ELECTRICAL CONDUCTIVITY - A NONDESTRUCTIVE TOOL FOR ASSESSING THE MECHANICAL PROPERTIES OF SINTERED STEELS

A. Simchi, H. Danninger

Abstract
It is well known that the properties of sintered steels are strongly influenced by the microstructure, particularly by the amount and morphology of internal pores. In this context, the application of the load-bearing cross-section (A_c) as an indicator of microstructural impact on the mechanical properties has been well established. However, the quantitative fractography technique, which is a destructive and tedious work, must be used to determine the A_c value. In the present work, a nondestructive method based on electrical conductivity measurement is presented. In this method, the relative conductivity of porous materials is related to the surface area of necks formed during sintering. Empirical equations are then established to predict the mechanical properties according to the relative electrical conductivity. It has been found that this technique is particularly suitable for materials with a homogeneous microstructure. Satisfactory agreement between the experimental results and the predicted values has been obtained within a wide range of porosity levels.
Keywords: load-bearing cross-section, mechanical properties, microstructure, electrical conductivity, nondestructive testing

INTRODUCTION

The role of microstructure on the mechanical properties of sintered materials has been investigated quite frequently. The microstructure of these materials can be considered as two- phase including “porosity” and “matrix”. It is known that the pores have a pronounced effect on the properties of PM materials, e.g. the influence of porosity on the tensile strength of sintered iron is enhanced by a factor of 3 [1]. To this point, many empirical and theoretical models have been proposed to determine the correlation between the total porosity and the properties of PM materials [2,3]. However, these relationships are not very helpful because of the complicated morphology of the pores. In fact, not only the total porosity but also the size, geometry and connectivity of pores determine the properties. Therefore, the assumption of isolated and spherical pores does not comprehensively describe the behavior. Additionally, quantifying the pore characteristics through metallographic techniques is quite difficult and may not give adequate information about real microstructural features, especially for interconnected pores that form a 3-dimensional network.

Abdolreza Simchi, Department of Materials Science and Engineering, Sharif University of Technology, Tehran, Iran
Herbert Danninger, Institute of Chemical Technologies and Analytics, Vienna University of Technology, Vienna, Austria

Another approach for describing the microstructure of sintered materials that includes pore morphology is the effective load-bearing cross-section (A_c) [4]. It has been shown that this factor can be used as an indicator of the porosity effect on the mechanical properties [1,5,6]. For instance, direct relationships between A_c value and tensile and fatigue behavior of PM materials have been reported. Recently, mechanical wear of sintered materials has also been related to this parameter [7]. Nevertheless, determining the effective load-bearing cross-section needs quantitative fractography [8]; a destructive and tedious work. Here, to get a reliable value, it is imperative to analyze many sections of the fracture surfaces obtained by impact testing at low temperature. An attempt to measure the A_c value by manual image analyzer computer programs proved not convenient and required a lot of manual work [6], while fully automatic image analysis depends on certain morphology types in the broken contacts [8]. Therefore, it would be helpful to measure this parameter using an experimentally simple, reliable, and non-destructive technique. Here, electrical conductivity measurement seems to be an attractive way at least for materials with a homogeneous matrix structure. In a porous body, the current passes throughout the sample, and the voltage drop in the material should be in a relationship with the area of the sintered necks. If the microstructure is simply considered as a chain of "matrix" and "pores", a network of resistors would be obtained (Fig.1). If the size of the sintered necks is not very large, the electrical conductivity of the material should be primarily controlled by the area of the metal-metal contacts. Since the load-bearing cross-section shows the fractional surface of the metal-metal contacts, there must be a direct relationship between the electrical conductivity and the A_c value. Here it is worth mentioning that some investigators [3,9-16] have shown that there is a simple relationship between the total porosity and the electrical conductivity of PM materials. In the present work, we show that the conductivity affords a sensitive description of the influence of microstructure on the mechanical properties of sintered materials. This paper presents the viability of the method for sintered ferrous materials.

