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# Ultrasonic Ranking of Toughness of Tungsten Carbide

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Alex Vary and David R. Hull  
*Lewis Research Center*  
*Cleveland, Ohio*



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# ULTRASONIC RANKING OF TOUGHNESS OF TUNGSTEN CARBIDE

Alex Vary and David R. Hull

National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

## ABSTRACT

The feasibility of using ultrasonic attenuation measurements to rank tungsten carbide alloys according to their fracture toughness was demonstrated. Six samples of cobalt-cemented tungsten carbide (WC-Co) were examined. These varied in cobalt content from approximately 2 to 16 weight percent. The toughness generally increased with increasing cobalt content. Toughness was first determined by the Palmqvist and short rod fracture toughness tests. Subsequently, ultrasonic attenuation measurements were correlated with both these mechanical test methods. It was shown that there is a strong increase in ultrasonic attenuation corresponding to increased toughness of the WC-Co alloys. A correlation between attenuation and toughness exists for a wide range of ultrasonic frequencies. However, the best correlation for the WC-Co alloys occurs when the attenuation coefficient measured in the vicinity of 100 megahertz is compared with toughness as determined by the Palmqvist technique.

## 1. INTRODUCTION

This report examines the feasibility of ultrasonic assessment of the fracture toughness of cemented carbides. Specific attention is given to tungsten carbides cemented with cobalt.<sup>1</sup> Cemented carbides are primary materials used for metal cutting tools. They have supplanted high speed steels because of their superior properties. Therefore, the assessment and verification of their toughness, hardness, and other relevant properties merits attention. Particular attention has been given to measurement of the fracture toughness of cemented carbides with a view toward simplified measurement techniques.<sup>2</sup> The currently preferred technique is the "short rod" ASTM test for measuring plane strain fracture toughness.<sup>3</sup> Another measure of toughness can be

achieved by evaluating the indentation crack resistance using the "Palmqvist" test. Because of its comparative simplicity and relative ease of use the "Palmqvist" test is frequently used as an alternative to the short rod test.<sup>4</sup>

The purpose of this report is to indicate the viability of a nondestructive ultrasonic approach for assessing the toughness of cemented carbides. Empirical correlations between ultrasonic attenuation measurements and short rod and Palmqvist measurements will be presented. It will be shown that the ultrasonic approach promises to be a useful alternative to these currently-used methods.

Bruce R. Carpenter of Kenametal, Inc., Latrobe, Pennsylvania supplied the tungsten carbide samples and short rod and Palmqvist toughness test data.

## 2. EXPERIMENTAL FACTORS

### 2.1 THEORY

When used as cutting materials it is necessary for cemented carbides to exhibit high fracture toughness. Toughness, as measured by plane strain fracture toughness tests, is a material property governed by microstructure. It has been found in the case of cobalt-cemented tungsten carbides that toughness increases with increasing cobalt binder content.<sup>5</sup> This increase in toughness has been attributed to the ductility of the cobalt phase. A model that describes the interrelation of cemented carbide microstructure and toughness has been verified.<sup>6</sup> According to the model the mean free path for dislocation movements in the cobalt phase and the contiguity of the carbide crystals govern toughness.

The previously-mentioned microstructural factors provide the basis for ultrasonic assessment of fracture toughness in cobalt-cemented tungsten carbide. Previous work has shown that polycrystalline aggregates will exhibit strong interrelations among microstructure, toughness, and ultrasonic attenuation.<sup>7,8</sup> These interrelations exist where attenuation measurements are made over ultrasonic frequencies in the Rayleigh scattering regime. This condition is satisfied if the wavelength is always much greater than the mean size of the scatterer. Therefore, we expect to see a correlation between toughness and ultrasonic attenuation if attenuation is measured over wavelengths that satisfy the Rayleigh scattering criterion for the tungsten carbide - cobalt microstructure.

