JST&M 6(2024), 8 - 14
DOI: 10.57131/jstm.2024.6.2

Original scientific paper

THE EFECT OF DIMENSIONALITY AND CURRENT STRENGHT ON CONDUCTIVITY OF GRANULAR METALS

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ABSTRACT

Metallic materials in granular packings show different electrical properties from their bulk counterparts. In this paper, we investigate the temporal evolution of the electrical conductivity of granular metals. We use metallic beads arranged in different one-, two- and three-dimensional ensembles through which different constant currents are injected. The conductivity behavior in all three types of systems is qualitatively similar. The results show the rise of conductivity which is more pronounced in the earlier stages of the time evolution. We investigate the influence of the dimensionality, number of the beads, and the values of the injected currents on the conductivity behavior.

Keywords: granular metals, electrical resistance, weak contacts

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1. INTRODUCTION

Granular metals display quite unique electrical resistance behavior when compared to their bulk counterparts. For any conducting wire, the resistance is proportional to its length and inversely proportional to its cross-section area while it remains constant in time. In granular metals, the resistance is caused by both the individual resistance of the grains as well as by the contacts between them [1]. A few authors have recorded the decrease in resistance with time in granular metals [2, 3, 4] which is more pronounced in the earlier stages of the time evolution. The origin of this phenomenon can be found in the theory of contact resistance. Because every surface has some roughness either on micro or even nano scales, the electrical contact between the granules is established through discrete spots, known as a-spots or asperities which determine the actual size of the contact area. It is usually much smaller than the nominal contact area [5]. This affects the electromechanical properties of the materials due to the large pressure exerted on these spots. Contact resistance can also originate from the tunneling, especially in metallic powders covered with thin oxide layers [2]. Over the years, many theoretical models have been developed to model contact resistance. However, most of them include major simplifications ignoring correlations between asperities, roughness of the surface, or existence of the oxide layer [6, 7]

Various authors suggest that the number of beads, temperature, vibrations, packing, and applied force [8, 9] can also influence the

electrical properties of these materials. According to [10], the properties of the granular materials seem to be universal i.e. independent of the type and size of the grains, but are rather attributed to the granular structure of the system itself.
In this paper, we measure a flow of different fixed currents through 1D, 2D, and 3D compact packings of steel cylinders to examine the effect of dimensionality, the number of cylinders, and the current value on the resistance behavior.

2. EXPERIMENTAL PROCEDURE

The schematic of the experimental setup is shown in Figure 1.

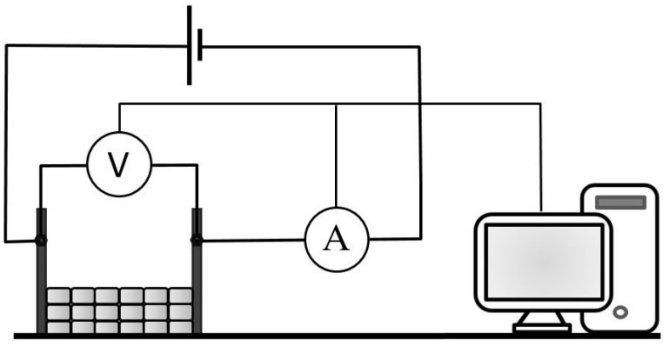

Figure 1. Sketch of the experimental setup. The current is injected into the cylinder packing. The voltage and the current are registered and the resistance is calculated

The steel cylinders with a diameter of 5 mm are placed in an isolating box with plate electrodes on the side walls. The box is placed under a small inclination angle of 15° onto an anti-vibration table. A fixed current is injected into a cylinder packing from a current source Kiethley 228, while the current and voltage are measured with Multimetars GDM 8621A (GW – Instek). The data is acquired by a computer program that calculates resistance using Ohm's law. The temperature is measured using PeakTech digital thermometer. Small variations between 1-2 °C are recorded and do not seem to alter the behavior of resistance.
The cylinders were first arranged in a 1D linear chain containing 18 beads (Figure 2 a) and a fixed current between 10 mA and 80 mA was imposed onto the chain for 600 s with 10 s step. For every fixed current value, a set of five measurements has been conducted in the following manner: After each measurement, new contacts between the cylinders were established by reducing the current to zero, removing the cylinders from the box, and after a couple of minutes placing them back to the same place as before, thus creating a new packing of cylinders for every measurement.
2D packings of cylinders were formed by placing them in rows, starting from two rows up to ten rows (Figure 2 b), thus containing 36 to 180 beads respectively. The current injected into 2D packings was 50 mA and one measurement was conducted for each number of rows. The current and voltage were measured and recorded every 10 s for 300 s.
3D packings were formed by placing the cylinders into rows and columns 3 by 3 (162 beads), 5 by 3 (270 beads), and 7 by 3 (378 beads) with 50 mA current injected into them (Figure 2 c). The current and voltage were measured every 10 s for 300 s. Note that for 2D and 3D arrangements of cylinders, new contacts were established after each measurement.

