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**Development of Fracture Toughness
Measurement Capability by
Ultrasound**

By G. D. Swanson

Published June 1981

Final Report

Prepared for the United States Department of Energy
Under Contract Number DE-AC04-76-DP00613.

**Kansas City
Division**

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DEVELOPMENT OF FRACTURE TOUGHNESS MEASUREMENT
CAPABILITY BY ULTRASOUND

By G. D. Swanson

Published June 1981

Final Report
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A correlation was developed between ultrasonic wave propagation factors and fracture toughness for Ti-6Al-6V-2Sn alloy. The important microstructural dimension for ultrasonic wave attenuation in this two-phase alloy appears to be the width of the β phase between the needlelike α -phase subgrains. Test specimens must have flat and parallel surfaces and be coupled to the ultrasonic transducer by a thin, uniform couplant layer. Good impedance matching of the specimen-couplant-transducer combination to the ultrasonic pulser-receiver is necessary for obtaining acceptable echo waveforms. This technique is a research test and requires a very knowledgeable operator for application to a two-phase metal.

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SUMMARY

Previous interest in fracture toughness of metallic materials resulted in an in-house capability for performing compact tension fracture toughness measurements by ASTM E-399. The desire for a quick and reliable quality control test using a minimum of material made a new ultrasonic method look attractive. This study was undertaken to use that method to develop a correlation between ultrasonic wave propagation factors and fracture toughness for the two-phase Ti-6Al-6V-2Sn alloy. Toughness data were available from a previous study.

The longitudinal ultrasonic wave velocity at a frequency of 30 MHz and the ultrasonic wave attenuation over a range of frequencies from 20 to 80 MHz were measured by Dr. Alex Vary, of NASA's Lewis Research Center, for Ti-6Al-6V-2Sn specimens of eight heat treatment conditions. Unlike the previous single-phase metals, where the grain size was the important microstructural dimension, the width of the β -phase layer between needlelike α -phase subgrains seems to be the important dimension for Ti-6Al-6V-2Sn. A complete ultrasonic test does not appear possible for Ti-6Al-6V-2Sn, because a monotonic correlation between ultrasonic velocity and the important microstructural dimension does not exist as it does for single-phase metals. One additional test therefore is needed.

A useable correlation was found between ultrasonic and fracture toughness factors for Ti-6Al-6V-2Sn. The important physical phenomena are not well understood for the interaction of an ultrasonic wave with a two-phase metal. Specimen surfaces must be flat and parallel and the couplant layer between the specimens and the transducer must be thin and uniform. The electrical impedance must be well-matched between the specimen-couplant-transducer combination and the pulser-receiver for acceptable echo waveforms to result. Therefore, this test is primarily a research test and requires a very knowledgeable operator for study of two-phase metals.

Dr. Vary is continuing his study of these specimens and that study will be followed closely. This test should be considered for future fracture toughness measurement applications when they arise.

DISCUSSION

SCOPE AND PURPOSE

This work resulted from continued interest in fracture toughness measurement for metallic materials. A quick and reliable quality control test was desired which was easier to prepare and used less material than the compact tension fracture toughness specimen of ASTM E-399. The objective was to develop quantitative correlations between ultrasonic factors and the previously measured fracture toughness of a Ti-6Al-6V-2Sn alloy.

PRIOR WORK

The method for correlating ultrasonic factors with fracture toughness was reported for two maraging steels and a single-phase titanium alloy.¹⁻⁴ A previous test program had measured the fracture toughness of Ti-6Al-6V-2Sn alloy specimens for various heat treatment conditions by the ASTM E-399 compact tension method.⁵ Remains of those specimens were available for this study. No other work has been reported that attempts to correlate ultrasonic factors with fracture toughness of metallic materials.

ACTIVITY

When this work was planned, the ultrasonic measurements were to be done in-house. However, when specimens were ready for testing, the Bendix equipment was being used full time in production testing and was not available for these measurements. A search for an outside contractor revealed that Dr. Alex Vary of NASA Lewis Research Center, the originator of the technique, would test the Bendix specimens. His offer was accepted. For that reason, the equipment described is Dr. Vary's experimental set-up, and the correlation results were obtained in his laboratory on specimens provided by Bendix.

