually turning the variac, the voltage across the specimen suddenly drops at breakdown. Before this happens, no passage of current could be detected. At breakdown, the current would flow through the powder column causing a sudden drop in voltage. Under this condition, the influence of column geometry and particle size was examined for three types of metal powders.

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The second arrangement was used to measure breakdown voltage under impulse discharge voltage. In this mode of testing, according to Fig. 1(b), the powder column was connected across the circuit, and the stored energy in the capacitor was suddenly discharged through it. This system uses 80 μF, 20 kV maximum, energy storage capacitor bank, charged via a commercial charging

Table 1
Percentage composition of metal powders used in experiments.

Powder	Label	C	S	P	Si	Mn	Ni	Cr	Mo	Sn	Cu	Fe
Steel	M84	0	0.01	0.014	0.02	0.31	0.31	0.38	0.58	0.012	0.09	Balance
Iron	JJM	0.02	0.018	0.012	0.03	0.29	–	–	–	–	–	Balance
Nickel	Ni	0.006	0.025	–	–	–	Balance	–	–	0.003	–	0.01
Copper	Cu	–	–	0.1	–	–	–	–	–	–	99.9	0.001

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