Research Programs

Electrostatic Density Measurements In Green-State P/M Parts

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The goal of this research is to show the feasibility of detecting density variations in green-state powder metallurgy (P/M) compacts from surface voltage measurements. By monitoring a steady electric current flow through the sample, and recording the voltages over the surface valuable information is gathered leading to the prediction of the structural health of the compacts. Unlike prior research that concentrated on the detection of surface-breaking and subsurface defects, the results presented in this report target the density prediction throughout the volume of the sample. The detection of density variations is achieved by establishing a correlation between the conductivity and their respective density. The data obtained from the surface measurements is used as part of an inversion algorithm, calculating the conductivity distribution, and subsequently the density within the compact.

In a first step, the relationship between conductivity and density of green-state P/M compacts was investigated. Tests were conducted for a number of parts of various powder mixtures. In all cases a clear correlation between conductivity and density could be established, indicating that measurements of electric conductivity could indeed be exploited in an effort to render valid information about the density of the sample under test. We found a linear correlation for non-lubricated parts and a non-linear behavior for lubricated samples. Specifically, it was found that the conductivity increases with increasing density only up to a maximum value obtained at approximately $6.9 g/cm^3$. Interestingly, any additional density increase leads to a reduction of the conductivity. This behavior was confirmed to be inherent in all powder mixtures with lubricants. Figure 1 and 2 show the measured relationship for non-lubricated and lubricated P/M samples, respectively. In both cases the base material was iron 1000B. The project research is able to provide a physical model and a mathematical formulation describing this counter-intuitive phenomenon. The newly developed model for the conductivity of green-state P/M parts is based on the theory of the conductivity of mixtures. Considering the depolarizing effect of the non-conducting lubricant particles in the powder mixture, we find the following equation for the conductivity of a green P/M sample:

$$\sigma_{PM} = \sigma_{Fe} (1 - f_{air})^{\frac{1}{1-L_{air}}} (1 - f_{\mathrm{lub}})^{\frac{1}{1-L_{\mathrm{lub}}}} . \quad (1)$$

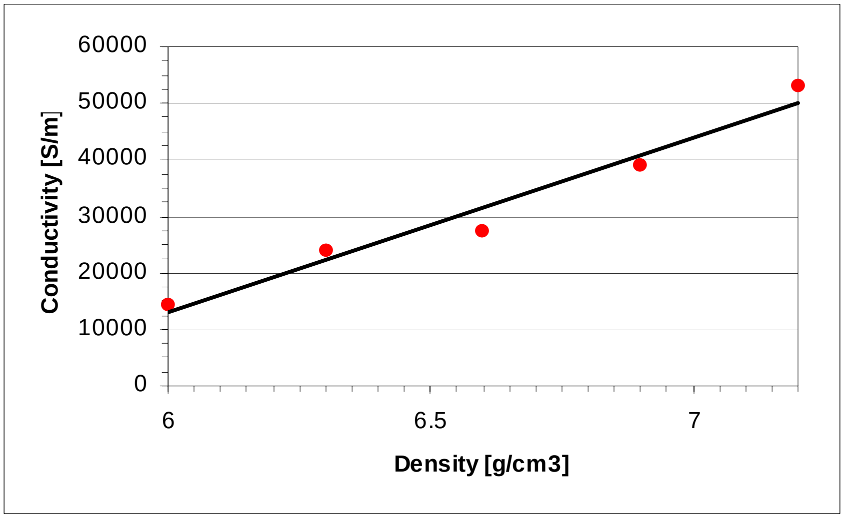

Figure 1: **Conductivity versus density for measured green state P/M samples from 1000B iron powder without lubricants added.**