Ultrasonic Test Method

The basics of the ultrasonic test method and the correlation with fracture toughness have been reported by Dr. Vary.¹⁻⁴ The discussion of the test method here will follow the more recently reported computer-assisted technique of data acquisition and analysis.⁶ The equipment arrangement is identical to earlier versions, except that data are now digitized, analyzed, and displayed by computer instead of by hand from analog data.

The original empirical correlation between ultrasonic and fracture toughness factors, and the later heuristic theoretical basis⁷, requires that two ultrasonic quantities be measured. These two are the ultrasonic wave propagation velocity and the attenuation over a range of frequencies. Both can be measured with a single ultrasonic test set-up.

The pulse-echo technique for measuring ultrasonic velocity requires only one specimen surface to be free for contact with the ultrasonic transducer, which acts as both pulser and receiver. The specimen-couplant-transducer combination is shown schematically in Figure 1. The specimen surfaces are smooth and parallel. The couplant is a viscous liquid, usually glycerine, squeezed into a thin layer. The 50-MHz resonant frequency transducer consists of a piezoelectric crystal sandwiched between a quartz or fused silica buffer and a metal-loaded epoxy absorber. These elements are surrounded by a metal case connected to the ground of the coaxial cable that leads to the broadband ultrasonic pulser-receiver.

Figure 2 schematically shows the computer system for ultrasonic signal acquisition and processing. The ultrasonic pulser-receiver must be impedance-matched to the transducer and a thin, uniform couplant layer must be used to ensure undistorted signals. The echos are immediately digitized and stored for computer analysis and selected hard copy output.

The longitudinal ultrasonic wave velocity is determined digitally by overlapping the first and second echos from the back surface of the specimen. This technique amounts to comparing the location of the first and second major oscillation peaks and the zero crossing point between them. The results determine the time delay t , caused by traversing the specimen twice, $2L$. The experimental measured velocity, V , is then given by Equation 1.

$$V = 2L/T \quad (1)$$

The velocity remains fairly constant over a wide range of frequencies and is thus usually measured only at 30 MHz. The attenuation, however, will usually vary by several orders of magnitude over the 20 to 80 MHz frequency range used here. The variation of attenuation with frequency changed is determined by frequency spectrum analysis. The ultrasonic frequency spectra at each pulser frequency are obtained by fast fourier transformation (FFT) of the time domain echo signals. Figure 3 shows the time domain spectra of the first two echos and the corresponding frequency spectra.

Not all the frequency domain data are useable. Zone limits for the valid range are obtained from the first and second derivatives of the truncated frequency spectrum of the second or weakest echo. The truncation sets minor trailing oscillations to

Figure 1. Cross Section of Buffered Broadband Ultrasonic Transducer Coupled to a Metal Specimen

Figure 2. Block Diagram of Computer System for Pulse-Echo Velocity and Attenuation Measurement

(a) ECHO OVERLAP OF B1 AND B2

(b) SPECTRA FOR B1 AND B2

Figure 3. Time and Frequency Domain Spectra of the First Two Echoes

zero and uses only the first five major oscillations of the classic "W" pattern. Figure 4 illustrates this truncation and derivative evaluation. The data in the valid zone, then, are used to compile the amplitude ratio curve (ARC) versus frequency, as shown in Figure 5. The reflection coefficient, R , is the ARC curve intercept and is between the reflection coefficient for the couplant (RCC) and that for the buffer (RCB). Now all data are available to determine the attenuation coefficient, α , versus frequency as given by Equation 2, where B is the frequency dependent amplitude ratio, B_2/B_1 , from the ARC curve.

(a) SPECTRA OF B1 AND B2

(b) DERIVATIVES OF B2

Figure 4. Normal and Truncated Frequency Spectra and Derivatives of Second Echo to Define Valid Zone

Figure 5. Typical Amplitude Ratio Curve Showing Curve Fit to Raw Data and Computed Reflection Coefficients for Couplant (RCC) and Buffer (RCB)

$$\alpha = \frac{1}{2L} \ln \frac{R}{B} \quad (2)$$

These experimental data are fit to the theoretical power function dependence on frequency, f , of Equation 3, where C and m are constants.

$$\alpha = Cf^m \quad (3)$$

An example of this data fit is shown in the log-log plot of Figure 6. The power law fit is excellent over the straight line portion which is the valid zone from 20 to 57 MHz. The power law can then be differentiated with respect to frequency to obtain the attenuation slope, β . This slope, when evaluated at specified points, enters into two correlations with fracture toughness, K_{IC} , and with 0.2 percent offset yield strength, $\sigma_{0.2}$. The first of these correlations uses the attenuation slope, β_1 , at unit attenuation gained experimentally from Equation 4.

