INVESTIGATING THE USE OF ULTRASOUND FOR EVALUATING AGING WIRING INSULATION

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ABSTRACT

This paper reviews our initial efforts to investigate the use of ultrasound to evaluate wire insulation. Our initial model was a solid conductor with heat shrink tubing applied. In this model, various wave modes were identified. Subsequently, several aviation classes of wires (MIL-W-81381, MIL-W-22759/34, and MIL-W-22759/87) were measured. The wires represented polyimide and ethylene-tetraflouroethylene insulations, and combinations of polyimide and flouropolymer plastics. Wire gages of 12, 16, and 20 AWG sizes were measured. Finally, samples of these wires were subjected to high temperatures for short periods of time to cause the insulation to degrade. Subsequent measurements indicated easily detectable changes.

INTRODUCTION

During the past several years, some visible incidents have energized the aviation and aerospace community to address the continuing problem of aging wiring. [1,2] A major difficulty that government and industry face in this problem is the lack of qualified, easy to use techniques that can be utilized to address the myriad of problems and conditions that aging wiring present. Some efforts to evaluate aging wiring insulation have focussed on adapting sophisticated electrical sensing systems such as Time Domain Reflectometry, Standing Wave Reflectometry, Frequency Domain Reflectometry, and resistance tests, which are usually used to evaluate the conductive part of wire. [3] Several of these methods also should be sensitive to deviations in the dielectric materials that surround the conductors. Also, there are some efforts to investigate dielectric sensors, chemical sensors, and thermographic methods in addition to the ultrasonic method highlighted here. All of these methods may have unique characteristics that could play a role in wire insulation NDE.

The concept for ultrasonic testing of wire insulation is based on using the wire as an ultrasonic cylindrical waveguide. A number of researchers have examined acoustic guided wave propagation in cylindrical geometry. [4,5,6,7] Some applications of ultrasonic guided waves include material testing or characterization of wire [8,9] and fibers and use as ultrasonic delay lines. The principle for wire insulation testing is that part of the wave will travel in the insulation material, which affects the wave speed and amplitude of the guided wave. Since the wave speed is a function of the material stiffness, the resulting signal will have information about the insulation's condition. If the method can obtain satisfactory information about the condition of the insulation, it has the potential to be made into a small, robust, portable system that would be convenient for field use.

In general many acoustic wave modes will propagate in an isotropic cylinder. The lowest order modes of vibration are the axial symmetric modes, which can be divided into axial-radial and torsional modes. The next order mode of vibration is the flexural mode and higher modes are screw modes [5]. The lowest branch of the axial-radial mode extends to zero frequency where the limiting phase velocity is called the bar velocity in the simple isotropic case, and is related to the Youngs modulus of the material. In the low frequency regime this mode is nearly non-dispersive. As the frequency is increased the phase velocity drops to a value slightly below the Rayleigh velocity and then approaches the Rayleigh velocity from below at higher frequencies. The first flexural mode's dispersion behavior is to approach zero phase speed at zero frequency. As the frequency increases, the phase velocity increases. It asymptotically approaches the axisymmetric wave speed from below.

To test our concept, we performed a series of simple tests. The first test was to evaluate a simple model consisting of a solid cylinder and then a solid cylinder coated with a polymer. In this model, we were able to generate several guided modes that we could verify. Follow on testing investigated mil-spec wiring materials (MIL-W-81381, MIL-W-22759/34, and MIL-W-22759/87) which are used in aircraft. Although the conductors for these materials have a stranded conductor construction rather than the solid cylindrical form of our initial model, the ultrasonic signals demonstrated the same behavior as was seen for the solid cylinder coated with a polymer model. Finally, several samples of these mil-spec wires were placed in an oven and heated for short periods of time to induce changes in the polymer's material properties. The changes in the ultrasonic signals were then measured.

EXPERIMENT

The experimental system shown in fig. 1 consisted of an ultrasonic spike generation pulser to generate the ultrasonic waves. Two similar longitudinal wave transducers were used in a pitch catch mode for generation and reception. The transducers were low frequency, broadband acoustic emission transducers with a bandwidth of 50 kHz to 2 MHz. On reception, a 20 kHz to 2 MHz pre-amplifier with 40 or 60 dB of switchable gain fed into an amplifier with a maximum of 42 dB of gain and with the bandwidth set at 10 kHz to 300 kHz. The output of the amplifier was recorded by an 8-bit/500 MHz digitizing oscilloscope. That signal was averaged 1000 times. Typically, 200 μsecs of signal were recorded.

