

ANALYSIS OF THE EFFECTIVE FLEXURAL MODULUS OF QUASILAYERED BARS MADE OF SINTERED IRON INFILTRATED WITH COPPER

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Abstract

Rectangular bar specimens, consisting of iron matrix and pores more or less filled with copper, were prepared and investigated. Distribution of Cu-filled pores exhibited a quasilayered character. When a dynamic resonant method was applied, differences were observed in effective flexural modulus values determined by means of specimen flexural vibrations parallel and perpendicular to quasilayers. Experimental results were compared with values of effective flexural modulus calculated for simple theoretical models of real specimens. Characteristic behaviour of modulus determined experimentally agreed with that predicted theoretically. This correspondence approved rightfulness to treat the real samples as a two-layer bars, and demonstrated that the infiltration with Cu improved the stiffness of sintered iron.

Keywords: *flexural modulus, Fe and Cu powders, quasilayered structures*

INTRODUCTION

The properties of sintered metallic materials are limited by their inherent porosity. One of ways how to improve the applicability of PM products consists in the possibility to fill the open porosity of sintered parts with a metal alloy by means of an infiltration process. It has been found that the infiltration can lead to almost the same mechanical properties which can be obtained for a pure material only by means of higher values of temperature and pressure applied for a longer time [1,2].

The infiltration process can lead to a quasilayered material. This product inhomogeneity usually makes the designing, testing and measuring more complicated. And the interpretation of results becomes less straightforward.

For design purposes, it is necessary to evaluate the response of structural parts to various external loading. For reason of efficiency, it is convenient to do with effective properties rather than to consider the exact microstructure. But it is necessary to keep in mind that for macroscopically heterogeneous parts such terms as the “effective modulus” are rather vague and less informative than for quasihomogeneous parts.

Tests and measurements carried out on quasilayered samples provide us with the effective properties, too. Therefore, to interpret the results correctly and to extract the useful information on a particular constituent, it is necessary to possess theoretical relationships that relate corresponding apparent properties to distribution and properties of constituents.

In the paper presented here, it is demonstrated how the variation of Cu content along the specimen cross section affects the value of effective flexural modulus measured by means of the dynamic resonant method [3]. Experimental results are compared to effective flexural modulus calculated for simple theoretical models of real specimens. It is found that the characteristic behaviour of experimental modulus agrees with that of theoretical one. This suggests that the partly infiltrated sample behaves like a two-layer bar with the infiltrated layer stiffer than the intact one.

EXPERIMENTAL

Specimens from iron and copper powders were prepared by pressing and sintering. As a basis, a water atomized iron powder ASC 100.29 and an electrolytic copper powder were employed.

To obtain the specimens with nonhomogeneously distributed content of Cu, the following technological procedure was applied. Samples were compacted within two steps. At first, the layer of iron powder was slightly pressed. Then a layer of exactly calculated amount of Cu powder was added and the entire sample was finally pressed at 600 MPa. The compacts were then sintered for 1 hour at 1050°C and 5 minutes at temperature 1120°C in H₂ atmosphere. The densified semi-products were subsequently shaped to the form suitable for testing. The final size of the resulting bars was 10 mm x 10 mm x 100 mm. The density of these rectangular bars was determined by measuring the dimensions and by weighing. Distribution of Cu within the samples was investigated by means of metallographic methods.

The dynamic resonant method [3] was applied for determining the effective flexural modulus. The frequency of specimens' natural vibrations was measured employing the apparatus Gringo Sonic MKS „Industrial“ at University of Vienna. In particular, the frequency of flexural fundamental mode of the bar vibrating with free ends was used for evaluating the modulus.

THEORY

To investigate the effect of a quasilayered structure on the effective flexural modulus in a theoretical way, it is necessary to possess the relationship that links corresponding modulus to the relevant material and geometric parameters of the test rod. Corresponding theoretical expressions were derived and are published in papers [4,5]. Here only the starting point is mentioned and the resultant relations are stated.

Dynamic resonant method is assumed to be used for determining the flexural modulus values E^fl . The effective flexural modulus, which is a “specific” quantity, really represents the “overall” physical characteristic – flexural rigidity of the bar, divided by the “overall” geometric characteristic – area moment of inertia of the bar cross section. For uniform, homogeneous bar the effective flexural modulus is the same as the Young's modulus of the material of the bar. But for a heterogeneous bar, this can be understood, for example, as a parameter representing a measure of the ability of the bar to resist bending.

Quasilayered rectangular bar undergoing free flexural vibration with free ends is considered. H, W and L are height, width and length of the bar, respectively.

For such situation, the following relations for effective flexural modulus were obtained [4,5]:

$$E_{\perp}^{fl} = \frac{12}{H^3} \left[\int_0^H E(x)x^2 dx - \left(\int_0^H E(x)xdx \right)^2 \left(\int_0^H E(x)dx \right)^{-1} \right] \quad (1)$$

for vibration in the HL plane, i.e. bending occurring perpendicular to quasilayers, and

$$E_{\parallel}^{fl} = \frac{1}{H} \int_0^H E(x) dx \quad (2)$$

for vibration in the *WL* plane, i.e. bending occurring parallel to quasilayers. $E(x)$ represents the materials' Young's modulus that can vary along the height of the bar.