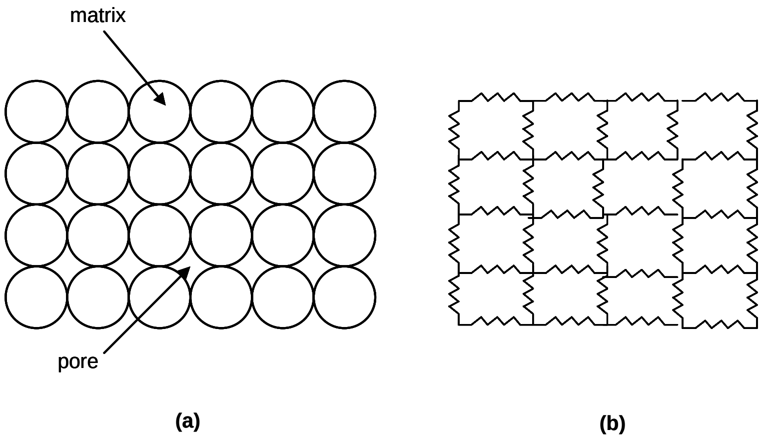


Fig.1. Schematic representation of microstructure of a sintered material that includes a network of pores and matrix (a). This structure can be assumed as a network of resistors (b) since the resistivity is controlled by the metal-metal contacts.

EXPERIMENTAL PROCEDURE

The starting materials were as follows: water atomised iron powder (Höganäs ASC 100.29); water atomised prealloyed steel powder Fe-1.5%Mo (AstaloyMo); natural graphite (Kropfmuhl UF4), and microwax C (Hoechst) as the pressing lubricant (0.8 wt.%). The powder mixtures were prepared by blending in a tumbling mixer for 60 min. Rectangular test specimens 55x10x5.5 mm^3) as well as standard dogbone bars (ISO 2740) were produced by uniaxial compaction in a pressing tool with floating die.

The green compacts were de-waxed and sintered in flowing hydrogen (dewpoint <-27ºC). The temperature ranged between 400 and 1300ºC, and the soaking time was 60 min. A getter box and a getter of alumina mixed with 5% graphite were afforded to prevent decarburization of the steel specimens. A few reference samples (with virtually full density) were prepared by double-pressing/double-sintering followed by hot isostatic pressing at 1100ºC.

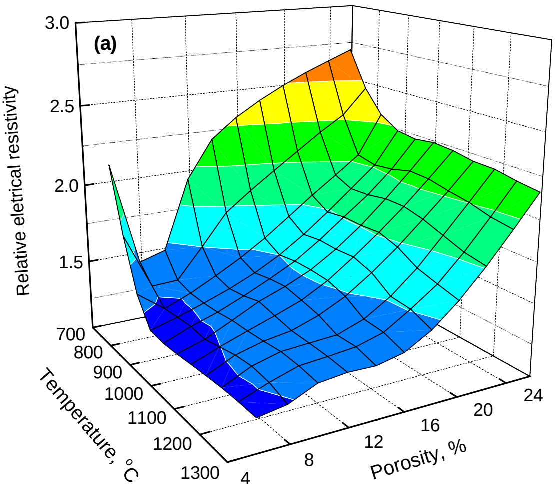
The density of the sintered specimens was measured by the water displacement method. The electrical conductivity of the compacts was examined by a Thomson bridge with a high sensitivity manipulator. Tensile and fatigue tests were performed on flat dog-bone shape specimens. The fracture surface of impacted tested samples at 77 K was examined by SEM. Quantitative fractography was performed by a semi-automatic image analyzer.