The transducers were mounted in simple sample holders that could be clamped on to a wire. (See fig. 2.) The transducer holder was designed to hold the wire across the center of the

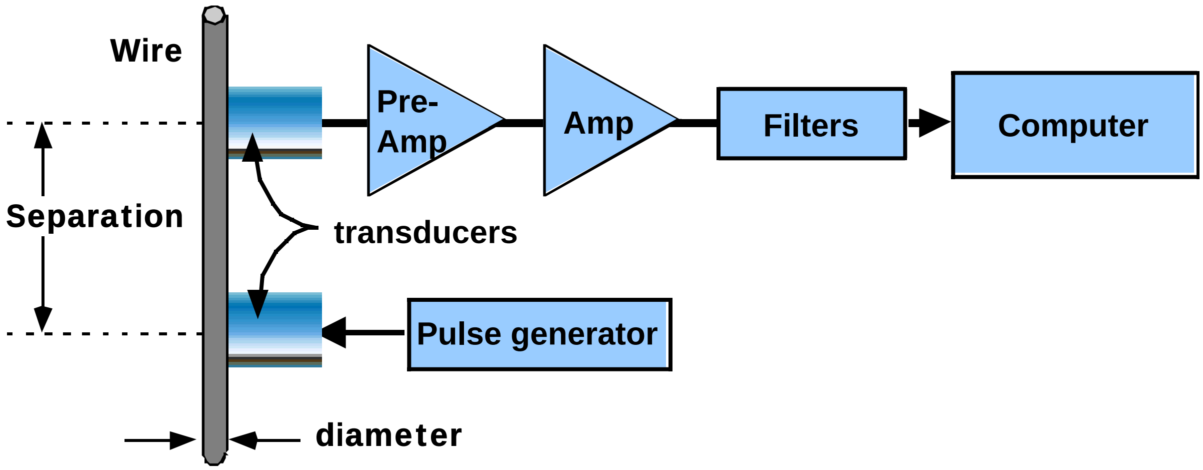

Figure 1. Experimental set up.

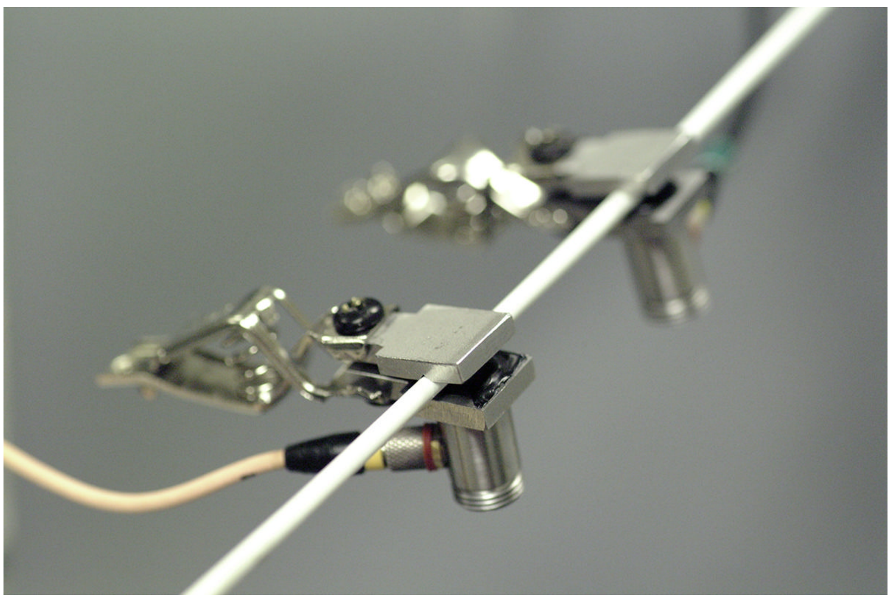

Figure 2. A transducers being attached to an insulated wire.

transducer's face. For this work, the wires were mounted on a 30 cm long optical rail with spacings marked off in millimeters. The spacing of the transducers was adjusted from 3 cm up to 29 cm to measure a range of arrival times and spacings. The wire samples were nominally 60 cm long and the ends of the wire samples were clamped to hold the samples straight while measurements were taken.

For the case of measuring the phase velocity, the first arrival peak of the signal at each distance was used to estimate a velocity. A least squares routine was used to calculate the velocity and to estimate the error of the velocity from the distance versus time data. When measuring the angular dependence of the ultrasonic waves transmitted in these wires, the receiving transducer was positioned on the wire at an angle with respect to the transmitting transducer and the angular orientations were measured with a protractor. Again, the first arrival peak of the measured mode was recorded.

