Multi-Probe Impedance Measurement System for Non-Destructive Evaluation and Test of "Green State" Powder Metallurgy Parts

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***Abstract* - This paper describes an instrument capable of detecting flaws in "green-state" (prior to sintering) powder metallurgy (P/M) parts. The instrument uses a matrix of impedance measurements from a multiprobe array which contacts the surface of the P/M part. The array of measured data is processed to not only detect the presence of flaws, but also determine their location, size, and orientation. Experimental results show detection of flaws ranging in size from 10μm to 200μm.**

I. INTRODUCTION

This paper describes an instrument capable of detecting flaws in "green-state" (prior to sintering) powder metallurgy (P/M) parts. The instrument uses a multiprobe array which contacts a large area on the surface of the P/M part. By injecting a known current and measuring the resulting voltage distribution over the array, a matrix of impedance measurements is developed. Algorithms have been implemented that process the measured data so that the instrument can not only detect the presence of flaws, but also determine their location, size, and orientation [1, 2].

The first section of the paper provides an introduction to the measurement problems posed by the task of nondestructive flaw detection in an industrial P/M production environment. The second section of the paper describes the development of the instrument, with results from measurements made on laboratory samples with controlled crack geometries, as well as production parts with flaw characteristics that are typical of an actual production environment. There is also a discussion of the data processing and detection algorithm, which is robust with regard to changes in process parameters in the P/M production environment. The third section of the paper relates electrical parameters (such as the noise, gain, and bandwidth of a signal conditioning amplifier) to system level parameters such as minimum detectable flaw size. The results indicate that the technique embodied in this instrument is capable of rapid detection of flaws ranging in size from 10μm to several mm. This will result in a substantial improvement of yields in the P/M manufacturing process, reducing scrap costs and improving profitability for P/M manufacturers.

A. Powder Metallurgy Manufacturing Process

To produce a mechanical part in a P/M manufacturing process, a mix of metal powder and a binding material (such as wax) are compacted to form a part with a desired shape. The compaction process takes a few seconds, depending on the complexity of the shape. After compaction, the part is referred to as "green". In the "green-state", the P/M part is composed of loosely packed particles with large grain sizes and weak interparticle bonds.

The part is then sintered at high temperature for several hours which "burns off" the binding material and strengthens the metallurgical bonds between the remaining grains of metal powder. After sintering, the parts are referred to as finished or sintered.

B. Detection of Flaws

Flaws in finished parts usually take the form of cracks that were present in the green-state material due to causes such as nonuniform compaction. These cracks are typically of order tens of microns in width. Previous approaches to the general problem of non-destructive flaw detection include ultrasound [3] and eddy current [3, 4] techniques. Due to difficulties with the material properties of the green-state parts, these techniques could be applied only to finished parts. Since the time involved in sintering is comparatively long, many flawed green-state parts may be produced before flaws are detected in post-sintering tests. Since the flawed parts must be discarded, the resulting scrap costs are extremely undesirable in the high volume, low margin P/M industry.

C. Four wire impedance test

The potential drop (four point impedance) measurement technique [5, 6] has been explored as a possible means of detecting flaws in the green state. In this technique, shown in Fig. 1, four probes contact the sample: current is injected into the part through the two outer probes and the resulting voltage drop between the two inner probes is measured. In an unflawed part, shown in Fig. 1a, the measured voltage and the injected current are related by the resistivity of the P/M material. In the presence of a flaw, shown in Fig. 1b, the path of the injected current is altered. This causes an increase in apparent resistivity compared to an unflawed part. Although this technique is capable of detecting flaws, it is subject to several difficulties:

- The area under test is very small, requiring a priori knowledge of the flaw location.

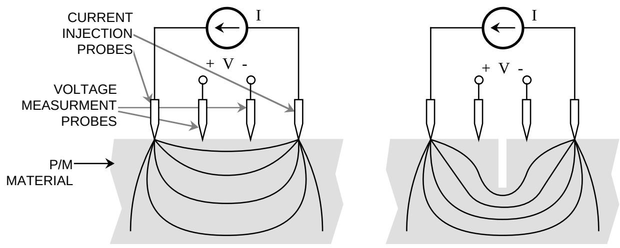

Fig. 1a. Current flow, unflawed P/M part.

Fig. 1b. Flaw alters flow of injected current.

Fig. 1. Four-wire impedance measurement technique.