RESULTS AND DISCUSSION

Several iron samples with different porosity levels and pore geometry were prepared by varying compacting pressure and sintering temperature. Fig.2a shows the 3D map surface of the relative electrical resistivity of sintered iron as a function of total porosity and sintering temperature. The resistivity of Armco iron (9.7 μΩcm) was taken as the reference sample. The changes of the resistivity with the sintering temperature and the porosity level determine that both the amount of pores and their morphology influence the voltage drop in the porous specimens. At a constant total porosity, with increasing sintering temperature lower resistivity is obtained, particularly at high porosity levels (Fig.2b). One may also notice that the change in the resistivity is more pronounced at low sintering temperatures. When the sintering temperature is kept constant, the resistivity decreases as the total porosity decreases. This holds true except at relatively low porosity levels, i.e. about 5%, in which case an increase in the relative resistivity was observed for the samples sintered at low temperatures (<800ºC). These specimens were produced at 800 MPa, and thus insufficient delubrication and microcracking due to the elastic spring back effect might be responsible for the higher resistivity measured. In any case, the results indispensably determine that beside the total porosity, the pore morphology affects the electrical conductivity, although some researchers [3,16] have attempted to relate the conductivity to the total porosity as a single dominating factor.

To establish a relationship between the mechanical properties and the electrical conductivity, the effective load bearing cross section A_c, i.e. the area fraction of the metal-metal contacts, can be used as a useful microstructural parameter.

Figure 3 shows representative SEM micrographs of the fracture surfaces of sintered iron. The fracture surfaces were obtained by impact testing of the rectangular specimens at 77 K. A progressive increase in the area of the sintered contacts is seen as the total porosity decreases and/or the sintering temperature increases. The change in the fracture mode from ductile rupture to cleavage fracture is attributed to the variation in the morphology of pores from interconnected to closed porosity. Here it is worth mentioning that the fracture surface of the specimen compacted at 800 MPa and sintered at 800ºC shows almost no metal-metal contacts. This is in accordance with the relatively higher electrical resistivity of this specimen as compared to the sample compacted at 600 MPa (Fig.2). Quantitatively, the fractional area of metal-metal contacts was measured by a semi-automated image analyzer program. The results are shown in Fig.4 as a function of porosity and sintering temperature. It is apparent that the effect of sintering temperature on the A_c value is more pronounced at lower porosity levels – as shown for the mechanical properties in [5] - and the influence of porosity on this parameter is significant when high temperature sintering is applied. One may also notice a slight decrease in this parameter in the transformation temperature range of ferrite to austenite, particularly at low porosity levels.



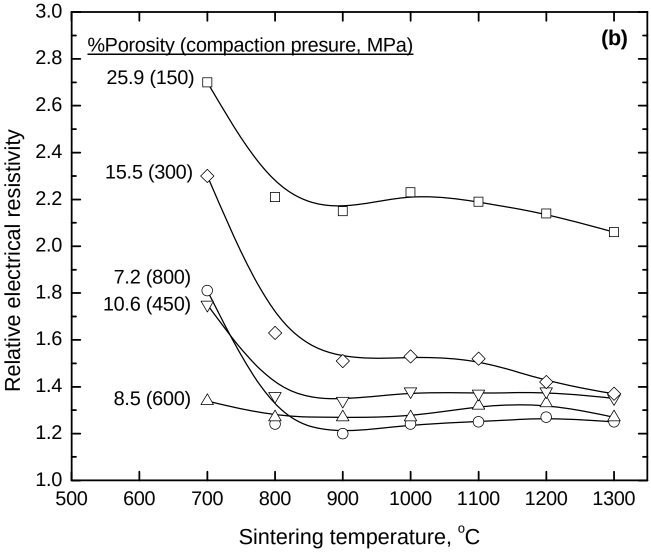


Fig.2. Relative electrical resistivity of sintered iron as a function of total porosity and sintering temperature (hydrogen; 60 min). Reference: Armco iron.