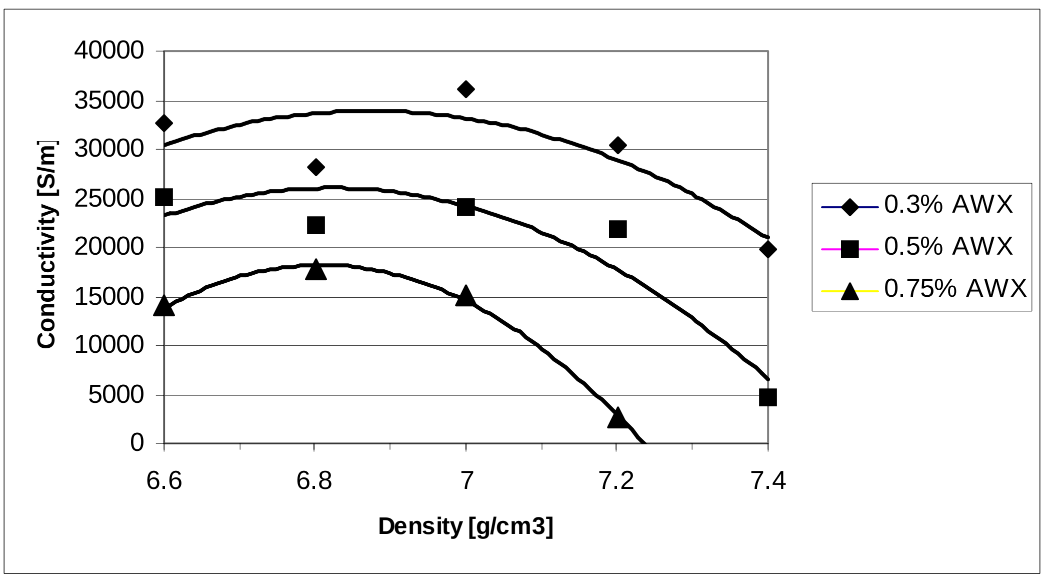

Figure 2: **Comparison between the conductivity of green-state samples from 1000B iron with different amounts of lubricant (AWX).**

Here σ_{Fe} is the background conductivity of the bulk material, f_{air} is the volume fraction of the enclosed air, f_{lub} the volume fraction of the enclosed lubricant, and L_{air} and L_{lub} are the depolarization factors of the air and lubricant particles, respectively. Taking into account the non-linear change of the depolarization factor with increasing density, the model explains the density-conductivity relationship as it was measured in the test samples.

A finite element solver in conjunction with an inversion algorithm was then implemented to study arbitrarily shaped part geometries. Based on the principles of electric impedance imaging, the developed algorithm faithfully reconstructs the density distribution from surface voltage measurements. Figure 3 shows the algorithmic approach used in calculating the conductivity distribution throughout the volume of a part, when given the source conditions and the surface measurements.