RESULTS

Solid Insulated Wire Model

Initial measurements were carried out on a simple model of an insulated wire to identify various wave modes. This model consisted of a solid aluminum rod with and without a polymer coating. The aluminum rod, simulating the wire, had a 3.23 mm diameter. The polymer coating, simulating the insulated wire had a thickness of 0.57 mm. The coating was a thermoplastic heat-shrink material of Polyolefin. Published [10] density and modulus of this material is 0.971 gm/cm^3 and 1.2 Gpa respectively, and the measured longitudinal wave velocity is 1870 m/s. The final diameter of the model was 4.37 mm. The published aluminum properties are 70.76Gpa and 2.7gm/cm^3 for Young's Modulus and density. They predict a bar velocity of 5119m/s.

Typical ultrasonic signals in the bare aluminum rod and in the insulated aluminum rod are shown in Figure 3a and 3b respectively. In Fig. 3a there is an initial small signal at about 20µs and then a much larger signal starts near 30µs. In Fig. 3b, the initial signal starts at about 25µs and a much larger signal starts about 35 µs. In both figures, these signals are followed by additional signals that are either additional modes or are reflections. Those signals overlap sufficiently to make

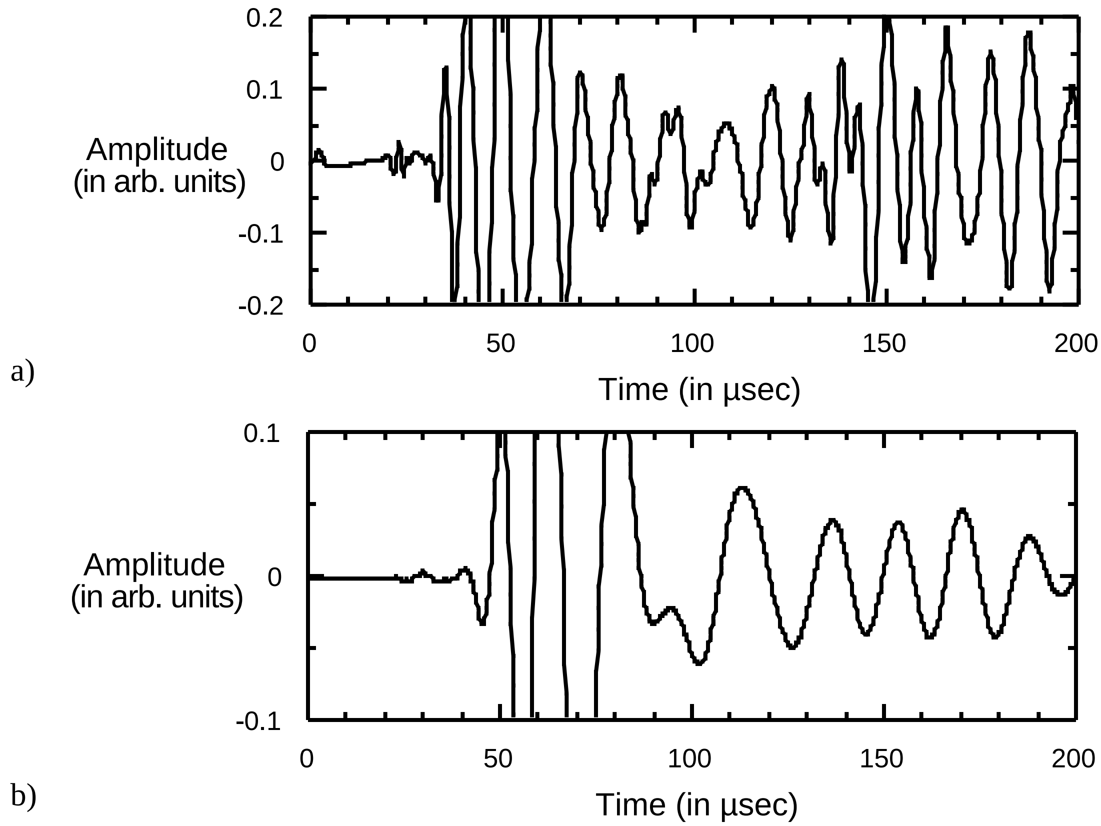

Figure 3. Typical ultrasonic signals showing the first axisymmetric wave mode and the first flexural mode wave. Fig. 3a) is from the bare aluminum rod while Fig. 3b) is from the polymer coated aluminum rod.

easy identification difficult. In both figures, the second arriving mode clearly illustrates dispersive behavior with the higher frequencies traveling faster. Also, it can be noted that the bare aluminum rod has a much higher frequency content.

To further distinguish the character of the first two modes, we examined the signals as a function of rotational angle between the transmitting and receiving transducers. The transmitting transducer was held stationary while the receiving transducer rotated around the aluminum rod in increments of 10^{o}. From theory [4,5], it would be expected that the axisymmetric wave would show no angular preference while the flexural mode would have cosine dependence. The results of the angular measurements are shown in Figure 4, where we have labeled the data as being either axisymmetric or flexural.

