Presented and submitted to 1992 Powder Metallurgy World Congress, June 21-26, San Francisco, CA

RESONANT FREQUENCY MEASUREMENTS FOR THE DETERMINATION OF ELASTIC PROPERTIES OF POWDER METALLURGY COMPONENTS

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ABSTRACT

The resonant frequency technique has proven to be valuable tool for measuring, nondestructively, the elastic properties of powder metallurgy materials. This paper reports the results of a study on the use of resonant frequency techniques to determine elastic moduli of a wide range of pressed and sintered P/M materials. Resonant frequency techniques that were utilized included sine wave excitation, random signal excitation and impulse excitation. Results show good agreement between the elastic moduli determined dynamically and those obtained from mechanical testing (as published in MPIF Standard 35). The variation of elastic moduli with density is also presented. Also, an effort has been made to evaluate the accuracy of frequency measurements and the calculated elastic moduli for various testing techniques. These results suggest the use of nondestructive resonant frequency techniques as an alternative tool to monitor elastic properties of P/M materials.

INTRODUCTION

In the design of powder metallurgy (P/M) components, use of reliable elastic property values is critical for engineering analysis. Recent advances in the use of computer techniques to model manufacturing processes require prior knowledge of these properties. Nondestructive resonant frequency testing techniques hold considerable promise in the evaluation of these properties [1-3]. While the determination of elastic properties by conventional mechanical tensile testing is time consuming, costly and subject to interpretation for non-linear moduli, resonant frequency techniques provide rapid and consistent measurement results. Nevertheless, the measurement results should be reliable and have to be compared with those obtained from mechanical testing. Such considerations determine whether a resonant frequency method can be a proper substitute for the mechanical tensile testing. This paper focuses on the evaluation of using these nondestructive techniques to determine elastic properties of P/M materials.

It is generally accepted that the Young's modulus increases as the density of P/M material increases [1-2,4]. However, little is known about the effect of the density on other elastic properties which are also critical for P/M engineering design. This study examines the variations of shear modulus and Poisson's ratio for P/M materials subjected to various processing conditions. Error analysis on the measurement results is also performed.

BACKGROUND

The representative formulae used for calculating Young's modulus, shear modulus and Poisson's ratio for a rectangular bar were given by Spinner and Tefft [3] as follows:

$$E = 0.9465 \cdot \frac{K_1 \cdot f_f^{2} \cdot L^4 \cdot \rho}{t^2} \tag{1}$$

$$G = 4 \cdot f_t^2 \cdot L^2 \rho \cdot K_2 \tag{2}$$

and $$\mu = \frac{E}{2G} - 1 \tag{3}$$

where E is Youngs' modulus, G is shear modulus, μ is Poisson's ratio, L is the length of the specimen, t is the thickness of the specimen, w is the width of the specimen, ρ is density, f_f is the fundamental flexural resonant frequency, f_t is the fundamental torsional resonant frequency. K_1 is the correction factor for the fundamental flexural mode to account for finite length, thickness of specimen, and Poisson's ratio. K_2 is the shape factor for the fundamental torsional mode and depends on specimen thickness and width. K_1 and K_2 are given as follows [3,5,7]:

$$K_1 = 1 + 6.585 \cdot (1 + 0.0752\mu + 2.173\mu^2) \cdot (t/L)^2 - 0.868 \cdot (t/L)^4 - [\frac{8.340 \cdot (1 + 0.2023\mu + 2.173\mu^2) \cdot (t/L)^4}{1.000 + 6.338 \cdot (1 + 0.1408\mu + 1.536\mu^2) \cdot (t/L)^2}] \tag{4}$$

$$K_2 = [\frac{B}{1 + A}] \tag{5}$$

where $$A = [\frac{0.5062 - 0.8776 \cdot (w/t) + 0.3504 \cdot (w/t)^2 - 0.0078 \cdot (w/t)^3}{12.03 \cdot (w/t) + 9.892 \cdot (w/t)^2}] \tag{6}$$

and $$B = [\frac{w/t + t/w}{4 \cdot (t/w) - 2.52 \cdot (t/w)^2 + 0.21 \cdot (t/w)^6}] \tag{7}$$

Accuracy of the resonant frequency measurements is vital for modulus calculations. The elastic moduli mentioned above are functions of several independent variables. An error propagation analysis of these equations can be performed by taking the total differential. The fractional error of the measured E value is related to the fractional errors of the other variables through the following expression:

$$(\frac{\Delta E}{E}) = 4\,(\frac{\Delta L}{L}) - 2(\frac{\Delta t}{t}) + 2(\frac{\Delta f_f}{f}) + (\frac{\Delta \rho}{\rho}) \tag{8}$$