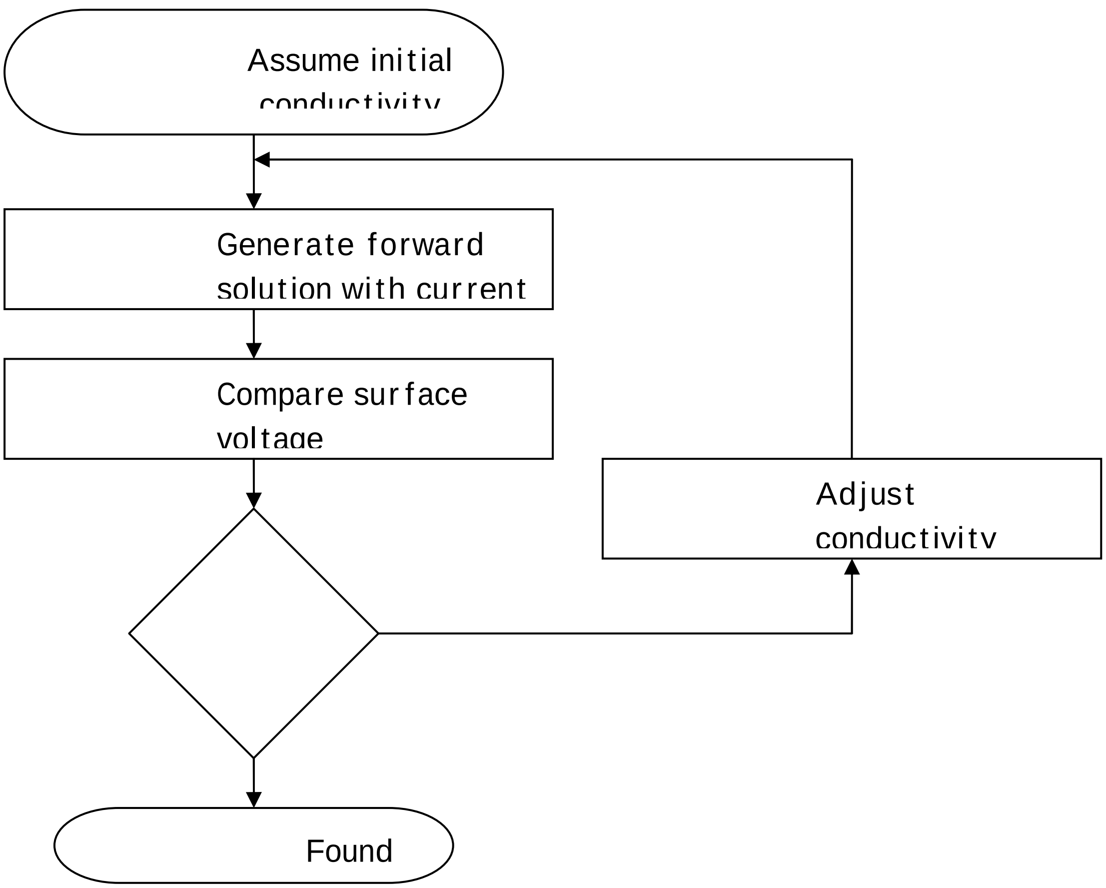

Figure 3: Flow diagram of inverse algorithm to determine the conductivity distribution.

The iterative update of the conductivity is achieved by using a variation of the Gauss-Newton method, trying to minimize the error between the calculated voltage values and the measured surface voltages. The conductivity value in step k is updated according to the following equation:

$$\boldsymbol{\sigma}_{k+1} = \boldsymbol{\sigma}_k + \left[\mathbf{J}^T(\boldsymbol{\sigma}_k)\mathbf{J}(\boldsymbol{\sigma}_k)\right]^{-1}\mathbf{J}^T(\boldsymbol{\sigma}_k)\left[\Phi(\boldsymbol{\sigma}_k) - \Phi_m\right], \qquad (2)$$

where J is the Jacobian matrix, $\Phi(\sigma_k)$ are the calculated voltages and Φ_m are the measured voltages. Additional regularization techniques are used to improve the convergence of the ill-posed inverse problem.

The feasibility of the instrumentation approach for both simple and complex parts can be demonstrated using a new sensor concept and measurement arrangement. Measurements were performed on both geometrically simple and complex parts. In a first step, simple cylinders were investigated, where the results of the inversion algorithm could easily be verified. Figure 4 shows the results of the conductivity reconstruction throughout the volume of the cylindrical parts. The comparative measurements from conventional, destructive techniques show good agreement for the respective results.