For a two-layer rod the relations (1) and (2) obtain the forms:

$$E_{\perp}^{fl} = \frac{v_1^4 E_1^2 + 2v_1 v_2 (2 - v_1 v_2) E_1 E_2 + v_2^4 E_2^2}{v_1 E_1 + v_2 E_2} \quad (3)$$

$$E_{\parallel}^{fl} = v_1 E_1 + v_2 E_2 \quad (4)$$

Here E_1 and E_2 are values of Young's modulus in particular layers, v_1 and v_2 are volume fractions of these layers ($v_1 + v_2 = 1$).

RESULTS AND DISCUSSION

Metallographic study revealed that the above described technological procedure led to a nonhomogeneous distribution of Cu concentration within the samples (Figs.1,2). The concentration of pores filled with Cu was varying along the pressing direction and structures with quite distinct two layers were created. One of layers is characterized by occurrence of pores in Fe- matrix structure filled (at least partly) with Cu; the other layer has empty pores. The thickness of the layer enriched with Cu depends on the total content of Cu.

Due to above mentioned facts; a two-layer sample seems to be a good model approximation of real specimens. Theory predicts in general different values for E_{\perp}^{fl} (3) and E_{\parallel}^{fl} (4) for a two-layer sample. The ratio of magnitudes of "longitudinal" and "transversal" effective moduli is ruled by both the Young's moduli and volume fractions of particular layers. That is, for a given material of layers, the "transversal" modulus can be higher than the "longitudinal" one for some thickness of layers, but for another thickness the situation can be opposite. Some examples of theoretical values E_{\perp}^{fl} and E_{\parallel}^{fl} are presented in Fig.3.

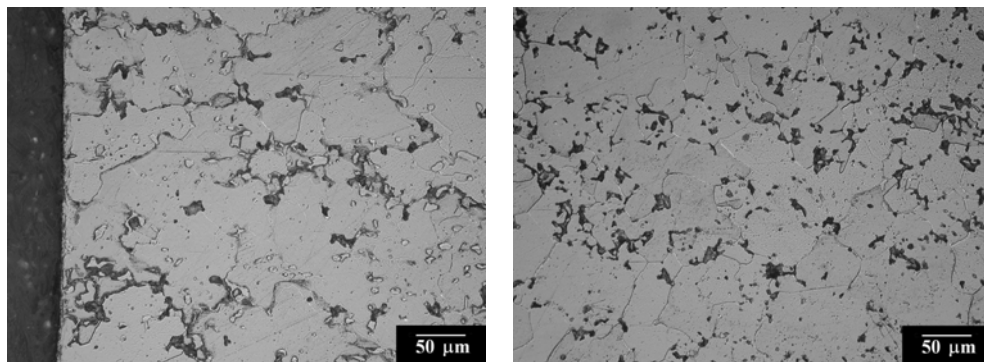


Fig.1. Micrographs of the parts of the cross section of sample with the low total Cu content. Region (a) is near the surface of the sample where the Cu powder was originally deposited, region (b) is near the opposite surface of the sample. For this sample only the part of the sample near surface with original Cu deposition contains pores filled with Cu (a), while the opposite region of the sample remained Cu-free (b).

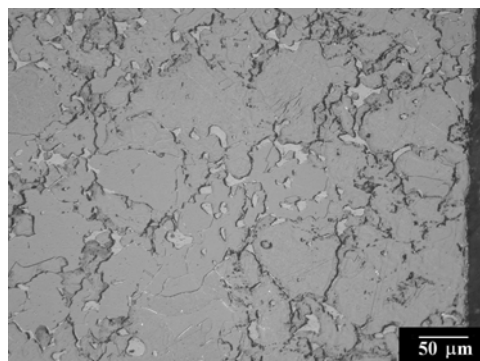
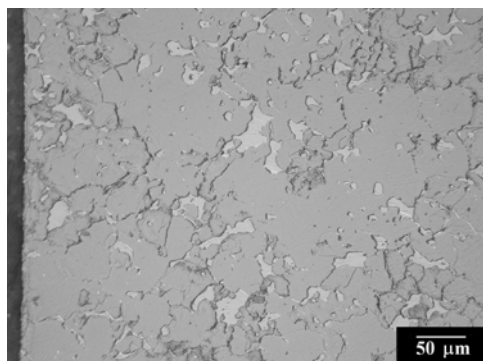


Fig.2. Micrographs of the parts of the cross section of sample with the high total Cu content. Region (a) is near the surface of the sample where the Cu powder was originally deposited, region (b) is near the opposite surface of the sample. For this sample the pores filled with Cu was distributed across the sample more or less regularly.