- The technique depends on the direction of current injection: if the axis of the flaw (crack) is parallel to the injected current, the path of the current will be substantially unchanged, and there will be no measurable increase in resistivity. Thus a priori knowledge of the flaw orientation is also required.
- The result of this technique is a single measurement of resistivity, which can change due to other factors which do not correspond to flaws. Otherwise acceptable variation in parameters such as temperature, density of the P/M compact, or resistivity of the starting material could cause an increase in resistivity which would give a "false positive" indication of a flaw, thus leading to scrapping of good parts. Thus a workable approach must be tolerant of variations in process parameters.

II. MULTI-PROBE MEASUREMENT SYSTEM

This instrument expands the concept of the potential drop method to multiple voltage measurement points, with multiple directions of current injection. A block diagram of the system is shown in Fig. 2. Figure 3 shows the configuration of the multiprobe assembly which contacts the part under test. The test current, provided by a constant current source, is applied to the part through two of eight spring loaded probes located around the periphery of the probe array. The probes are selected by a current multiplexer controlled by the system computer. The different probes allow the direction of current flow to be varied over a full 360° range in 45° increments. The voltage distribution on the surface of the part is measured using an array of 64 spring loaded probes. Two of the 64 probes are selected by a voltage multiplexer which is controlled by the system computer. The voltage difference between the probes is amplified by an instrumentation amplifier. Noise is attenuated by a lowpass filter prior to the input of a 12-bit analog to digital converter. The digital data is recorded by the system computer. By sampling the voltage difference between adjacent pairs of pins, the voltage distribution on the surface of the part under test can be determined. An algorithm executed by the computer compares the measured voltage distribution to that of a known good part. A deviation in the measured distribution indicates a flaw, which can be identified in terms of location (the specific voltages showing a deviation), size (number of locations showing a deviation), and orientation (direction of current for which the maximum deviation was measured).

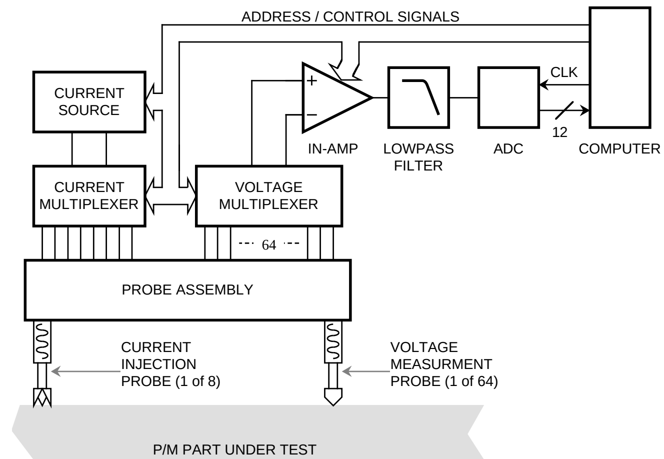

Fig. 2. Block diagram of multiprobe measurement system.

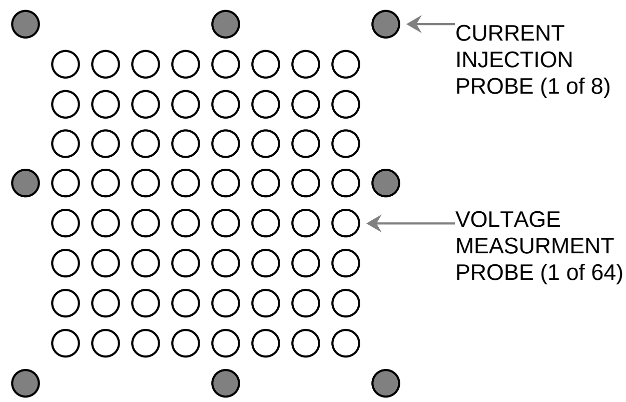

Fig. 3. Multiprobe assembly probe configuration.

A. Fundamental Characteristics of Flaw Measurements

A cross-sectional micrograph of a typical surface-breaking flaw is shown in Fig. 4. The width of a surface-breaking flaw is of order 100µm, but may be as small as 10µm. The depth d of the flaw may be as large as 1 mm or more, but the ability to resolve flaws as small as 10µm is desirable. A target of 10µm for minimum detectable flaw size was chosen as the goal of the instrumentation design process. As shown in [2], the depth of flaw is more important to the measurement process than the width, since a flaw of any width will alter the current flow.