### 2.2 MATERIAL SAMPLES

Six samples of tungsten carbide were examined in this study. The samples had a range of carbide crystal sizes and cobalt binder content. From sample to sample the mean

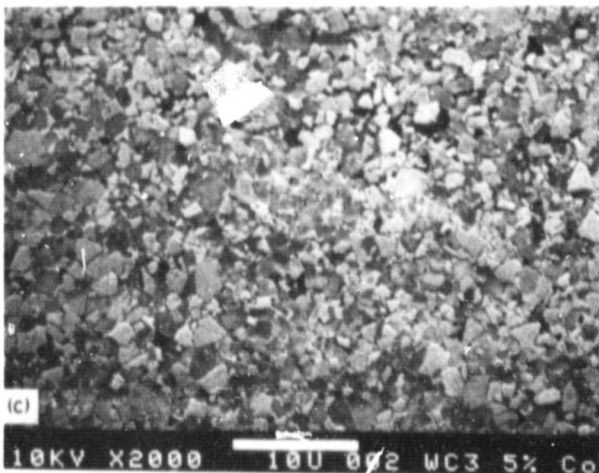
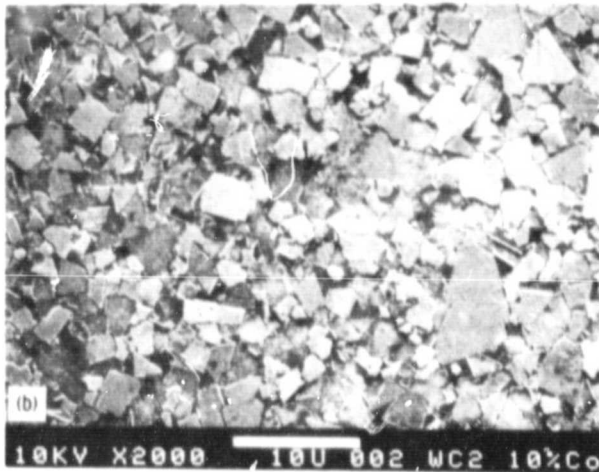
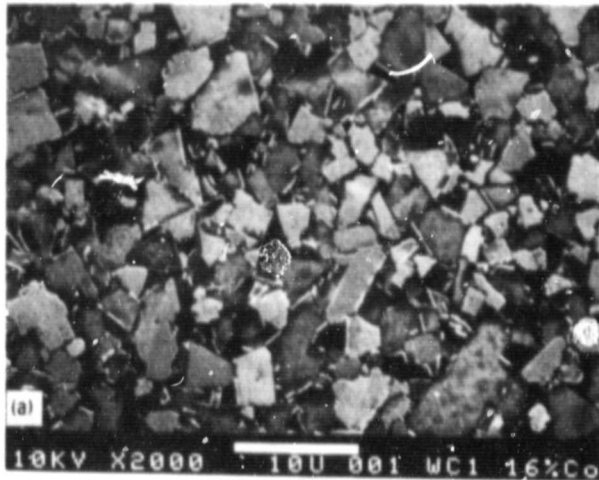
crystal size ranged from less than 1 to approximately 3 micrometers. Representative photomicrographs of this range in carbide crystal size appear in figure 1. Corresponding variations in the cobalt binder content are also apparent in figure 1. As indicated in table I, the cobalt content varied from approximately 2 to 16 weight percent with the balance consisting of tungsten carbide plus some trace elements. Generally, toughness increases and density decreases with increasing cobalt binder content in cemented tungsten carbides.

The samples of tungsten carbide used in this study were taken from material specimens that had been previously tested by mechanical methods; short rod plane strain fracture toughness and Palmqvist test (see table I). Figure 2 shows the correlation between plane strain fracture toughness and Palmqvist measurements for the six material samples.

### 2.3 APPARATUS AND APPROACH

Each sample to be used for making ultrasonic measurements was cut and ground to a size of 2 by 2 by 0.28 centimeters. The opposing 2 centimeter square surfaces were flat, parallel, and metallographically polished. The 0.28 centimeter thickness was selected for convenience in making velocity and attenuation measurements on a uniform basis.