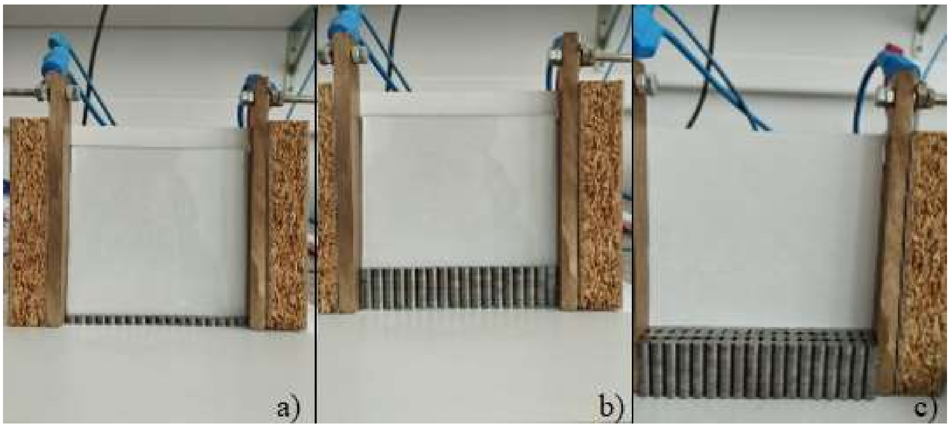

Figure 2. a) 1D packing b) 2D packing containing 6 rows and c) 3D packing containing five rows and three columns of the cylinders

Scanning electron microscopy (SEM) was performed using JEOL JSM IT 200LA while atomic force microscopy (AFM) imaging was performed using Nanosurf CoreAFM. AFM imaging was acquired in dynamic mode using Nanosurf DynAl-900 tips (nom. freq. 190 kHz, nom. force const. 48 N/m) with linear scanning time of 1 s and scan resolution of 256 points per line. The measurements were performed in air ambient temperature and humidity. Analysis of the images was carried out using WsXM software [11].

3. RESULTS AND DISCUSSION

Typical behavior of the electrical conductivity σ in a 1D linear chain is presented in Figure 3.

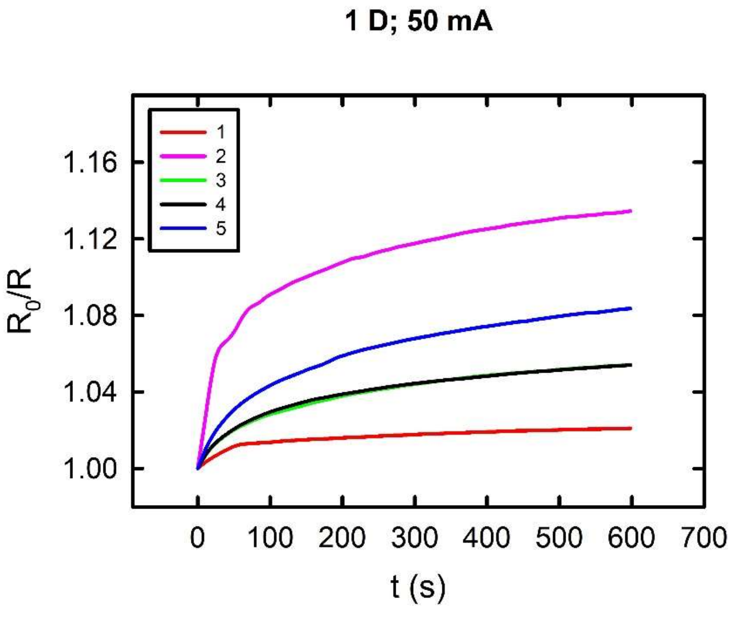

Figure 3. Five measurements of the normalized conductivity ($\sigma=R_0/R$, where R_0 is the initial resistance and R is the measured resistance) for 50 mA current injected into the 1D chain

Five measurements of conductivity were performed for 50 mA current injected into the 1D chain of cylinders. Before each new measurement, a new packing of cylinders was created following the procedure as previously explained in the experimental section of this article. According to our results (Figure 3), electrical conductivity rises with time which is more pronounced in the earlier stages of the experiment. Also, the initial value of the resistance as well as the rate of the resistance change for every packing, which had been previously established and can be attributed to the establishment of new microcontacts between the cylinders [4].

Qualitatively, the electrical conductivity in 2D arrangements of cylinders (Figure 4) is similar to the one in 1D linear chains.