Figure 5 shows a cross sectional view of the measurement when the multiprobe assembly bridges a flaw. To simplify the explanation, only one line of probes in the matrix will be considered. The differential voltages V1, V2, ..., V7 between adjacent probe pairs are multiplexed to the instrumentation amplifier, and the amplified voltage is converted to digital form by a 12-bit ADC for processing and storage in the system computer.

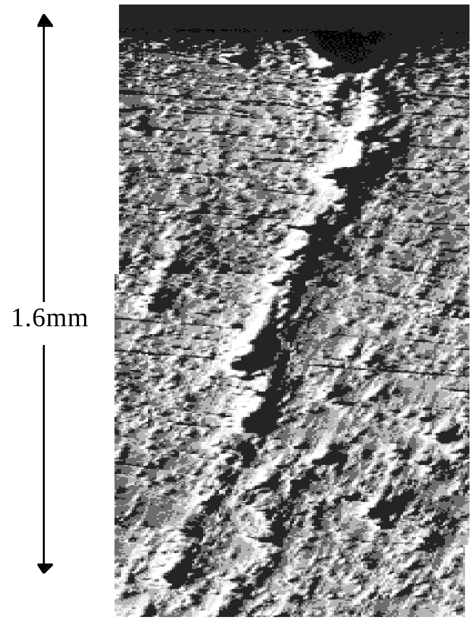

Fig. 4. Typical surface-breaking flaw.
Flaw width at surface: 100µm. Flaw depth: 1.6mm.

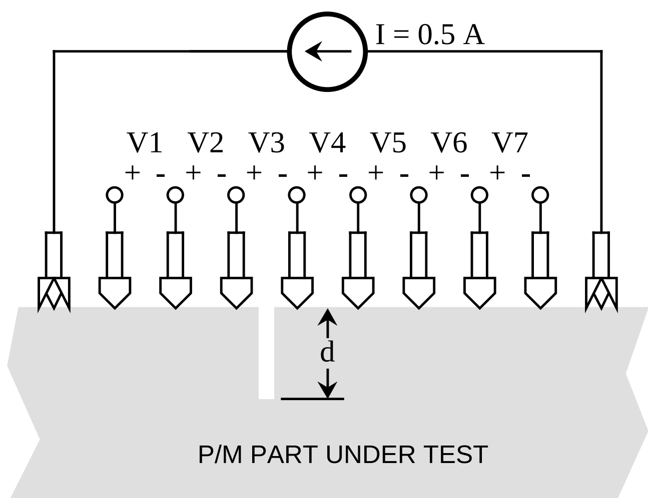

Fig. 5. Measuring voltage drops along axis of current flow.

Figure 6 shows measured differential voltages from the surface of the part, for an unflawed part and a part with a surface-breaking flaw. (For all of the measurements presented in this paper, the injected current was 0.5A DC and the separation of the voltage measurement probes was 2.54 mm.) As can be seen from the figure, the differential voltage signal on the surface of the P/M part is of order mV. The voltage drop is larger near the current injection probes due to higher current density there. The maximum measured voltage was approximately ±8mV; to provide margin the upper limit of the system dynamic range was set to 25 mV peak-to-peak.

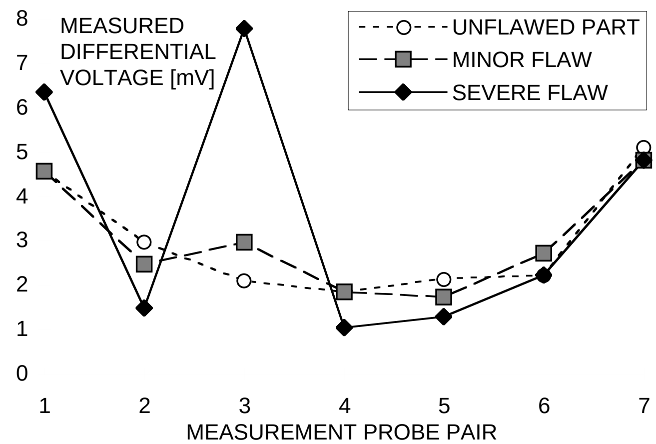

Fig. 6. Measured differential voltages.