Ultrasonic measurements were made with a quartz-buffered broadband transducer having a center frequency of approximately 70 megahertz. The transducer was coupled to the surface of each sample with glycerine as the couplant. Measurements were made using the pulse-echo technique illustrated in figure 3. A number of velocity and attenuation measurements were made through each sample at various arbitrary locations over the polished 2 centimeter square surface. At each location two consecutive back-surface echoes were acquired, digitized, and processed to extract velocity and attenuation data. Essential aspects of the signal processing methodology are described in refer-



- (a) Sample A. 16% cobalt.
- (b) Sample B. 10% cobalt.
- (c) Sample C. 5% cobalt.

Figure 1. - Photomicrographs showing range of microstructure in cobalt-cemented tungsten carbide samples. Etchant was Murakami's reagent: 40 KFeCN<sub>4</sub> + 40 KOH + 100 H<sub>2</sub>O (boiling). White bar at bottom of photomicrographs is a 10 micrometer scale.

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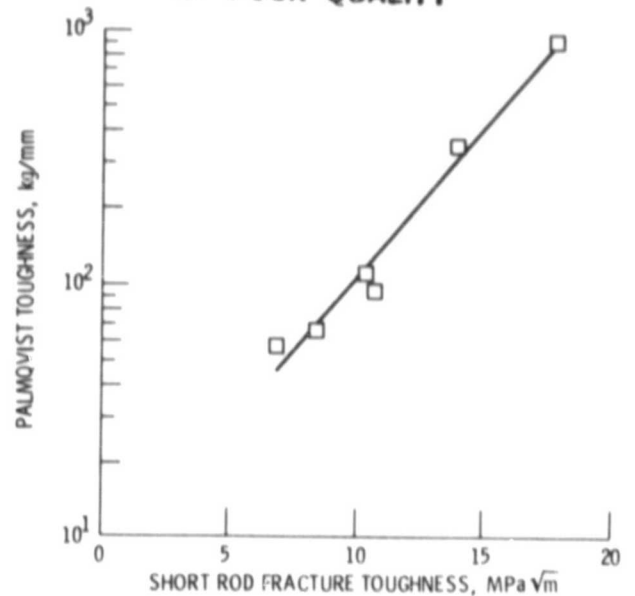


Figure 2. - Comparison of Palmqvist test measurements with short rod plane strain fracture toughness test measurements for cobalt cemented tungsten carbide samples (data taken from table I). Correlation coefficient is 0.987

ences 9 and 10.

The key ultrasonic variable was the attenuation coefficient which is a strong function of frequency and material microstructure. The attenuation coefficient was measured over the range from 20 to 120 megahertz, approximately. Because of insignificant dispersion effects velocity was essentially constant over this frequency range.

### 3. EXPERIMENTAL RESULTS

#### 3.1 ULTRASONIC PARAMETERS

To establish correlations between ultrasonic and fracture toughness measurements it is necessary to determine attenuation as a function of frequency over a sufficiently broad range of frequencies.<sup>10</sup> This was accomplished for each tungsten carbide sample by determining the attenuation parameters  $c$  and  $n$ . The attenuation coefficient  $\alpha$  as a function of ultrasonic frequency  $f$  was defined for each sample's microstructure by an equation of the form  $\alpha = cf^m$ . Figure 4 shows attenuation coefficient versus frequency for three of the