Similarly, an expression for the fractional error in the shear modulus G can be obtained as:

$$\left(\frac{\Delta G}{G}\right) = 2\left(\frac{\Delta L}{L}\right) + 2\left(\frac{\Delta f_t}{f_t}\right) + \left(\frac{\Delta \rho}{\rho}\right) \qquad (9)$$

and $$\left(\frac{\Delta \mu}{\mu}\right) = \left(\frac{\Delta E}{E}\right) - \left(\frac{\Delta G}{G}\right) \qquad (10)$$

EXPERIMENTAL INVESTIGATION

1. Test Samples

The test specimens were produced under another program to measure a broad range of mechanical and physical properties [6]. The test specimens are representative of commercial practice as opposed to samples made under laboratory conditions. The pressing is done in production presses and the sintering in production furnaces. The test samples were sintered Iron-Nickel (Fe-Ni) and Iron-Copper (Fe-Cu) P/M alloys, nominal densities varying from 6.27 to 7.41 g/cm^3. The samples with density less than 6.5 g/cm^3 were compacted from sponge iron powders, the balance from atomized powder. The samples utilized for the sine wave and random signal excitation techniques were thin bars of dimensions 2.3 x 10 x 75 mm . Thicker bars (10 x 10 x 75 mm) were better suited for the impulse excitation technique. Densities were measured after sintering using the oil-impregnation technique. Table 1 and 2 list the density, chemical composition of various Fe-Ni and Fe-Cu specimens.

2.Testing Techniques

The following resonant frequency testing techniques were utilized for the determination of flexural and torsional resonant frequencies.

Sine Wave Excitation [7,8]: The free-free beam resonant frequency method was utilized to measure the fundamental flexural and torsional resonant frequencies of the specimens. ASTM Standard C1198 [7] was followed to evaluate the dynamic Young's modulus, shear modulus and Poisson's ratio. The specimen was suspended by threads and set to resonate by generating sinusoidal waves of a specific frequency using a frequency generator (Figure 1). Two phono-cartridges were attached to the threads to transmit and receive the vibration motion through the specimen. The frequency of a specific resonant mode can be determined on the oscilloscope screen by analyzing the Lissajou figures [7]. (The Lissajou figure is the combined trace of the input and output signals, acting mutually perpendicular to each other.)

Random Signal Excitation : This approach is similar to the first one except the excitation method is different. Instead of using specific frequency sine waves, random signal excitation was used to set the specimen in resonance. All the frequency modes were generated in a short period of time using a white noise generator. The transmitter and receiver phono-cartridges were directly coupled to the specimen surfaces. Various resonant frequency modes were obtained and recorded in the computer. Through the use of Fast Fourier Transformation (FFT) spectrum analysis, the overall frequency modes were identified. The schematic diagram of the experimental set-up is shown in Figure 2.

Impulse Excitation [9,10]: For this particular test method, the specimen was set to resonate by applying a light tap which induces a mechanical impulse to the surface of the specimen. A small piezoelectric probe was located beneath the specimen to pick up the transient vibrations of the bar. Subsequent FFT analysis was conducted to identify the fundamental

Table 1 Densities, chemical compositions of various Iron-Nickel specimens

Iron-Nickel MPIF Std.35	Alloy	Density g/ccm	Composition		
			% Nickel	% Carbon	%MnS
FN-0200-20	N0A	6.71	2.05	0.03	
FN-0200-25	N0B	7.41	2.21	0.02	
FN-0205-25	N5A	6.98	1.99	0.52	
	N5B	7.11	1.99	0.52	
FN-0205-30	N5C	7.23	2.46	0.50	
FN-0205-35	N5D	7.46	2.11	0.49	
FN-0208-35	N8A	6.89	2.28	0.80	
	N8B	7.05	2.23	0.81	
FN-0208-40	N8C	7.11	2.17	0.83	
	N8E	7.41	2.27	0.84	
FN-0405-25	N45A	6.57	4.23	0.52	
	N45B	6.73	4.37	0.52	
FN-0405-35	N45D	7.02	4.18	0.52	
FN-0405-45	N45E	7.46	4.38	0.50	
	N48A	6.94	4.23	0.80	
	N48B	7.12	4.37	0.82	