The phase velocity of the axisymmetric mode of the bare rod and the polymer coated aluminum rod were measured to be 5119 ± 26 m/s and 4597 ± 36 m/s respectively. The decrease in the measured phase velocities from the bare aluminum rod to the coated aluminum rod demonstrates the pronounced effect the polymer coating has on the phase velocity of insulated wiring. It indicates that some of the ultrasonic energy is traveling in the insulation.

To see if this method might be applied to aging wiring, several mil-spec wire samples were heated to induce changes in the insulation. The samples were 12, 16, and 20 gauge MIL-W-81381, MIL-W-22759/34, MIL-W-22759/87 wires (see Table 1). The MIL-W-81381 wires have polyimide insulation, the MIL-W-22759/34 wires have ethylene-tetraflouroethylene (E-TFE) insulation, and the MIL-W-22759/87 wires have an insulation that is a combination of polyimide and a flouropolymer (FP).

MIL-W-22759/34 wire, ethylene-tetraflouroethylene insulation

The first samples tested were the MIL-W-22759/34 wires. We used one sample of each gauge for baseline measurements, one of each gauge were heated in an oven at 349^{o}C for one

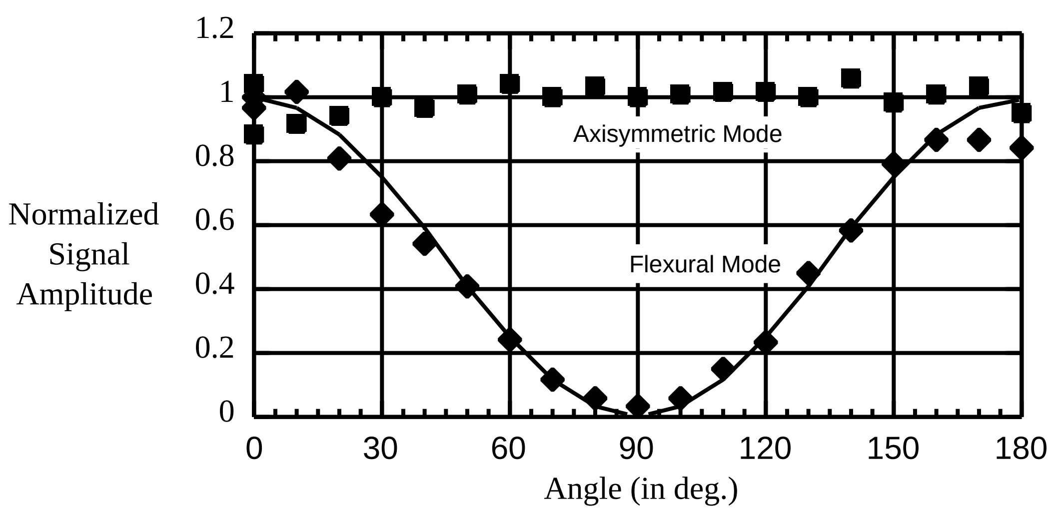

Figure 4. Plot showing the axisymmetric and flexural mode amplitudes as a function of angle between the transmitting and receiving transducers.

hour, and one of each gauge was heated in an oven at 399^{o}C for one hour. The insulation on the baseline sample is smooth, flexible, and off-white in color. The samples heat-damaged at 349^{o}C remained smooth, but its color changed to gray. The samples heat-damaged at 399^{o}C became charred, brittle, and cracked (exposing the conductor,) and its color became almost black. Figure 5 shows photographs of the 16-gauge wire. A comparison of the phase velocities of these samples is shown in Figure 6. For the 20 gauge wires, the baseline velocity is 2971 ± 28 m/s which increases to 3372 ± 8 m/s after the first heating cycle and then finally rises to 3595 ± 9 m/s. For the 16 gauge wires, the values are 3211 ± 30 m/s, 3500 ± 11 m/s, and finally 3765 ± 17 m/s respectively. For the 12 gauge wires, the measured values are 3183 ± 40 m/s, 3966 ± 31 m/s and 3615 ± 9 m/s for the three wire conditions.

MIL-W-81381 wire, polyimide insulation

The next set of samples that were measured was the MIL-W-81381 wires. Polyimide coated wires can tolerate much greater temperatures before signs of damage than the E-TFE insulation. In these samples, we had the following sets, one sample of each gauge was measured for baseline; one set of each gauge was exposed to 399^{o}C for one hour; and one set of each gauge was

Table 1: MIL-W specification information on wire types used in this study.