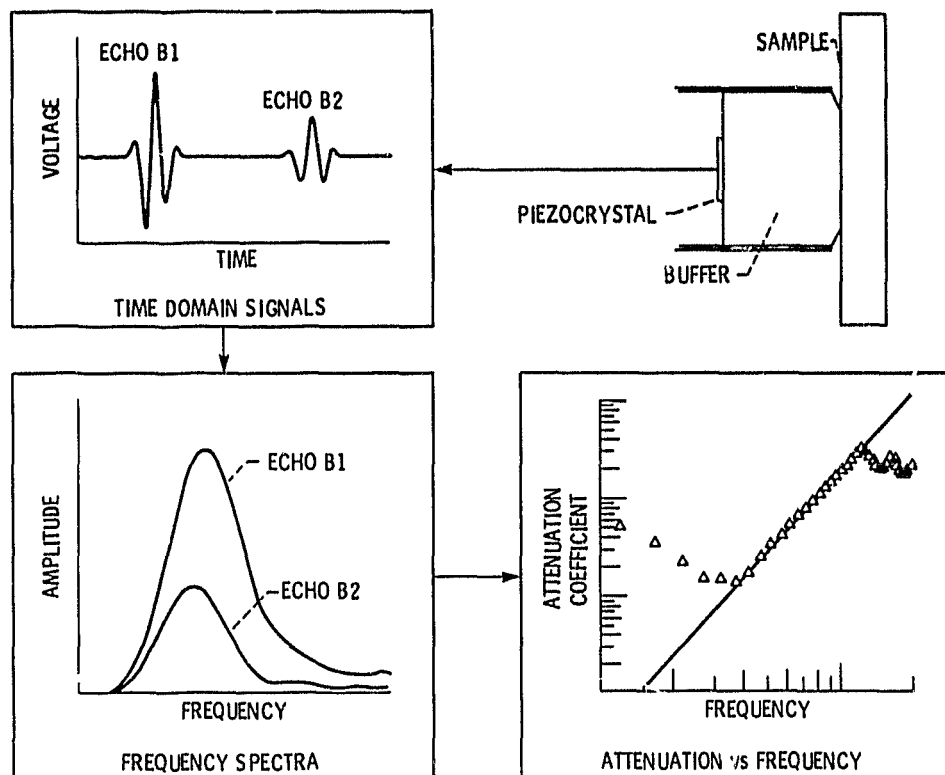


Figure 3. - Diagram showing steps in ultrasonic signal acquisition, digitization, processing, and analysis to determine velocity and attenuation properties of material samples. The procedure is computer automated and in general accordance with that described in ref. 9 and 10. The procedure involves digital Fourier transformation of back surface echoes B1 and B2. Frequency domain processing is then used to determine velocity and attenuation.

Table I. - Chemical, Mechanical, and Ultrasonic Properties of Tungsten Carbide Samples

Sample	Chemical Analysis, <sup>a</sup> weight percent Co	Density, gm/cc	Short Rod Toughness, <sup>b</sup> MPa $\sqrt{m}$	Palmqvist Toughness, <sup>c</sup> kg/mm	Knoop Hardness <sup>d</sup>	Velocity, <sup>e</sup> mm/ $\mu$ s	Attenuation Coefficient, <sup>f</sup> Np/cm	Attenuation Parameters <sup>g</sup>	
								(c) $\times(10)^6$	m
A	16.	13.9	17.75	909	1125	6.63	4.48	94.	2.34
B	10.	14.3	13.96	350	1304	6.76	1.74	18.	2.51
C	5.3	14.9	10.64	95	1718	6.87	0.356	0.727	2.84
D	6.4	15.0	8.50	66	1958	6.86	0.100	0.130	3.00
E	2.4	15.0	6.90	57	1959	6.81	0.080	0.092	3.53
F	6.8	12.8	10.40	110	1694	6.91	0.227	2.42	2.58

- Cobalt content measured via energy dispersive x-rays, balance is tungsten carbide with exception of sample F which also contained 15.7 weight percent Ta and 7.2 weight percent Ti.
- Short rod plain strain fracture toughness ( $K_{Ic}$ ) measurements per ref. 3.
- Palmqvist fracture toughness ranking per ref. 4.
- Knoop hardness by diamond indentation at 500 kg load.
- Velocity determined to accuracy of 0.1 percent at center frequency in 20-120 MHz range.
- Attenuation coefficient determined to estimated accuracy of  $\pm 10$  percent.
- Attenuation parameters are related to attenuation coefficient  $\alpha$  via  $\alpha = cf^m$ , ref. 10.