Table 2 Densities, chemical compositions of various Iron-Copper specimens

Iron-Copper MPIF Std.35	Alloy	Density g/ccm	Composition		
			% Copper	% Carbon	%MnS
FC-0205-35	C25A*	6.35	1.83	0.46	
	C25B	6.47	1.75	0.53	
FC-0205-40	C25C	6.63	1.75	0.52	
	C25CR	6.65	1.75	0.55	
	C25D	6.76	1.75	0.52	
FC-0205-40	C28A*	6.27	1.91	0.64	
	C28B*	6.40	1.91	0.64	
	C28D	6.84	2.09	0.77	
FC-0508-50	C58A*	6.28	4.77	0.69	
FC-0508-60	C58B	6.75	4.71	0.75	
	C5A5*	6.23	2.00	0.46	0.46
	C5B5	6.62	2.02	0.54	0.46
	C5C5	6.94	2.02	0.51	0.46
	C8A8*	6.27	1.86	0.77	0.81
	C8A5*	6.28	1.85	0.75	0.48
	C8B3	6.69	1.94	0.79	0.29
	C8B8	6.70	2.07	0.75	0.67
	C8B5	6.71	1.97	0.77	0.52

* Sponge Iron Powder

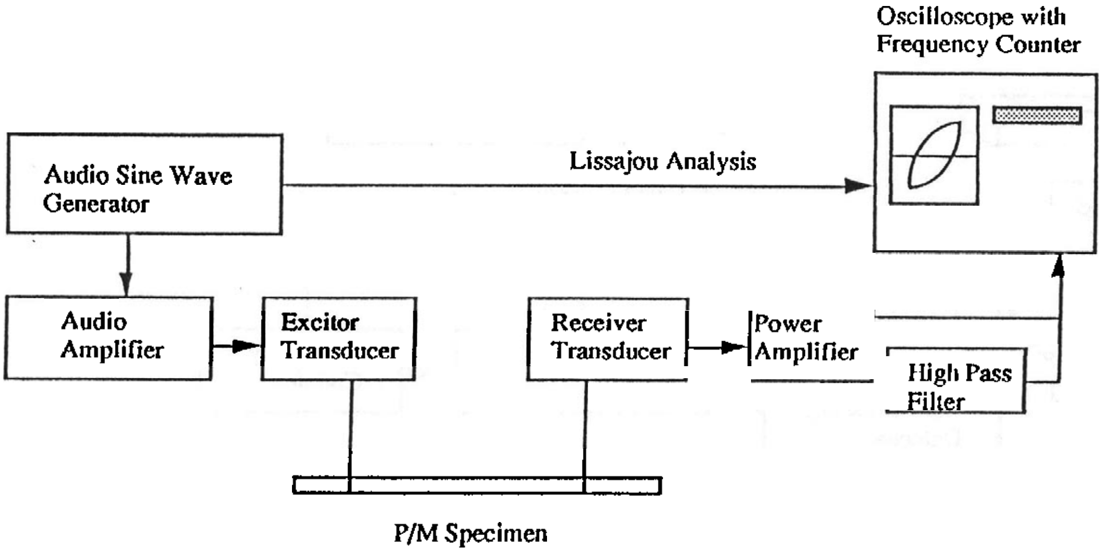

Figure 1 Schematic diagram of the experimental set-up for the free-free beam sine wave excitation resonant frequency testing.

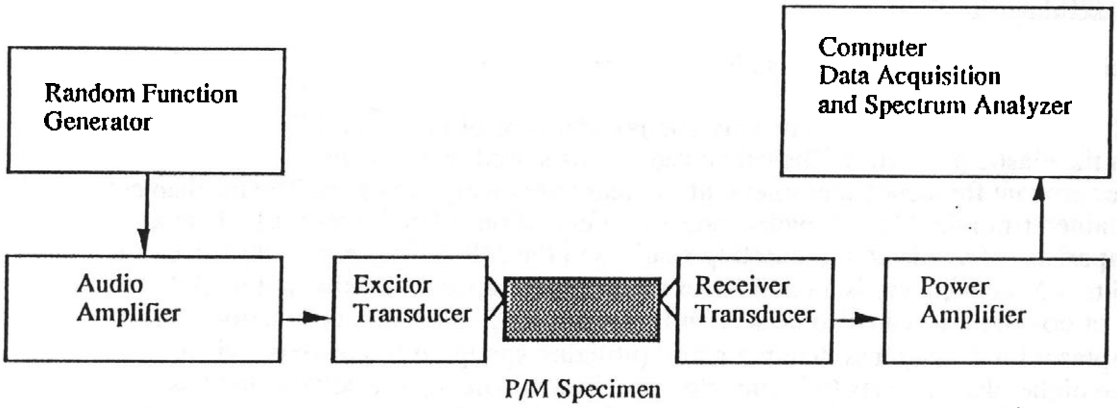

Figure 2 Schematic diagram of the experimental set-up for the random signal excitation resonant frequency testing.