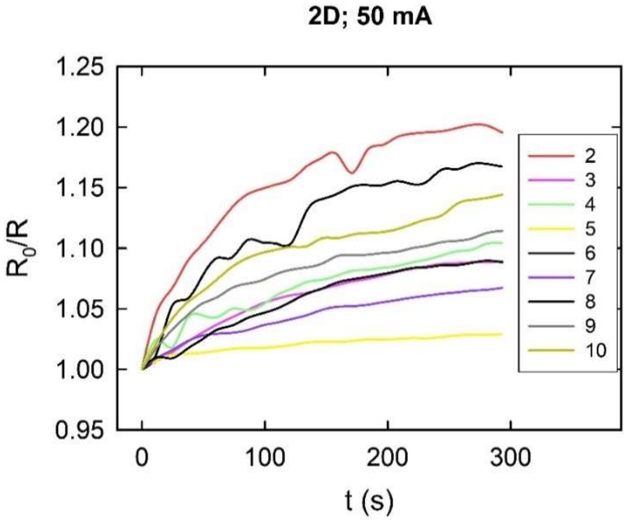

Figure 4. Normalized conductivity ($\sigma=R_0/R$, where R_0 is the initial resistance and R is the measured resistance) for 50 mA current injected into the 2D packings containing from 2 to 10 rows

This unusual result can be understood when analyzing the current paths in 2D systems. According to [12] the current in 2D systems seems to be localized in desecrate linear paths regardless of the strength of the injected current.

3D packings display similar conductivity behavior as 1D and 2D systems, as illustrated in Figure 5.

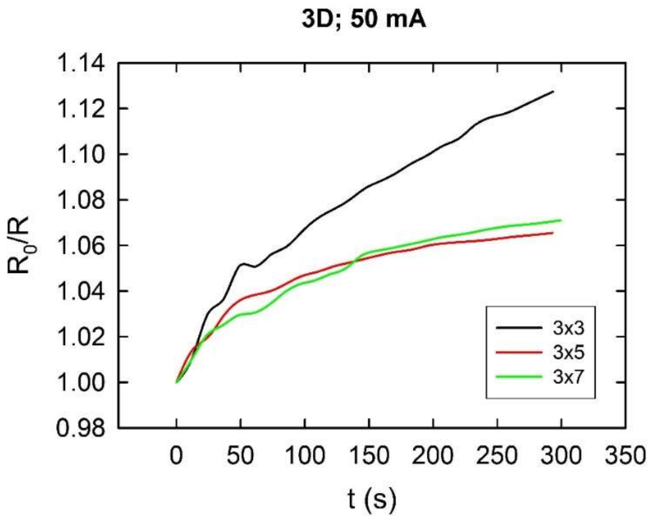

Figure 5. Normalized conductivity ($\sigma=R_0/R$, where R_0 is the initial resistance and R is the measured resistance) for 50 mA current injected into the 3D packings of cylinders

According to our results, dimensionality does not seem to influence the behavior of the time evolution of conductivity in granular metals because the current seems to stay localized in linear paths.

Next, we examine the current strength on the conductivity behavior. Since all the packings regardless of the dimensionality display similar behavior, we examined only 1D packings of cylinders for the current values between 10 mA and 80 mA, as presented in Figure 6.

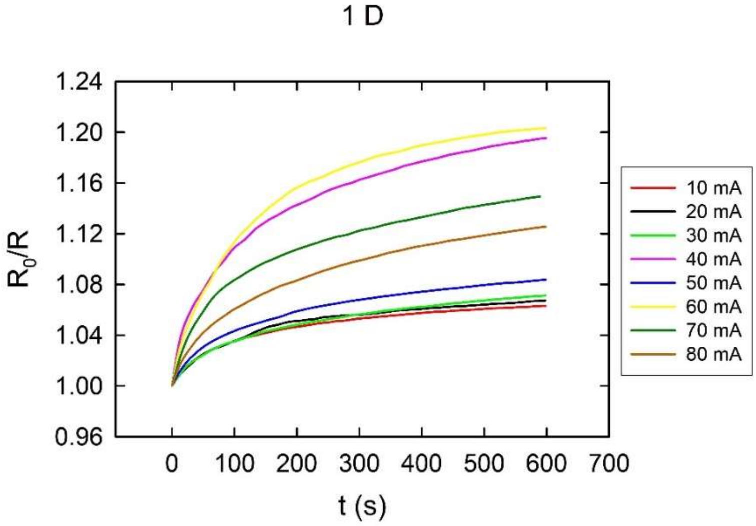

Figure 6. Normalized conductivity ($\sigma=R_0/R$, where R_0 is the initial resistance and R is the measured resistance) for currents between 10 mA and 80 mA injected into the linear chain of cylinders

Qualitatively, the conductivity behaves in the same manner for all the current values. The initial values of conductivity and the rates of conductivity rise do not seem to correlate with the current strength. Namely, for each stronger current imposed on the system, the initial conductivity can either be smaller or larger than for the previously imposed weaker current. According to our measurements, the most significant influence on conductivity seems to be originating from the contact resistance which is greatly affected by the cylinders' surfaces. To examine the cylinder surfaces, SEM imaging, presented in Figure 7 was performed. The surface showed visible scratches due to the cutting.