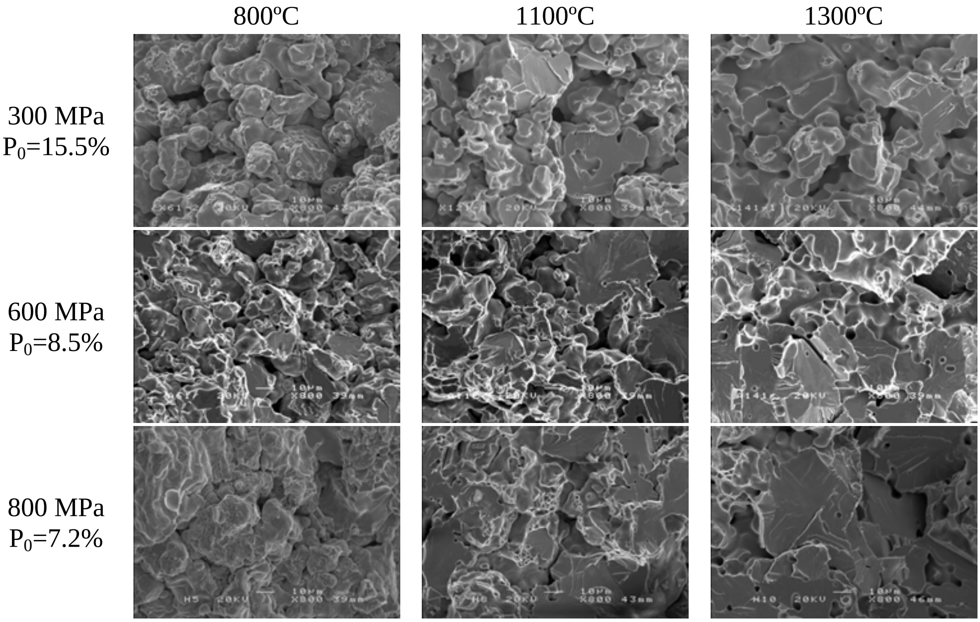


Fig.3. SEM micrographs of fracture surfaces of sintered iron produced at different compacting pressures and sintering temperatures. The specimens were impact fractured at 77 K. P_0 is the initial (green part) porosity.

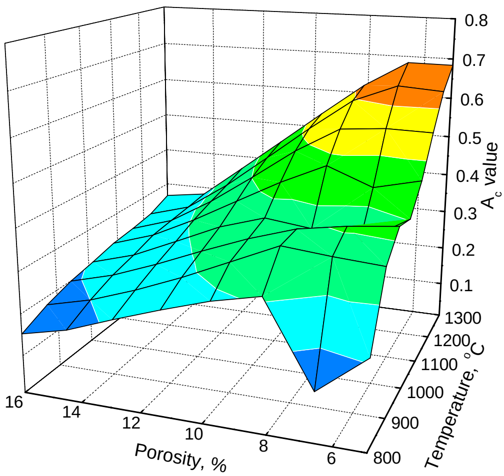


Fig.4. Load-bearing cross section of sintered iron as a function of total porosity and sintering temperature (hydrogen; 60 min).

Similar results were obtained for Fe-C and Fe-C-Mo alloys. Figure 5 shows the relationship between the relative conductivity and total porosity of the sintered steels. As can be seen, with increasing porosity lower conductivity is measured. Higher sintering temperature and longer sintering time also result in higher conductivity. One may use a linear relationship (*1-K P*) to fit the experimental results convincingly.

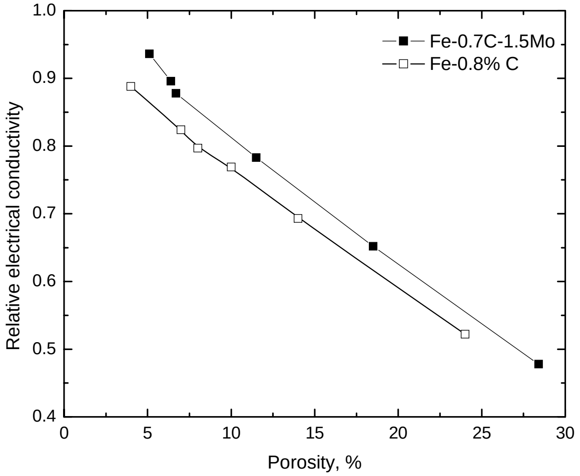


Fig.5. Relative electrical conductivity of sintered Fe-0.8% C (1200°C for 60 min) and Fe-0.7% C- 1.5% Mo (1280°C for 120 min) as a function of total porosity.