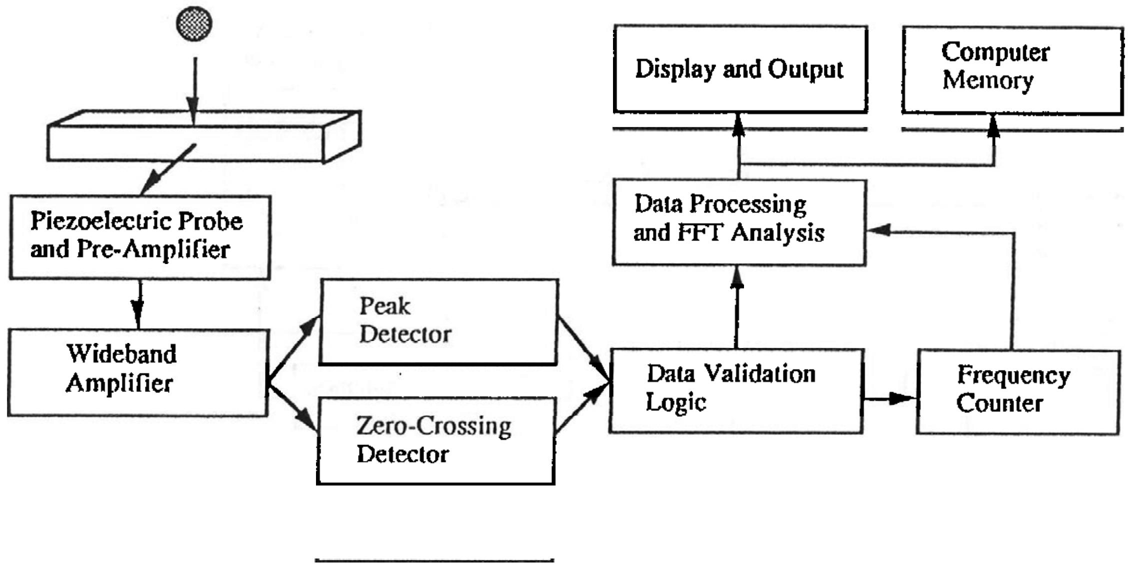

Figure 3 Schematic diagram of the instrumentation used for the impulse excitation resonant frequency testing.

resonant frequency. Torsional frequency was acquired through tapping on the corner of the diagonally opposite surface. Figure 3 shows the schematic diagram of the instrumentation used for the impulse excitation method.

RESULTS AND DISCUSSIONS

1. Effect of Density and Powder Type on Elastic Properties

Figures 4 and 5 show the effect of density and powder type of Fe-Cu and Fe-Ni metal powder alloys on the elastic properties. The calculated Young's modulus and shear modulus obtained from the resonant frequency measurements increase as density increases. The mechanical testing values obtained from the Metal Powder Industries Federation (MPIF) Standard 35 are also presented. A comparison of nondestructive testing results and the MPIF data reveals that, over the density range 6.5 to 7.5 g/cm^3, there is a good linear relationship between density and modulus value. The effect of powder type can also be seen in Figures 4 and 5. Different correlations were observed for samples with density less than 6.5 g/cm^3 (utilizing sponge iron powders) when compared with the higher density ones (utilizing atomized iron powders). We believe that this effect is caused by differences in the structural behavior of the sintered compact. It is commented that the structural effect on the elastic property determination due to change in powder type needs to be understood. Figure 6 shows the distribution of Poisson's ratio as a function of density derived from both resonant frequency and mechanical testing results (MPIF). In this density range, no specific correlation between density and Poisson's ratio was observed for these alloys.