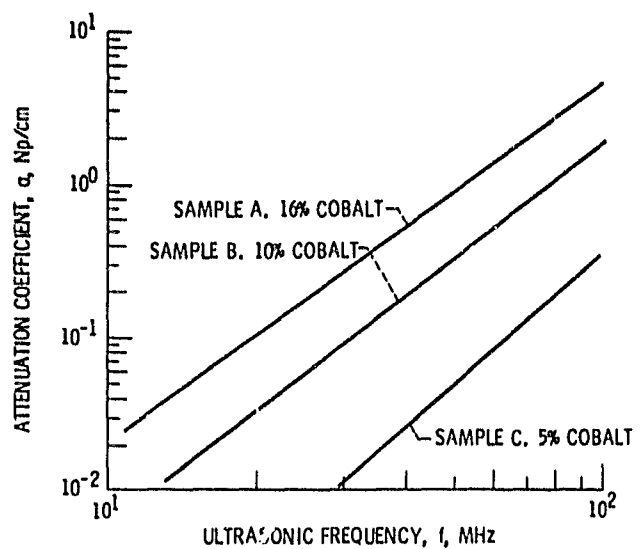


Figure 4. - Characteristic attenuation versus frequency curves for three cobalt-cemented tungsten carbide samples. Plots are based on attenuation parameters given in table I.

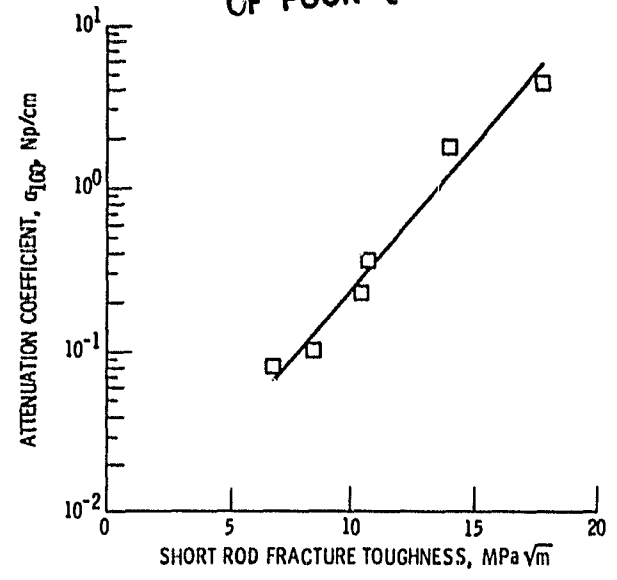


Figure 5. - Correlation of attenuation coefficient evaluated at 100 megahertz and short rod plane strain fracture toughness for cobalt-cemented tungsten carbide samples. Plot based on data from table I. Correlation coefficient is 0.969.

tungsten carbide samples. Ultrasonic parameters for each of the six samples appear in table I.

### 3.2 EMPIRICAL CORRELATIONS

Two correlations of interest for the purposes of this study are shown in figures 5 and 6. These are correlations between ultrasonic attenuation and fracture toughness as measured by the short rod method and between ultrasonic attenuation and fracture toughness as measured by the Palmqvist method. In both cases the correlation coefficient exceeded 0.97 provided that the attenuation coefficient was evaluated at a frequency of 100 megahertz or greater. The attenuation coefficient was calculated as  $\alpha = c(100)^m$  for each sample to produce the results shown in figures 5 and 6. Use of frequencies less than 100 megahertz in this equation gave correlation coefficients less than 0.97. Frequencies greater than 100 megahertz gave greater values for the correlation coefficient, approaching unity. However, use of frequencies much greater than 100 megahertz would require extrapolation beyond the bandwidth of the transducer and instrumentation.