$$\ln \beta_1 = \ln m + \frac{\ln C}{m} \quad (4)$$

Empirical Equation 5, with A_1 , A_2 , and A_3 as constants, has fit data for two maraging steels and one titanium alloy.

$$\sigma_{0.2} + A_1 K_{IC} + A_2 \beta_1 = A_3 \quad (5)$$

In order to use ultrasonic properties to infer the fracture toughness, another equation is needed to separate the toughness from the yield strength. This is obtained by evaluating the attenuation slope at the transition from Rayleigh to stochastic scattering of the ultrasonic waves. This occurs at a wavelength equal to a key microstructural dimension, D , of the metal. This dimension is the grain size for the single-phase metals previously investigated. Equation 6 gives this slope, β_2 .

$$\ln \beta_2 = \ln mC + (m-1) \ln \frac{V}{D} \quad (6)$$

A heuristic theoretical derivation then predicts Equation 7, where A_4 is a material dependent constant. This also fits experimental data well.⁷

$$\left(\frac{K_{IC}}{\sigma_{0.2}} \right)^2 = A_4 \sqrt{\frac{VB_2}{m}} \quad (7)$$

Once a correlation is established for a given material, the constants in Equations 5 and 7 will be known. These two equations can then be employed in reverse to predict fracture toughness for future specimens of that material solely from ultrasonic measurements and knowledge of D .

Figure 6. Logarithmic Plot of Attenuation Versus Frequency and Straight Line Power Law Fit to Experimental Data

Material Properties

The fracture toughness and yield strength of the Ti-6Al-6V-2Sn material available for study had been measured previously. The grain size needed for Equation 6 was measured on photomicrographs of polished and etched surfaces parallel to the crack propagation direction. The density and Rockwell C hardness were measured for reference. All of these data plus the factor $(K_{IC}/\sigma_{0.2})^2$ for Equation 7 are compiled in Table 1.

The first seven specimens from 18A to 78A were all from a single heat-treatment condition, and, consequently, all had the same yield strength and toughness within expected experimental variation. Note the variation in grain size. The second seven specimens, 89 through 111, had succeeding higher aging temperatures which increased the toughness while decreasing the yield strength and hardness. This was the key set of specimens for the experimental correlation because of the range of toughness and yield strength.

Ultrasonic Test Results

The ultrasonic test specimens were cut from the remains of compact tension fracture toughness specimens, as shown in Figure 7. The 5-mm-thick wafer was then coupled to the 50-MHz ultrasonic transducer, as shown in Figures 1 and 2, so that the ultrasonic wave was propagated in the same direction as the crack.

Preliminary results showed the correlation between the ultrasonic attenuation factor and fracture toughness of Figure 8 for the grain size used as D in Equation 6. Even though an acceptable straight line correlation results, the slope is less than the theoretical prediction of Equation 7. This raised questions about the microstructure of this two-phase α - β alloy. The 100X photomicrograph of Figure 9a shows the grain boundaries and subgrain structure for specimen 18A. The subgrain structure is seen better in the 1000X view of Figure 9b. The needlelike α -phase subgrains are separated by layers of β -phase material.

When the approximate width of the α -phase subgrains was used for D , the preliminary correlation of Figure 10 was obtained. Specimen 89 gave different values consistently for two transducer locations. The data fit the theoretical slope fairly well. However, when the α -phase width was measured more accurately from 1000X photomicrographs of every specimen, the data departed from the theoretical slope, as seen in Figure 11. When the width of the β -phase layer between α -phase subgrains is used, a good fit to the theoretical slope is seen, as indicated in Figure 12.