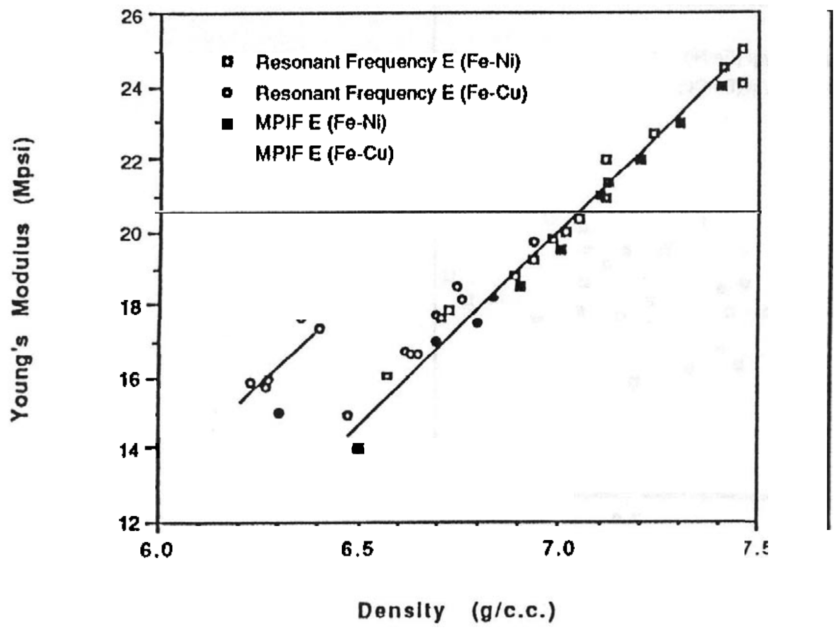

Figure 4 Young's modulus, predicted by the resonant frequency technique and measured by MPIF, plotted against density for various Fe-Cu and Fe-Ni materials.

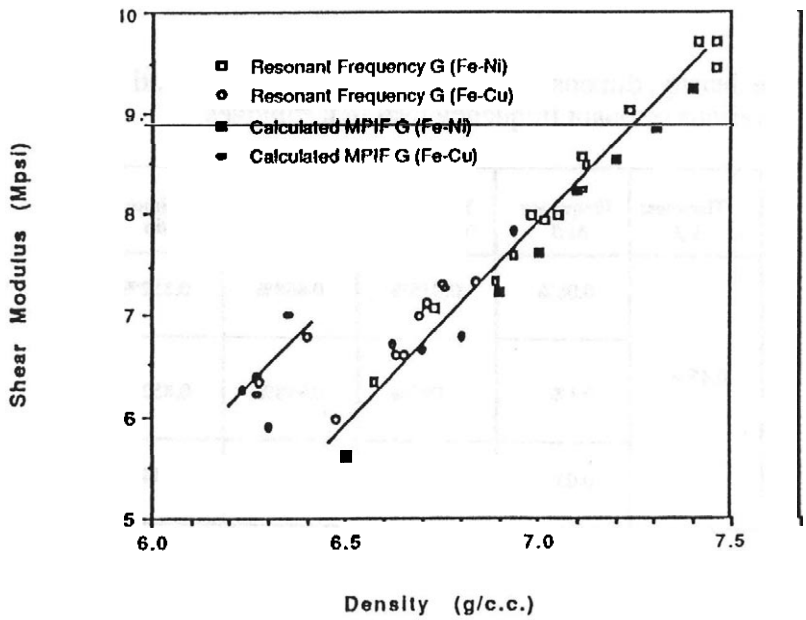

Figure 5 Shear modulus, predicted by the resonant frequency technique and calculated from MPIF Standard 35, plotted against density for various Fe-Cu and Fe-Ni materials.