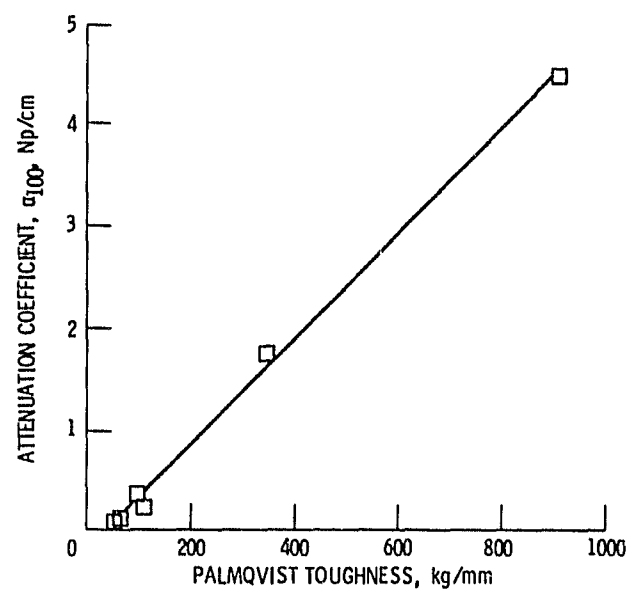


Figure 6. - Correlation of attenuation coefficient evaluated at 100 megahertz and Palmqvist toughness for cobalt-cemented tungsten carbide samples. Plot based on data from table I. Correlation coefficient is 0.994.

#### 4. DISCUSSION

##### 4.1 GENERAL CONSIDERATIONS

It was deemed sufficient for the purposes of this study to demonstrate that ultrasonic measurements can be used for ranking tungsten carbide samples according to fracture toughness. It became apparent that the ultrasonic approach can be an alternative to the short rod and Palmqvist test methods. However, the successful application of ultrasonic measurements demonstrated in this study raises a number of questions. The primary question is concerned with the exact nature of the interrelations among microstructure, fracture toughness, and ultrasonic factors. This and associated questions will be discussed in light of the findings presented herein.

A basis for the correlations in this study can be found by noting that the authors of references 6 and 11 demonstrated the influence of carbide crystal and cobalt binder dimensions on fracture toughness in cemented carbides. Although they may be somewhat fortuitous the empirical results of this study indicate that ultrasonic attenuation properties influence toughness as suggested in reference 10. It appears that, as a rule, the greater the attenuation the greater will be the toughness exhibited by the microstructure. Attenuation and toughness were direct functions of increasing cobalt content in those samples (A through E) that contained no additional carbides as in the case of sample F.

##### 4.2 RAYLEIGH CRITERION

A higher correlation coefficient (0.994 vs. 0.969) was realized between attenuation and Palmqvist measurements (figure 6) than between attenuation and short rod measurements (figure 5). This was true for all ultrasonic frequencies in the vicinity of 100 megahertz. However, the preliminary nature of the results given herein preclude making any judgement

concerning a preference for either the short rod or Palmqvist method.

At 100 megahertz the condition for Rayleigh scattering was satisfied since the wavelength substantially exceeded the size of the scatterers, i. e., the carbide crystals which ranged in size from less than 1 to about 3 micrometers, as noted previously. That is, the wavelength as defined by the ratio of velocity to frequency,  $v_\lambda/f$  was much greater than the mean crystal size.<sup>12</sup> Velocity data from table I and 100 megahertz for frequency give, typically,  $v_\lambda/f = 70 \gg 3$  micrometers. A similar finding regarding the satisfaction of the Rayleigh scattering criterion results from assuming that the cobalt binder regions in the microstructure also contribute to scatter attenuation.

It is true that frequencies considerably below 100 megahertz also satisfy the Rayleigh scattering criterion. At these lower frequencies the wavelengths were increasingly greater than the 70 micrometers indicated above. However, at lower frequencies diffraction effects become more pronounced. In this case attenuation will be a strong function of factors other than material microstructure, e. g., factors such as sample thickness and transducer (piezo-crystal) aperture.<sup>13</sup> This probably accounts for the lower correlation coefficients obtained when frequencies much less than 100 megahertz were used to calculate attenuation coefficients,  $\alpha$ , for comparison with toughness measurements.