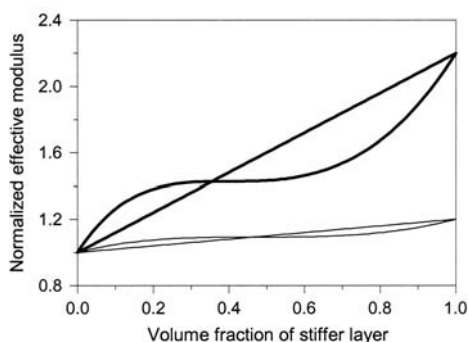


Fig.3. Theoretical effective flexural modulus of a model two-layer bar as a function of the volume fraction of a stiffer layer. Straight lines are for E_{\parallel}^{fl} , waved ones are for E_{\perp}^{fl} . Corresponding ratio of Young's moduli of the two layers is 1.2 (thin lines) and 2.2 (thick lines).

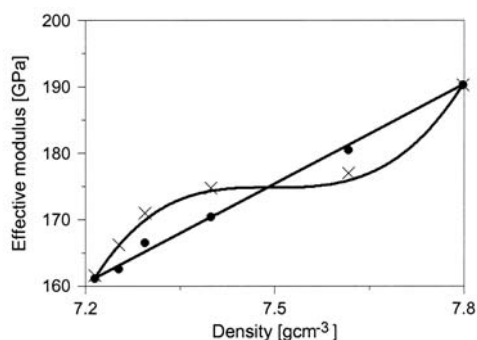


Fig.4. Effective flexural modulus as a function of density of the sample. Crosses represent experimental values of E_{\perp}^{fl} , circles those of E_{\parallel}^{fl} . Solid lines are theoretical curves calculated for a two-layer bar with proper values of Young's modulus of particular layers.

Since investigated specimens were not homogeneous, the modulus measured by means of dynamic resonant method was an effective modulus and, as mentioned, the differences in values obtained parallel and perpendicular to the layers were expected. In fact it turned out that the "parallel" and "perpendicular" values of effective flexural modulus were usually different, and the density of sample determined which one of the two values was higher (Fig.4).

The density of samples increased due to increasing content of Cu, as the Cu filled the pores in the original structure. On the other hand, as demonstrated above by metallographic methods, the increasing Cu content increases the volume fraction (relative thickness) of the Cu-enriched layer. So, the increment in density of sample is connected with the increment in volume fraction of Cu-enriched layer and vice versa. Consequently,

assuming that the Young's modulus of Cu-enriched layer is constant independent of the total Cu content, the relation between "transversal" and "longitudinal" moduli is determined by the relative thickness of particular layers.

Besides the experimental data, Figure 4 also presents the theoretical curves calculated by means of eq. (3) and (4). Experimental value of Young's modulus for a Cu-free sample ($\nu_2=0$) was used as E_1 and the experimental value of the Young's modulus for entirely Cu-saturated sample ($\nu_2=1$) was used as E_2 in theoretical calculations. There is a satisfactory agreement between experimental and theoretical values, despite the fact that the sintered experimental samples can resemble the model two-layer rods (with constant cross section, constant thickness of layers, constant material properties of layers along the bar, material properties independent of layer thickness, etc.) always only approximately.

This agreement indicates that the two-layer bar is a good approximation for samples under consideration. That is, the total Cu-content determines only the thickness of Cu-enriched nearly planar layer, but the Young's modulus of material within this layer is constant independent of the total Cu-content. The stiffness of Cu-enriched layer is higher than that of the pure material, so in this sense the infiltration with Cu improved the properties of sintered iron.

CONCLUSIONS

The samples made of sintered iron infiltrated with Cu were investigated both in experimental and theoretical ways. Rectangular bar – shaped samples were prepared from iron and copper powders by means of powder metallurgy technology. The specimens possessed a "two-layer" structure consisting of a region with a higher Cu concentration and a layer without copper. Flexural module determined by means of flexural vibration parallel to quasilayers were different from those determined by means of vibrations perpendicular to quasilayers (Fig. 4). This effect of a layer with higher stiffness on the effective flexural modulus was demonstrated also theoretically by calculating the relevant module for model bars simulating the real specimens. Comparison of experimental and theoretical results confirmed that the two-layer bar is a good approximation and consequently that the variations in measured values of the "parallel" and "perpendicular" flexural modulus can be due to an increasing volume fraction of the stiffer (Cu-rich) layer of a two-layer sample. So, the infiltration with Cu actually led to the higher stiffness of Cu-enriched sintered iron.

Acknowledgements

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REFERENCES

- [1] Rosso, M., Morandi, O. In: Proc. of the 1998 PM World Congress. Vol.3. Granada, 1998, p. 435
- [2] Rosso, M., Rossetto, M., Goglio, L., Radici, F. In: Proc. Of the International Conference, DF PM'99. Vol. 1. Piešťany, 1999, p. 233
- [3] Spinner, S., Tefft, W.E.: Proc., Am. Soc. Testing Mats., vol. 61, 1961, p. 1221
- [4] Kupková, M., Kupka, M.: Kovove Mater., vol. 37, 1999, p. 96
- [5] Kupková, M., Dudrová, E., Kabátová, M., Kupka, M., Danninger, H., Weiss, B., Melišová, D.: J. Mater. Sci., vol. 34, 1999, p. 3647