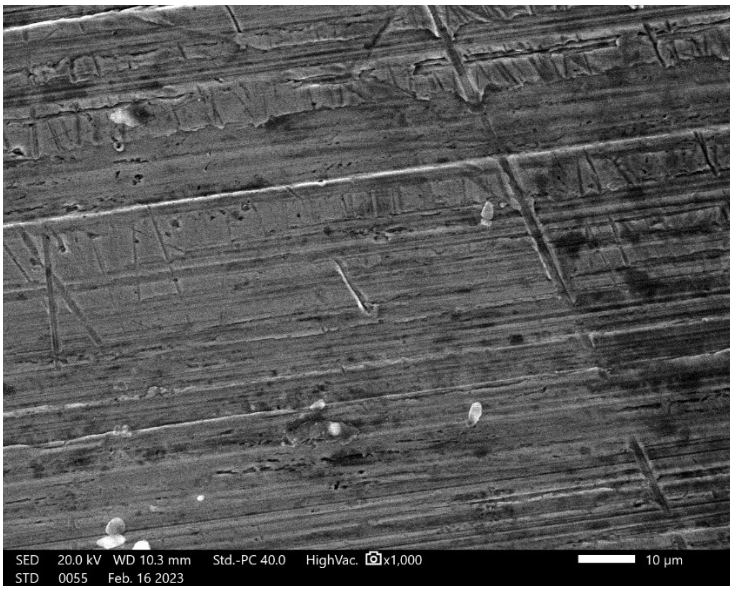

Figure 7. SEM image of the cyllinder surface

To examine the topography of the cylinders, AFM imaging was conducted. Figure 8 represents a 3D image of a flat surface of one cylinder. The image revealed needle-like asperities and also some deep furrows. Surface roughness is 93 nm rms, but the differences in height are rather pronounced and go up to 592 nm in some places.

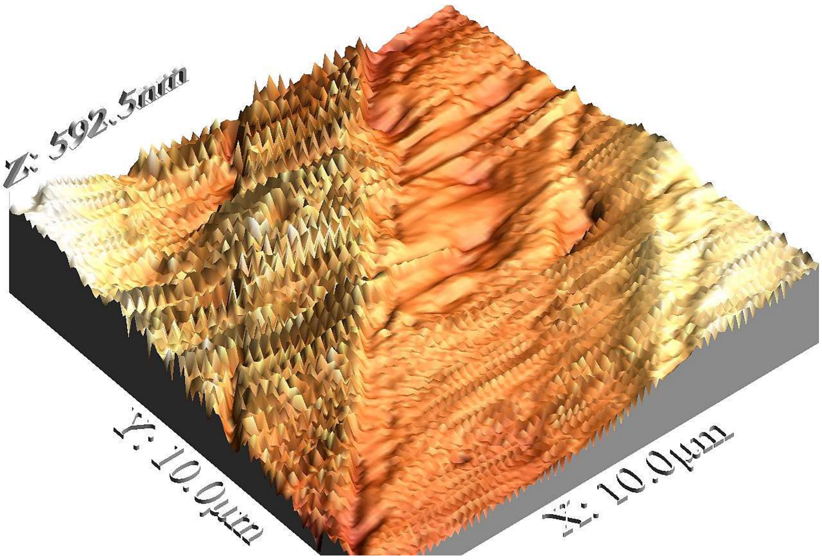

Figure 8. 3D image of the cyllinder surface

4. CONCLUSION

Our results show that in granular ensembles of steel metallic cylinders, the conductivity rises with time regardless of the dimensionality or the current strength injected into them. A similar trend was observed in other granular systems of different metals. This may be attributed to the granular nature of the material itself, which seems to not depend on the dimensionality, number of grains, shape, size, or even grain material. A predominant factor in this behavior originates from the contact resistance which is associated with the number and height of asperities as well as with the oxide layers on the metallic surface. AFM measurements of our samples revealed very rough samples with a lot of needle-shaped asperities. The highest of them contribute to conductivity, while the shorter ones, especially if they are in the furrows, probably do not influence the conductivity. To investigate whether it is possible to influence the conductivity behavior with mechanical treatment of the surface of the cylinders, in our next experiments we are planning to measure conductivity after polishing.

Conflicts of Interest

The authors declare no conflict of interest.

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