##### 4.3 CRITICAL FACTOR ANALYSIS

In recently published works it was shown that ultrasonic attenuation and fracture toughness could be associated with specific microstructural feature.<sup>7,8</sup> Therefore, we expected to evaluate the attenuation coefficient,  $\alpha = cf^m$ , for each sample in terms of a frequency defined in terms of a critical microstructural dimension  $\delta_c$ , that is  $f = v_\lambda/\delta_c$ . An obvious choice for  $\delta_c$  is the tungsten carbide crystal



mean grain size. However, this and similar "obvious" choices based on mean microstructural dimensions failed to give the high correlation coefficients that were obtained simply by taking  $f = 100$  megahertz. As a practical matter this approach is quite acceptable since it requires no a priori knowledge of the microstructure. Nevertheless, it is worth examining the reasons why microstructural factors governing cemented carbide toughness evade ready analysis by ultrasonics.

Although the Rayleigh scattering criterion was met in the frequency range of the measurements the exponent on frequency (i. e.,  $m$  in table I) did not always agree with that predicted for Rayleigh scattering (2.3 to 3.5 vs 4).<sup>12</sup> This is not uncommon in the case of polycrystalline aggregates. A fourth power relation between attenuation coefficient and frequency occurs only rarely and in special cases.<sup>14</sup>

Some of the actual exponents found in this study are consistent with stochastic scattering where theory predicts a second power relation (i. e.,  $m = 2$ ). This suggests a mixture of Rayleigh and stochastic scattering to produce the exponents given table I. Stochastic scattering presumes that the ultrasonic wavelength is of the order of the mean dimension of the scatterer. However, there is no individual microstructural feature with the dimension needed to meet the criterion for stochastic scattering in the frequency and, hence, wavelength range used in this study.

If, as observed above, mean crystal size cannot be used to argue for stochastic scattering, then a larger-scale microstructural feature needs to be postulated. The authors of reference 11 have proposed a superstructure in cemented carbides that appears to meet this need. This superstructure consists of an essentially continuous carbide skeleton formed by junctions of contiguous carbide crystals. This model assumes long range continuity through direct carbide-carbide contacts. The carbide junctions assumed by the model seem to

be present in the photomicrographs of figure 1.

The authors of reference 6 inferred that both the contiguity of carbide crystals and volume fraction of the cobalt phase are pivotal in governing fracture toughness. According to their model plastic deformation occurs in the cobalt phase where dislocations pile up against carbide crystals causing their fracture. Reference 6 contains data showing that toughness is weakly dependent on carbide crystal size and strongly dependent on carbide contiguity and cobalt content. It is likely that ultrasonic attenuation depends on these same factors in cemented carbides. This suggests that attenuation parameters will be influenced by dislocation damping and hysteresis in the cobalt phase as well as by scattering effects due to the carbide structure. Similar conclusions also seem to apply to low carbon steels where there are parallels with cemented carbide microstructure.<sup>15</sup>

The above observations illustrate the complexities of attempting to establish a theoretical base for predicting attenuation in polycrystalline multiphase aggregates. Evidently there is no simple, readily identifiable microstructural factor that governs either fracture or ultrasonic properties of cemented carbides.

## 5. CONCLUSION

The feasibility of ultrasonically ranking cemented tungsten carbides according to fracture toughness was demonstrated. It was shown that ultrasonic attenuation measurements correlate with both short rod and Palmqvist measurements for determining toughness. The ultrasonic approach is a nondestructive alternative to these two mechanical, destructive methods. Generally, it was found that there is a strong increase in ultrasonic attenuation corresponding to increased toughness in cobalt-cemented tungsten carbides. The best correlation with toughness was found when the attenuation coefficient was measured in the vicinity of

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100 megahertz and compared with Palmqvist test measurements.

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