This two-phase α - β titanium alloy thus has raised some questions about the appropriate microstructural dimension, D . The grain

Table 1. Properties of Ti-6Al-6V-2Sn

Specimen*	Toughness** K _{IC} (MPa√m)	Yield Strength $\sigma_{0.2}$ (MPa)	$(K_{IC}/\sigma_{0.2})^2$ ** (mm)	Density P(g/cm ³)	Grain Size*** D (μm)	Hardness†
18A	108	870	15.4	4.52	220	34
28A	96	870	12.2	4.51	181	32
38A	108	870	15.4	4.51	257	33
48A	99	870	12.9	4.54	246	34
58A	98	870	12.7	4.51	218	33
68A	101	870	13.5	4.52	295	33
78A	97	870	12.4	4.51	222	33
89	34.7	1170	0.88	4.51	213	44
91	39.2	1138	1.19	4.53	220	46
93	47.9	1150	1.74	4.52	289	43
95	60.0	1103	2.96	4.51	229	42
97	70.4	1048	4.51	4.51	210	40
109	81.4	931	7.65	4.51	226	37
111	90.5	870	10.82	4.51	201	35

*Specimens 18A through 78A were heat-treated at 900°C for 2 hours plus 785°C for 2 hours. Specimen 89 was heat-treated at 850°C for 8 hours plus 8 hours at 400°C. Specimens 91 through 111 heat treatments were increased 50°C each for the last 8 hours, up to 700°C for Specimen 111.

**Test 18A through 78A were invalid per ASTM E399. Tests 89 through 111 were all valid.

***Average of 8 measurements on 100X photographs.

†Average of 3 measurements each, Rockwell C scale.

Figure 7. Compact Tension Fracture Toughness Specimen Showing Location for Removal of Ultrasonic Specimens

size looked like the correct dimension for two maraging steels and a single-phase titanium alloy tested previously. However, the width of the β -phase layer between the α -phase subgrains appears to be a better choice for this two-phase alloy.

Figure 13 shows an appropriate straight-line fit that corresponds to Equation 5 for specimens 89 through 111 that are plotted as open squares. The fit deteriorates when specimens 18A through 78A, which are plotted as filled squares, are included; however, this result might be just the cumulative effect of experimental error plus the specimen-to-specimen variation for supposedly identical material.

For a complete evaluation to be made by ultrasonic means, the critical microstructural dimension also needs to be inferred by ultrasonics rather than by metallography. Figure 14 shows a plot of velocity versus β -phase width. Because a straight line is not obtained, the β -phase width must be determined metallographically. Alternatively, since a good correlation exists between hardness and yield strength, the hardness could be used to infer the yield strength and the toughness could then be inferred from yield strength and ultrasonic measurements by using Equation 5.

Figure 8. Preliminary Data Using 181 to 295 μ m Grain Size

Conclusions

Even though Dr. Vary is continuing tests on Ti-6Al-6V-2Sn and the final results are not yet available, the following conclusions may be made, based on the preliminary data.

1. A useable preliminary correlation between ultrasonic and fracture toughness factors has been obtained for Ti-6Al-6V-2Sn. The width of the β -phase between the α -phase subgrains seems to be the appropriate microstructural dimension.
2. Specimen surfaces must be flat and parallel and the couplant layer must be thin and uniform. Good impedance matching also is necessary to achieve acceptable echo waveforms.

(a) 100X

(b) 1000X

Figure 9. Photomicrographs of Specimen 18a Showing the Subgrain Structure

Figure 10. Preliminary Data Using Mean α Phase Width of 2 μm

3. The basic physical phenomena are not completely understood for ultrasonic wave attenuation in two-phase metal alloys.
4. This test technique appears to be very promising as a quality control test. However, it is currently a research test and requires a very knowledgeable operator. When developed, it can be attractive when large numbers of tests are required.

Figure 11. Preliminary Data Using Average Width of α Phase for Each Specimen

ACCOMPLISHMENTS

A preliminary correlation was established between ultrasonic and fracture toughness factors for Ti-6Al-6V-2Sn alloy. Some factors were identified that currently limit the use of this test to quality control purposes. Dr. Vary's computerized experimental test capability has been personally observed in operation, and is indeed impressive in the speed and versatility of data collection and analysis.

FUTURE WORK

Dr. Vary is continuing his ultrasonic investigation of the Ti-6Al-6V-2Sn specimens. In addition, tests on specimens of

Figure 12. Preliminary Data Using Average Width of β Phase for Each Specimen

purely β -phase material are planned in an effort to better understand the physical phenomena involved. That work will be followed closely. No further work will be done at Bendix at this time; however, the technique should be considered when future fracture toughness test needs arise.

Figure 13. Preliminary Data Correlation Between Yield Strength and Ultrasonic Factor

Figure 14. Nonlinear Correlation Between Ultrasonic Velocity and β Phase Width

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SPECIAL PROJECTS: Measurement

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