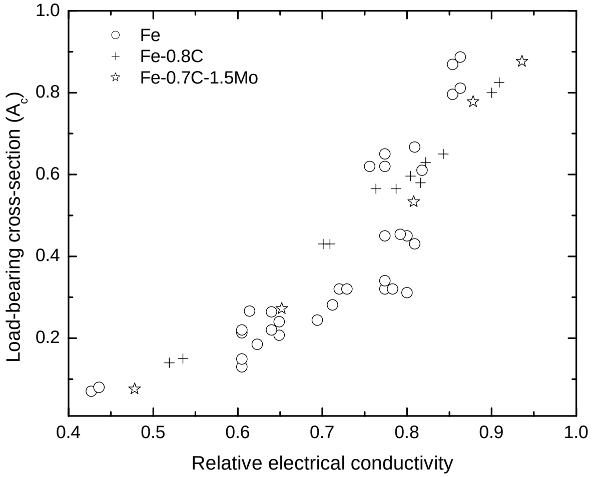


Fig.6. Load-bearing cross section of sintered ferrous materials versus relative electrical conductivity.

Figure 6 shows the relationship between the load-bearing cross-section and the relative electrical conductivity for Fe, Fe-0.8%, and Fe-0.8%-1.5% Mo compacts. It appears that there is a direct relationship between these two parameters. For the sintered steels, a linear relationship is well governed with low standard deviation. However, the data scattering for sintered iron is relatively high and a linear relationship cannot be taken without a large standard variation. This might be due to the significant grain growth which occurs during the course of sintering. Furthermore, it showed that measuring A_c of plain iron is tricky since ductile rupture also occurs at 77 K, which tends to result in too low A_c values. Hovewer, if the relationship between A_c and the electrical conductivity is known, one may use this simple, fast and nondestructive method to assess the mechanical properties of the sintered. A linear and direct relationship between the load-bearing cross-section and yield strength, true fracture stress and fatigue limit was reported previously [1,5,7,15]. A square root function was also found for Young's modulus. By measuring the electrical conductivity, the load-bearing cross-section was predicted and the mechanical properties were assessed. Figure 7 compares the predicted values with the experimentally measured quantities for the investigated iron and steel compacts. A convincing agreement is visible.

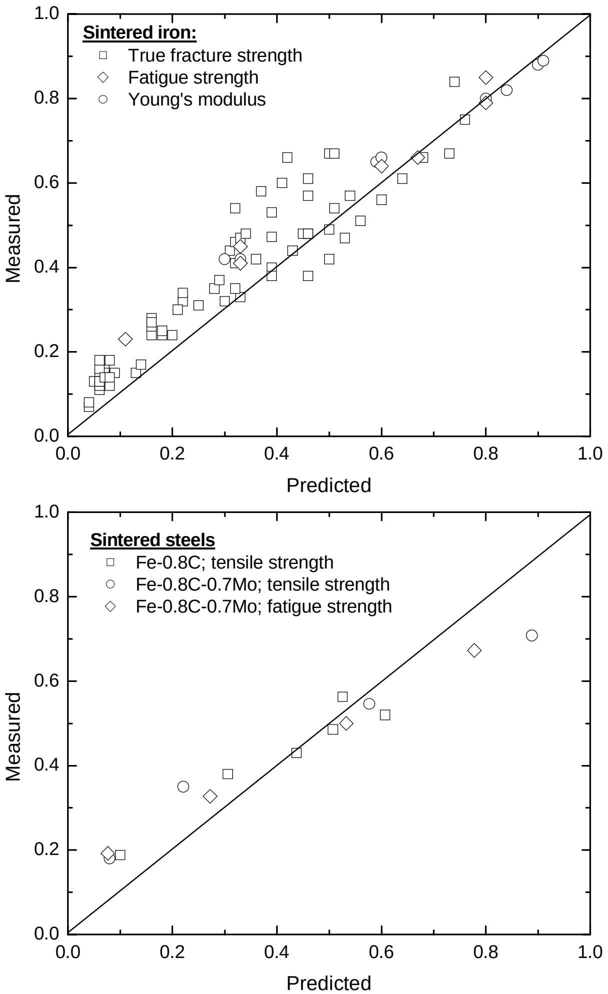


Fig.7. Normalized mechanical properties (normalized to fully dense reference material) of investigated sintered materials compared with values predicated from electrical conductivity measurement.