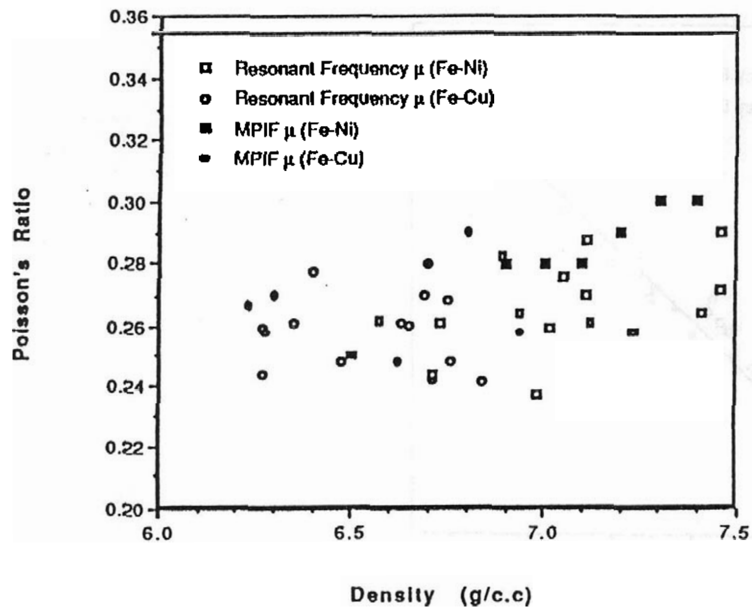

Figure 6 Poisson's Ratio, predicted by the resonant frequency technique and measured by MPIF, plotted against density for various Fe-Cu and Fe-Ni materials.

Table 3 Percentage errors in the density, dimension, frequency measurements and the calculated moduli for various resonant frequency testing techniques

Method \ Percentage Error	Density $\Delta\rho/\rho$	Length $\Delta L/L$	Thickness $\Delta t/t$	Frequency $\Delta f/f$	Young's Modulus	Shear Modulus	Poisson's Ratio
Sine Wave Excitation	0.7%	0.024%	0.45%	0.06%	0.016%	0.868%	0.852%
Random Signal Excitation				0.1%	0.096%	0.948%	0.852%
Impulse Excitation				0.05%	0.004%	0.848%	0.844%

2. Error Analysis

It can be seen that the error in modulus value calculated from resonant frequency measurement depends on variables including density (ρ), length (L), thickness (t), frequency (f) measurements, and the applied technique. Table 3 lists the fractional errors in these measurements for the various resonant frequency test methods, and the corresponding errors of calculated elastic moduli.

Due to the inherent nature of powder metal compacts, fractional errors in the density and thickness (dimension in the pressing direction) measurements seem to outweigh the overall errors in the measured resonant frequency. Since it is difficult to achieve density accuracy better than 0.7% in powder metals, fractional error in density measurement dominates the accuracy of calculated moduli. Relatively large fractional error in the thickness measurement also contribute significantly to the overall error calculation. It is believed that nonuniform powder fill in the pressing operation leads to non-parallel top and bottom surfaces of the pressed specimen which causes this error. Figures 7 and 8 compare the calculated elastic moduli using the three resonant frequency techniques which are in good agreement with each other. The root mean square (rms) deviation of the calculated moduli obtained from three resonant frequency excitation methods is less than 2.3%. The rms deviation of the calculated moduli measured by resonant frequency technique as compared with the MPIF mechanical testing values is approximately 3% (refer to Figures 4 and 5). It appears that the determination of dynamic elastic moduli using various resonant frequency techniques are a proper substitute for the conventional tensile testing. However, further mechanical testing will be conducted on the same specimens to verify the conclusion.

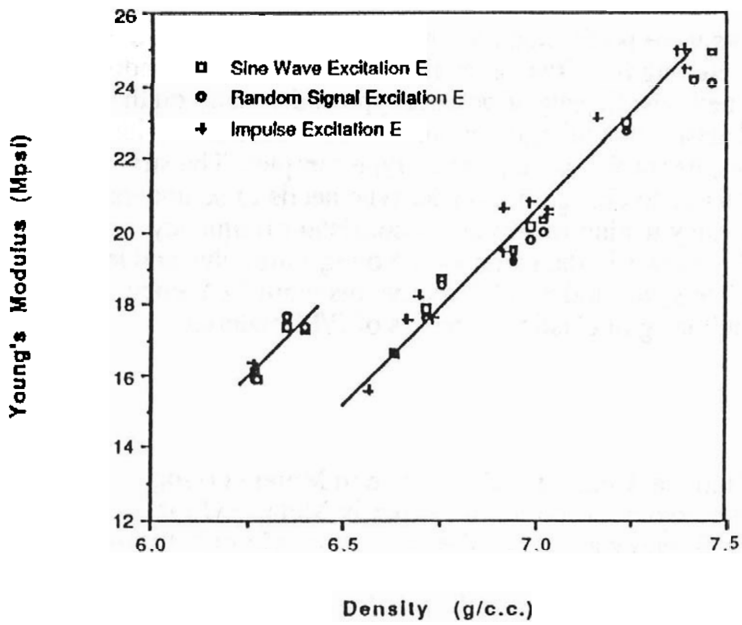

Figure 7 Young's modulus, predicted by three resonant frequency techniques, plotted against density for various Fe-Cu and Fe-Ni materials.