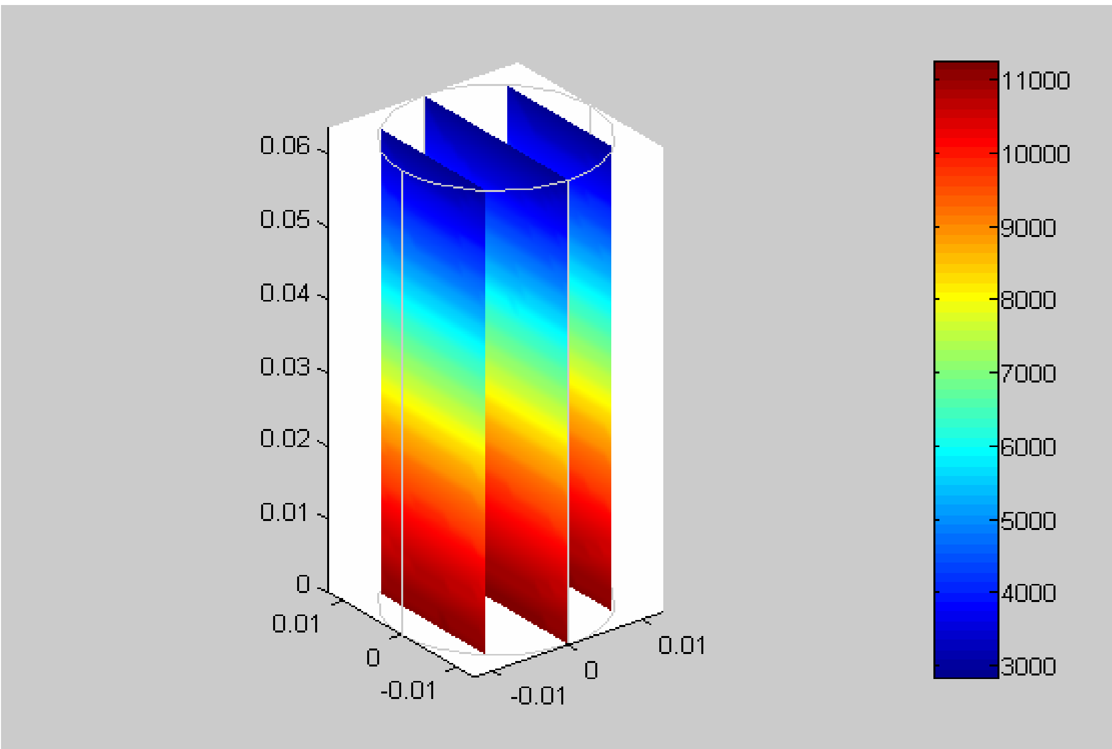

Figure 4: Reconstructed conductivity throughout the volume of the cylinder.

In a next step, the inverse algorithm was applied to geometrically complex parts. Figure 5 shows the results, indicating density variations in the inspected part, which are most pronounced in the top section and the corners of the hub shaped sample. These results clearly indicate the potential of the new technique in detecting density variations within the part by applying a DC current and measuring the resulting voltage pattern on the surface.

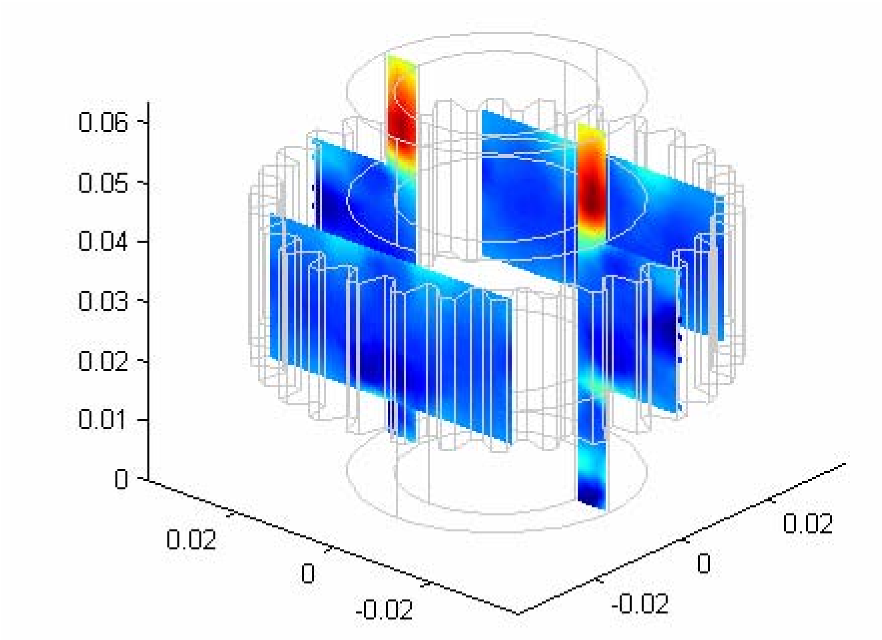

Figure 5: **Cross-sectional view of reconstructed density distribution throughout the volume of the hub-shaped gear. Dimensions are given in meters.**