Therefore, it can be concluded that the electrical conductivity of sintered parts is closely related to their microstructure and thus to the mechanical properties. However, it should be noted that besides the total porosity and the pore morphology, the electrical conductivity is very sensitive to other factors such as grain size, impurities, and microstructural heterogeneity. The effect of the metal matrix on the conductivity is particularly significant when the sintered contacts are large enough, i.e., the voltage drop through the porous specimen is not only influenced by the sintered necks, but also by the internal structure of each particle. Consequently, a large deviation from the real A_c value and thus the predicted mechanical properties may be obtained. Therefore, more detailed experimental examinations and reference data collection are regarded as necessary to develop a nondestructive procedure.

CONCLUSIONS

A nondestructive method based on the electrical conductivity/resistivity measurement has been proposed for assessing the mechanical properties of sintered materials. It was shown that the voltage drop in a porous material is in direct relationship to the area of metal bridges formed during sintering. Since this area actually bears the mechanical loads, it is possible to relate the conductivity to the mechanical properties. By using the already established relationships between the load bearing cross-section, A_c, and the mechanical properties, the latter can be predicted by conductivity measurement. The viability of this approach was shown for sintered Fe, Fe-0.8% C, and Fe-1.5% Mo-0.7% C compacts. A convincing agreement between the measured mechanical properties including tensile and fatigue strength and the dynamic Young's modulus, and the predicted values by conductivity measurement was observed. This implies that conductivity measurement could be a fast, simple and nondestructive method for assessing the mechanical properties of sintered materials, at least of those with homogeneous metal matrix structure.

REFERENCES

[1] Danninger, H., Spoljaric, D., Weiss, B.: Int. J. Powder Metall., vol. 33, 1997, no. 4, p. 43
[2] Haynes, R.: Mechanical Behaviour of Sintered Metals. London : Freund Publishers, 1981
[3] Bocchini, GF.: Int. J. Powder Metall., vol. 22, 1986, no. 3, p. 185
[4] Šlesár, M., Dudrová, E., Rudnayová, E.: Powder Metall. Int., vol. 24, 1992, no. 4, p. 232
[5] Danninger, H., Jangg, G., Weiss, B., Stickler, R.: Powder Metall. Int., vol. 25, 1993, no. 4, p. 170
[6] Xu, C., Yang, Q., Danninger, H. In: Proc. Int. Conf. on Powder Metallurgy for Automotive Parts, PM Auto '05, 2005, Isfahan, Iran
[7] Simchi, A., Danninger, H.: Powder Metall., vol. 47, 2004, no. 1, p. 73
[8] Danninger, H., Sonntag, U., Kuhnert, B., Ratzi, R.: Pract. Metallogr., vol. 39, 2002, no. 8, p. 414
[9] Fricke, H.: J. Physical Rev., vol. 24, 1924, p. 575
[10] Meyer, R.: Powder Metall., vol. 4, 1972, no. 2, p. 63
[11] Yarton, D., Davies, TJ.: Int. J. Powder Metall., vol. 8, 1972, no. 2, p. 51
[12] Leheup, ER., Moon, JR.: Powder Metall., vol. 21, 1978, no. 1, p. 1
[13] Brettell, JM.: Powder Metall. Int., vol. 13, 1981, no. 2, p. 86
[14] Piszczek, T., Stolarz, S.: Powder Metall. Int., vol. 18, 1986, no. 1, p. 9
[15] Simchi, A., Danninger, H.: Powder Metall., vol. 43, 2000, no. 3, p. 219
[16] Montes, JM., Rodriguez, JA., Herrera, EJ.: Powder Metall., vol. 46, 2003, no. 3, p. 251