Wire Type MIL-W-	Gauge	Conductor Type	Insulation Type	Insul. ID in mm	Insul. OD in mm	Max Oper. Temp.
81381/7	20	Stranded silver coated copper	Polyimide/FEP laminated tapes/Modified aromatic polyimide resin coating	0.942	1.286	200^{o}C
81381/21	16	Stranded tin coated copper	Polyimide/FEP laminated tapes/Modified aromatic polyimide resin coating	1.326	1.628	200^{o}C
81381/12	12	Stranded nickel coated copper	Polyimide/FEP laminated tapes/Modified aromatic polyimide resin coating	2.086	2.496	200^{o}C
22759/34	20	Stranded tin coated copper	Modified ethylene-tetraflouroethylene	0.942	1.452	150^{o}C
22759/34	16	Stranded tin coated copper	Modified ethylene-tetraflouroethylene	1.326	1.906	150^{o}C
22759/34	12	Stranded tin coated copper	Modified ethylene-tetraflouroethylene	2.086	2.798	150^{o}C
22759/87	20	Stranded nickel coated copper	Composite tape (FP/polyimide/FP tape) and FP tape	0.942	1.346	260^{o}C
22759/87	16	Stranded nickel coated copper	Composite tape (FP/polyimide/FP tape) and FP tape	1.326	1.742	260^{o}C
22759/87	12	Stranded nickel coated copper	Composite tape (FP/polyimide/FP tape) and FP tape	2.086	2.578	260^{o}C

exposed to 399^{o}C for 50 hours. Figure 7 shows photographs of the 16 gauge polyimide wires. The polyimide insulation layers are thin, but stiff materials on these wires. The color of the baseline samples is a yellowish color. The first thermal exposure caused the wire insulation to darken slightly. The extended exposure severely damaged the outer layer causing the layer to peel and crack. In places where the inner layers were exposed, they would peel and flake. Measurements of the phase velocity for the various polyimide coated wire samples are shown in Figure 8. For the 20 gauge wires, the baseline velocity is measured at 3038 ±7 m/s, which increases to 3560 ± 8 m/

a)

b)

c)

Figure 5: Images of MIL-W-22759/34 16 gauge wires that were exposed to different thermal conditions. Fig. 5a) is the virgin wire. Fig. 5b) is a wire that was exposed to 349^{o}C temperatures for one hour. Fig. 5c is a wire that was exposed to 399^{o}C temperatures for one hour.

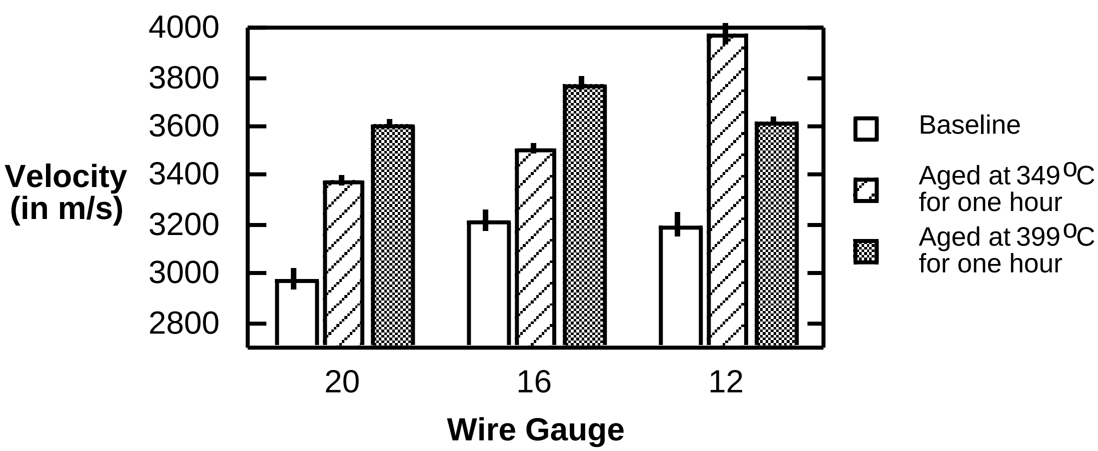

Figure 6. Bar chart showing phase velocity for each gauge family and each heat-damage condition in E-TFE insulated wire (MIL-W-22759/34).

s after the first heating cycle and then finally rises to 3614 ± 6 m/s.   For the 16 gauge wires, the velocity values are 3269 ± 5 m/s, 3664 ± 5 m/s, and finally 3716 ± 6 m/s respectively. For the 12 gauge wires, the measured values are 3407 ± 11 m/s, 3673 ± 15 m/s and 3768 ± 11 m/s for the three wire conditions.