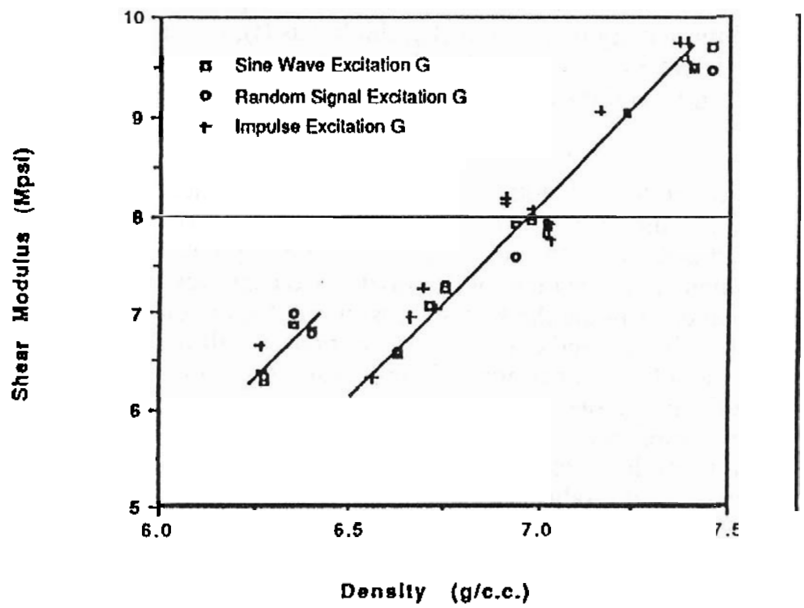

Figure 8 Shear modulus, predicted by three resonant frequency techniques, plotted against density for various Fe-Cu and Fe-Ni materials.

SUMMARY

A series of resonant frequency tests were performed on a wide range of Fe-Cu and Fe-Ni P/M materials using various techniques including free-free beam sine wave excitation, random signal excitation, and impulse excitation methods. Effects of powder type and density on the elastic properties were evaluated. The calculated elastic moduli agree within 3% rms deviation with the mechanical testing (MPIF Standard 35) results for the same powder type samples. The structural effect on the elastic property determination due to change in powder type needs to be understood. Further analysis on various resonant frequency testing results show consistent frequency measurements which result in less than 0.1% error in the calculated Young's modulus and less than 1% in the calculated shear modulus. Thus, we find nondestructive resonant frequency techniques can be a potent tools in the monitoring of elastic properties of P/M materials.

ACKNOWLEDGMENTS

This work was conducted by the National Center for Excellence in Metalworking Technology, operated by Concurrent Technologies Corporation (formerly Metalworking Technology, Inc.), under contract to the U.S. Navy as part of the U.S. Navy Manufacturing Technology Program. We would like to acknowledge Mr. M. Aesoph of CTC for the free-free beam resonant frequency measurements, Dr. B.R. Tittmann of Pennsylvania State University for random signal excitation measurements and Mr. A.V. Leuven of J.W. Lemmens, Inc., for impulse excitation measurements. Useful discussions with Dr. B.R. Tittmann, Mr. R.R. Phillips of Engineered Pressed Materials, Inc., Dr. Y.T. Chen of Pitney Bowes, Inc. and Mr. H.I. Sanderow of the Center for Powder Metallurgy Technology (CPMT) are also acknowledged.

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10. GrindoSonic is a trademark of J.W. Lemmons-Electronika, N. V. Leuven, Belgium.

APPENDIX A:

Table A.1 Calculated Young's moduli measured by three resonant frequency methods for various Iron-Nickel specimens.

Iron-Nickel MPIF Std.35	Alloy	Density g/ccm	Sine Wave Excitation E	Random Signal Excitation E	Impulse Excitation E
FN-0200-20	N0A	6.71	17.884	17.616	
FN-0200-25	N0B	7.41	24.203	24.138	
FN-0205-25	N5A	6.98	20.126	19.741	
		6.91			19.420
	N5B	7.11	21.995	22.036	
FN-0205-30	N5C	7.23	22.967	22.743	
FN-0205-35	N5D	7.46	24.934	25.012	
		7.37			25.000
FN-0208-35	N8A	6.89	19.838	18.803	
		7.03			20.00
	N8B	7.05	20.657	20.403	
		6.91			20.660
FN-0208-40	N8C	7.11	21.290	20.931	
	N8E	7.41	24.842	24.505	
		7.39			25.050
FN-0405-25	N45A	6.57	16.072	16.023	
		6.56			15.620
	N45B	6.73	17.652	17.828	
		6.73			17.60
FN-0405-35	N45D	7.02	20.308	19.990	
		7.03			20.470
FN-0405-45	N45E	7.46	24.114	24.062	
		7.39			24.50
	N48A	6.94	19.472	19.182	
	N48B	7.12	21.559	21.371	

Table A.2 Calculated Young's moduli measured by three resonant frequency methods for various Iron-Copper specimens.