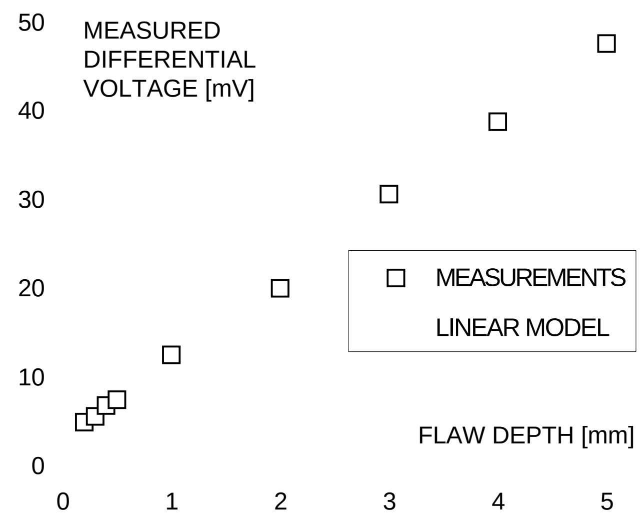

Fig. 7. Peak measured voltage as a function of flaw depth.

B. Flaw Detection

In presence of a flaw, a larger differential voltage is measured for the probe pair which spans the flaw. This can be seen from Fig. 6, in which the probe pair measuring V3 spans a flaw. The flaw detection algorithm [2] compares the measured voltage distribution to a "baseline" distribution for unflawed parts; a location at which the measurement deviates from the baseline indicates a flaw at that location. The algorithm is implemented in a scaling form that effectively compares the shape of the voltage measurements to the shape of the baseline. Thus if all measured voltages change (for example, due to a process shift such as a change in P/M powder resistivity), the scaling nature of the algorithm preserves the shape of the curve, and flaw detection can be performed accurately.

Fig. 7 shows the results of measurements of voltage deviation for controlled flaws of various depths. The relationship is approximately linear over a wide range of flaw depths. Extrapolating the linear model to the desired goal of 10µm gives a voltage of 100μV. This voltage sets the lower limit of the system dynamic range.

III. INSTRUMENTATION DESIGN ISSUES

A. Dynamic Range

The required dynamic range for the system is given by

$$D.R. = \frac{25mV}{100\mu V} = 250:1 \tag{1}$$

which is easily achieved with the 12-bit ADC chosen for the system. The gain of the signal path is chosen to match the 25mV peak-to-peak maximum signal to the 10V peak-to-peak (±5V) input full scale range of the ADC:

$$GAIN = \frac{10V}{25mV} = 400\,V/V \tag{2}$$

B. Noise Floor

Due to the high gain required in (2), the system noise floor is dominated by the input referred noise of the instrumentation amplifier. The input-referred system noise is given by the input voltage noise density of the in-amp, multiplied by the square root of the system noise bandwidth imposed by the lowpass filter. The current noise of the in-amp is not a factor since the source resistance of the P/M part is very low, of order 1Ω.

Multiplexer settling time considerations dictated a bandwidth of 10kHz for the lowpass filter [2].

To determine the input voltage noise density required to achieve an analog noise floor equivalent to 1/2 LSB of the ADC, this voltage (1.22 mV) is referred to input and then equated to the rms input referred noise expression:

$$\frac{1.22mV}{400} = 3.1\mu V = e_n\sqrt{\frac{\pi}{2}(10kHz)} \tag{3}$$

which gives a value of

$$e_n = 24\,nV/\sqrt{Hz} \tag{4}$$

This value is easily achievable with commercially available IC instrumentation amplifiers. Note that the rms noise of 3μV in (3) is well below the 100μV corresponding to the minimum detectable flaw size of 10μV.

C. Probe considerations

Note from Fig. 5 that different probes are used for current injection and voltage measurement. The location of voltage measurements is critical, and needs to conform to the ideal matrix locations as closely as possible. For this reason, single-point-contact probes are used. This type of probe has a high contact resistance due to the small contact area, but this is not a problem since no current flows in the voltage sensing path. For current injection, a high series resistance is undesirable since the relatively large injected current causes a significant voltage drop, placing severe compliance voltage requirements on the current source. Since the requirement on location of current injection is less critical than that for voltage measurement, multipoint contact probes are used for current injection, which provide a much lower contact resistance.

In practice, the mechanical uncertainty in the placement of the voltage probes set the limit on minimum detectable flaw size. Work is in progress to obtain probes with better mechanical precision, which will improve minimum detectable flaw performance.

IV. CONCLUSION

An instrument capable of detecting flaws in "green-state" (prior to sintering) powder metallurgy (P/M) parts has been presented. The instrument uses a matrix of differential voltage measurements from a multiprobe array which contacts the surface of the P/M part. The array of measured data is processed to not only detect the presence of flaws, but also determine their location, size, and orientation. Analysis of the fundamental aspects of the measurement process show that detection of flaws ranging in size down to 10μm is possible.

References

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