MIL-W-22759/87 wire, sandwich, composite insulation

The final wire type that was measured was MIL-W-22759/87 wire. The insulation on these

a)

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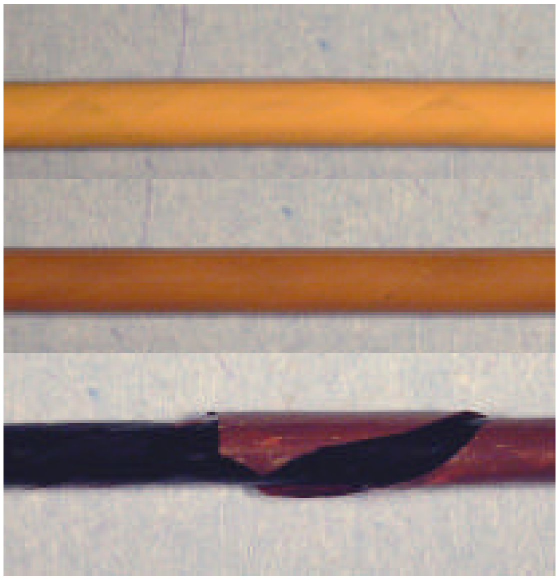

Figure 7. Photographs of 16 gauge polyimide wiring. Fig. 7a) shows the baseline condition. Fig. 7b) shows the wire after one hour at 399^{o}C and Fig. 7c shows the wire after 49 hours at 399^{o}C.

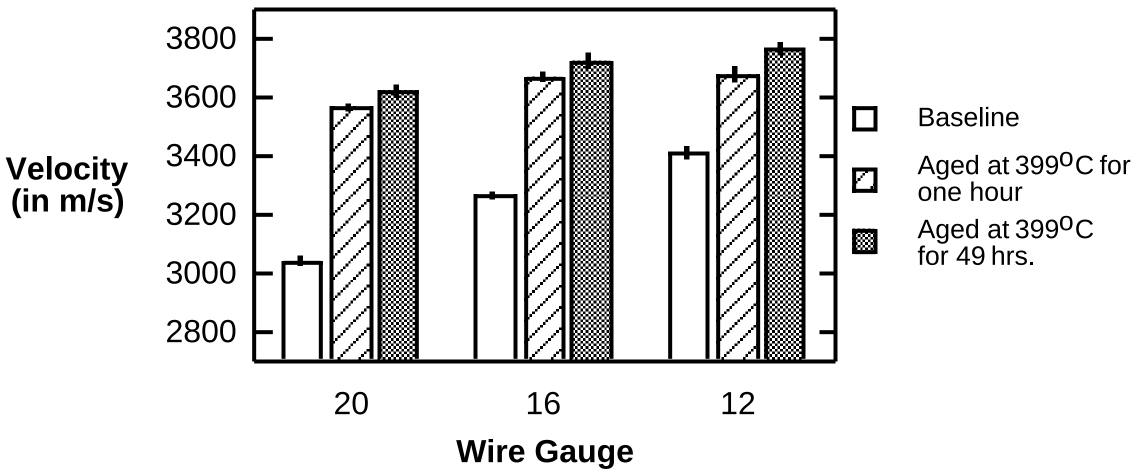

Figure 8. Bar chart showing phase velocity for each gauge family and each heat-damage condition in polyimide insulated wire (MIL-W-81381)

wires was constructed with a sandwich construction and is sometimes noted as a composite insulation. The sandwich layers consisted of outer layers of flouropolymer with a central layer of a polyimide. This type of insulation tolerated high temperatures very well. It had the highest operating temperature of the three types of wires that were investigated. In these samples, we had the following sets, one sample of each gauge was measured for baseline; one set of each gauge was exposed to 399^oC for one hour; and one set of each gauge was exposed to 399^oC for 50 hours. Figure 9 shows photographs of the 12 gauge MIL-W-22759/87 wires with composite insulation. The color of the baseline samples is white. The first thermal exposure caused the wire insulation to darken only slightly. The wire also had a glossy shine to its surface. In the extended exposure sample, numerous cracks of the outer layers are evident, especially along the overlap seams. Also, this wire had lost its glossy shine becoming rather flat in texture, but it continued to keep its white color. Measurements of the phase velocity for the various polyimide coated wire samples are shown in Figure 10. For the 20 gauge wires, the baseline velocity is measured at 3595 ± 15 m/s, which increases to 3668 ± 160 m/s after the first heating cycle and then finally rises to 3957 ± 19 m/s.   For the 16 gauge wires, the values are 3533 ± 18 m/s, 4073 ± 47 m/s, and finally 4098 ± 29 m/s. For the 12 gauge wires, the measured values are 2947 ± 142 m/s, 3685 ± 21 m/s and 3694 ± 29 m/s for the three wire conditions.