Iron-Copper MPIF Std.35	Alloy	Density g/ccm	Sine Wave Excitation E	Random Signal Excitation E	Impulse Excitation E
FC-0205-35	C25A*	6.35	17.402	17.653	
	C25B	6.47	14.934	14.945	
FC-0205-40	C25C	6.63	16.637	16.682	
	C25CR	6.65	16.725	16.651	
	C25D	6.76	18.263	18.150	
FC-0205-40	C28A*	6.27	16.158	15.882	
	C28B*	6.40	17.306	17.323	
	C28D	6.84	18.421	18.203	
FC-0508-50	C58A*	6.28	15.934	15.963	
FC-0508-60	C58B	6.75	15.934	18.521	
	C5A5*	6.23	16.007	15.880	
		6.26			16.380
	C5B5	6.62	16.744	16.733	
		6.66			17.540
	C5C5	6.94	19.989	19.720	
		6.98			20.840
	C8A8*	6.27	16.010	15.963	
	C8A5*	6.28	16.334	16.086	
		6.26			16.38
	C8B3	6.69	17.842	17.718	
	C8B8	6.70	17.606	17.596	
	C8B5	6.71	17.931	17.706	
		6.69			18.250

* Sponge Iron Powder

Table A.3 Calculated shear moduli measured by three resonant frequency methods for various Iron-Nickel specimens.

Iron-Nickel MPIF Std.35	Alloy	Density g/ccm	Sine Wave Excitation G	Random Signal Excitation G	Impulse Excitation G
FN-0200-20	N0A	6.71	7.092	7.083	
FN-0200-25	N0B	7.41	9.476	9.494	
FN-0205-25	N5A	6.98	7.947	7.982	
		6.91			8.20
	N5B	7.11	8.559	8.557	
FN-0205-30	N5C	7.23	9.036	9.039	
FN-0205-35	N5D	7.46	9.697	9.694	
		7.37			9.73
FN-0208-35	N8A	6.89	7.785	7.330	
		7.03			7.924
	N8B	7.05	8.023	7.998	
		6.91			8.20
FN-0208-40	N8C	7.11	8.240	8.242	
	N8E	7.41	9.718	9.694	
		7.39			9.550
FN-0405-25	N45A	6.57	6.377	6.349	
		6.56			6.320
	N45B	6.73	6.992	7.070	
		6.73			7.050
FN-0405-35	N45D	7.02	7.832	7.940	
		7.03			8.081
FN-0405-45	N45E	7.46	9.475	9.456	
		7.39			9.730
	N48A	6.94	7.918	7.589	
	N48B	7.12	8.375	8.474	

Table A.4 Calculated shear moduli measured by three resonant frequency methods for various Iron-Copper specimens.

Iron-Copper MPIF Std.35	Alloy	Density g/ccm	Sine Wave Excitation G	Random Signal Excitation G	Impulse Excitation G
FC-0205-35	C25A*	6.35	6.895	7.000	
	C25B	6.47	5.965	5.988	
FC-0205-40	C25C	6.63	6.562	6.615	
	C25CR	6.65	6.572	6.607	
	C25D	6.76	7.197	7.27	
FC-0205-40	C28A*	6.27	6.387	6.385	
	C28B*	6.40	6.823	6.778	
	C28D	6.84	7.241	7.336	
FC-0508-50	C58A*	6.28	6.276	6.344	
FC-0508-60	C58B	6.75	7.279	7.303	
	C5A5*	6.23	6.305	6.269	
		6.26			6.670
	C5B5	6.62	6.606	6.702	
		6.66			6.974
	C5C5	6.94	7.872	7.837	
		6.98			8.080
	C8A8*	6.27	6.306	6.232	
	C8A5*	6.28	6.411	6.448	
		6.26			6.470
	C8B3	6.69	6.983	6.978	
	C8B8	6.70	6.926	6.964	
	C8B5	6.71	7.036	7.130	
		6.69			7.27

* Sponge Iron Powder