DISCUSSION

One feature evident in this measurement and seen in Figure 2 is that the flexural wave is much larger than the axisymmetric wave because of the method of generation. From Fig. 1, it is seen that the generation is performed by pulsing the transducer on the side of the wire. This has

a)

b)

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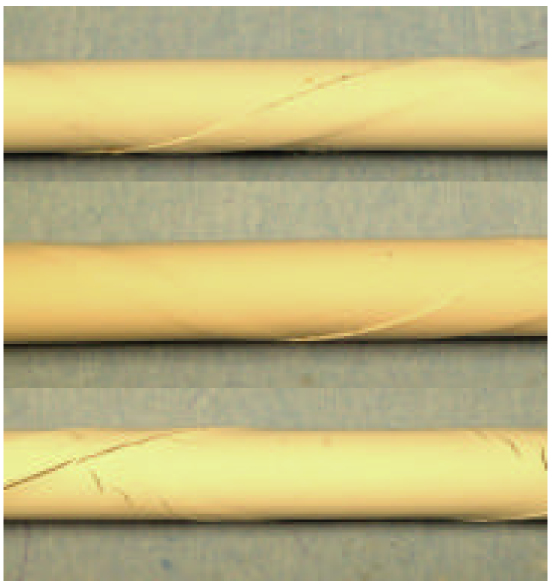

Figure 9. Photographs of 12-gauge FP/polyimide/FP insulated wiring. Fig. 9a) shows the baseline condition. Fig. 9b) shows the wire after one hour at 399^oC and Fig. 9c shows the wire after 50 hours at 399^oC.

the effect of pushing a whole section of wire to the side and thus producing mostly a flexural wave. A small amount of an axisymmetric mode was always produced, and because it is much faster than the flexural mode at low frequencies, this mode was easily identified, and it could be detected without interference with the flexural wave. Therefore, we chose to measure several examples of wires using this mode.

Our investigation of a simple model matches well with basic theory for cylindrical guided waves. The axisymmetric mode's velocity measurement in the aluminum rod was within 0.2% of the calculated value. The properties that have been observed in this model show that the use of a soft material for an insulating layer will shift the wire's ultrasonic axisymmetric mode velocity significantly. The frequency content of the transmitted waves in Figure 2a indicates that the frequency of the axisymmetric wave in bare 3.23 mm diameter aluminum rod is on the order of 330 kHz to 400 kHz, while the first flexural mode has a much lower frequency content which is on the order of 100 to 390 kHz. In the polymer insulated aluminum rod model (Fig. 2b), the frequencies were in the range of 100 kHz to 140 kHz for the axisymmetric wave and about 45 kHz to 125 kHz for the first flexural mode. Adding the extra layer halved the frequencies that were generated. Experimentally, in both figures, it was seen that the high frequency part of the flexural wave arrived earlier than the lower frequency components. Theoretically, this is the expected dispersion of the first flexural mode. Similarly, at low frequencies, the axisymmetric wave is not expected to be nearly as dispersive as the flexural wave. This appears to be the case.

Our measurements of this simple model indicate that the concept of using guided waves to interrogate wire insulation has merit. The smaller amplitude axisymmetric wave arrived first in both Figs. 2a and 2b. The larger amplitude flexural wave arrived later in both Fig. 2a and 2b. The measured velocity of the axisymmetric wave was strongly affected by the insulation layer, with a 10% drop from the bare aluminum wire speed.

Generally with age, many polymer materials lose plasticizers and mass and become stiffer. Stiffening of the insulation material would then cause the velocity to increase. The use of heat is a typical method to accelerate aging, although, raising the temperature to too extreme a value can

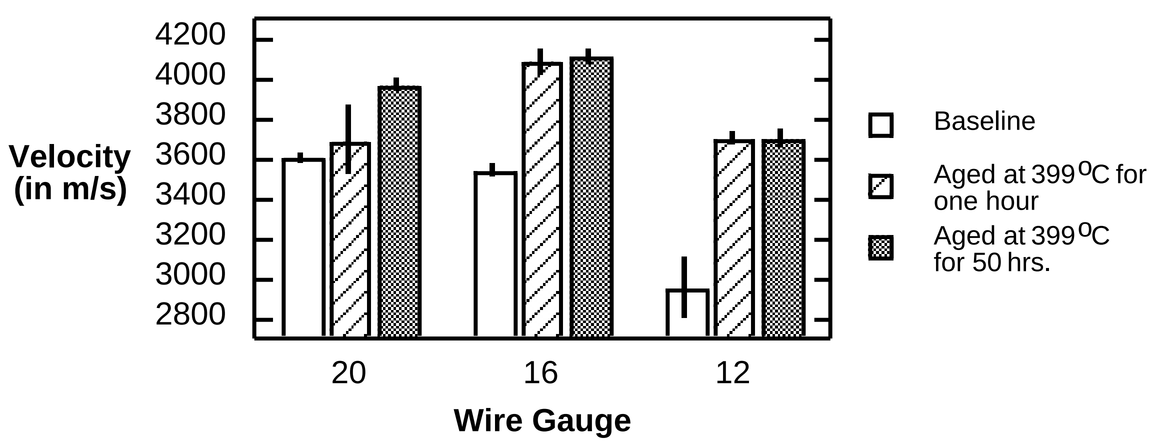

Figure 10. Bar chart showing phase velocity for each gauge family and each heat-damage condition in FP/polyimide/FP insulated wiring (MIL-W-22759/87).

cause some changes that do not emulate simple aging. In the case of ethylene tetraflouroethylene, heating will cause a general mass loss. [11] In the examples of the E-TFE insulation and the polyimide insulation, our second conditioning stage may have been too extreme to model aging, which is suggested by the charring or destruction of the insulation seen in the MIL-W-2259/34 and MIL-W-81381 wire. Still, obvious changes were generated in the sets of wires, which provided a simple test for the model.

The measurements of the velocity in the wire samples appeared to mimic the measurements of the simple wire model discussed earlier. Thus, it appears that the ultrasonic transmission down concentric cylinders with intimate contact is a reasonably good model for the insulated wire, even with a stranded conductor. In general, in the method used here, the error bars were on the order of a few tens of m/s or less, which compares favorably with the measured changes of several hundred m/s. It should be noted that in some of the insulated wire samples we generated some higher order modes, which interfered with the measurement of the lowest order axisymmetric mode. This was most evident in a few of the FP/ polyimide/FP insulated wiring (MIL-W-2259/87), which caused rather large error bars in two instances. We also saw some slight evidence of higher order modes in the baseline E-TFE insulated wires (MIL-W-2259/34), but not to the same extent.

The velocity behavior of each wire group to heat damage was generally similar. In all cases, the velocities increased between the baseline values and after the first heat cycle values. The E-TFE insulated wires showed the largest changes in velocity of the axisymmetric waves of approximately 9% to 25% from baseline to the first heat cycle, which represents rather large changes for velocity measurements. The polyimide insulated wires had changes of 8 to 17% from baseline to the first heat cycle, while the FP/ polyimide/FP insulated wiring had changes in the range of 2 to 25% from baseline to the first heat cycle. Also, it can be noted that the slowest velocities were for the E-TFE insulated wires, which had the largest changes. In our model, that would suggest that this polymer was the softest and that the heating cycle caused the most change to that polymer. This appears to be the case since this polymer showed a more significant change compared to the other two after the first heating.

In most cases, the velocities increased after the second heat cycle and the increases were not as great as the changes caused by the first heat cycle. In the case of the ethylene tetraflouroethylene insulated wires, the 16 and 20 gauge wires' sound velocities increased by an additional 6.5% to 8% after the second heat cycle. The polyimide insulated wires had changes of 2 to 3% from the first heat cycle to the second heat cycle, and the FP/ polyimide/FP insulated wiring had change of 8% in the 20 gauge wire and no changes in the 12 and 16 gauge wires. The second heat cycle represents a more complex situation in this test because the insulations were badly damaged with many cracks and breaks after the second heating. From Figures 5 and 7, the insulation's condition has obviously failed at this point, while in Figure 9, visually, the insulation shows serious degradation. In general, in ultrasound, large flaw densities such as large crack density numbers will cause the sound velocities to decrease. This would counter the possible effect of increases in velocity due to increases in the stiffness of the polymers with aging and needs more studying in this system.

CONCLUSION

This work demonstrated the generation of ultrasonic axisymmetric and flexural guided wave in a plastic coated solid aluminum rod and in insulated wire samples. We used clip-on piezoelectric transducers to generate and detect ultrasonic guided cylindrical waves in wires. From the guided wave measurements on the bare aluminum rod we were able to determine the axisymmetric and flexural guided wave modes. We measured the axisymmetric wave mode speeds in numerous examples. In the case of the aluminum rod vs. the polymer insulated aluminum rod, the velocities decreased because of the presence of the soft polymer as expected. In the testing of the commercial wire, in all cases, the axisymmetric wave speed increased over the baseline values after thermal treatment. From these measurements, we infer that the lowest order axisymmetric mode appears sensitive to stiffness changes in the wire-insulation. Currently, large sets of wire samples have been prepared to more fully investigate the behavior of the three types of wire insulations, MIL-W-81381, MIL-W-22759/34, and MIL-W-22759/87. The wires are being exposed to more gentle thermal degradation to test our concept. Although the heat-damage conditions may not be the same as natural aging conditions we believe that with further development and refinements, the small clip on transducers or possibly a non-contacting laser generation and detection system can be used to inspect wire-insulation for detrimental local aging conditions via ultrasonic guided waves.

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