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THE USE OF ACOUSTIC EMISSION IN PREDICTING THE TENSILE STRENGTH OF LEATHER

ABSTRACT

This investigation is to establish a foundation for developing a nondestructive tester with an acoustic analyzer for predicting the tensile strength of leather. Observations showed an excellent correlation between the tensile strength of leather and the corresponding acoustic cumulative energy at break, read from an acoustic emission analyzer. Moreover, a linear relationship was observed between the acoustic cumulative energy at break and the initial acoustic cumulative energy when leather was stretched to 10 percent of it original length. More importantly, a correlation was observed between the initial acoustic cumulative energy and the tensile strength of leather. The implication of these phenomena is that the tensile strength of leather may be predicted without breaking the leather, by measuring the initial acoustic cumulative energy. The result of this study thus provides an essential base facilitating the possible design of a portable leather stretcher attached with an acoustic sensor. This would allow the prediction of tensile strength by measuring the cumulative acoustic energy during initial stretching without breaking or damaging the leather.

INTRODUCTION

Currently, there is no on-line test method to monitor the physical properties of semi-products such as wet blue or crust during the leather-making processes.[1] This causes a tremendous waste in terms of chemicals and energy. Having the right monitoring tool, inferior leather semi-products, such as wet blue, could be down graded earlier or removed before going through many expensive leather making processes including retanning, fatliquoring, dyeing, drying, staking, and finishing. Therefore, developing a nondestructive tester to perform on-line testing of the physical properties of semi-products is very desirable. By early detection of weakness or defects, tanneries will be able to adjust the processing parameters to correct the problems or remove the inferior semi-product at an earlier time in the process to prevent unnecessary use of chemicals and energy, while providing better quality control.

Acoustic emission has been recognized for some years now as a valuable nondestructive test method for detecting the onset of cracking or other kinds of failure in engineering structures, aircraft wings or pressure vessels for example, which are exposed to considerable stress or strain in service.[2] Acoustic emission (AE) is a passive procedure in that propagating cracks emit a noise and ultrasonic transducers are used to detect it. The AE method has also been applied in coatings research and the technique is proving extremely useful in earlier identification of coating adhesion failure.[3] For leather, Kronick and Thayer have demonstrated that the strength of fiber adhesions can be determined by "listening" to the sounds emitted by the sample when it is stretched.[4] Moreover, Kronick and Maleeff reported that by observing a sudden increase in energy and the frequency of acoustic pulses, they were able to determine when the leather was about to fail far before it broke or tore.[5] The implication of this finding is that AE methods could be a useful tool to monitor the tensile strength of leather during the leather-making processes without interrupting the processing.

Tensile strength is one of the most important qualities of leather. To determine the tensile strength, samples are cut from a side of leather, brought to a quality testing room, and measured for tensile strength. This operation not only is time-consuming but can also damage or even waste the whole side. We therefore aim to develop a nondestructive process control tool based on the AE methods to monitor the tensile strength of leather. Our first task is to examine whether there is a relationship between tensile strength and any of the AE data - number of hits, the acoustic energy generated during stress-strain tests, or amplitude distribution.

EXPERIMENTAL

Materials

A mature bovine hide was tanned by the standard ERRC process[6] and was air-dried without fatliquor, and then was conditioned at 23°C and 50 percent RH for several months. Samples were cut following ASTM method D2813-91. The moisture content of the samples was 10 ± 2 percent (dry weight base) determined by a leather moisture meter (Delmhorst Instrument Co.).

Principle of Acoustic Emission

The deformation of leather caused by an external uniaxial force is accompanied by a rapid vibration of structural elements such as fibrils, fibers and fiber bundles. As a result, this produces mechanical waves that can be detected by an acoustic transducer and converted into electronic signals, as reported by Kronick et al.[7,8] This phenomenon may be defined as an acoustic emission event or "hit."[9] A single acoustic emission event may consist of several emission counts, which are the number of times a signal crosses a preset threshold of amplitude, as illustrated in Figure 1. Because of the nature of the fibrous composite structure of leather, the sonic wave belongs to "burst type" acoustic emissions. The waveform associated with this type of acoustic emission generally shows a transient, fast-rise/slow-decay nature to the signal. The peak signal amplitude can be related to the intensity of the source in the leather producing an acoustic emission. High amplitude events of long duration tend to have many threshold crossings. The amplitudes of AE are customarily expressed on a decibel (logarithmic) scale, in which 1 μV at the transducer is defined as 0 dB, 10 μV as 20 dB, 100 μV as 40 dB, and so on.

A common measure of acoustic emission activity is ring-down counts: the number of times the sensor signal exceeds a counter threshold. Since acoustic emission activity is attributed to the rapid release of energy in leather material, the energy content of the acoustic emission signal can be related to this energy release and can be measured electronically. As shown in Figure 1, the energy is proportional to the area under the acoustic emission waveform. The electrical energy U present in a transient event can be defined as:

$$U = \frac{1}{R} \int_0^{\alpha} V^2 (t) dt$$

where R is the electrical resistance of the measuring circuit, t is time, α is the duration time of detectable signal, and V is the output voltage of the acoustic transducer induced by the sonic waves. Direct energy analysis can be performed by electronically digitizing and integrating the waveform signal. The advantage of measurement over ringdown counting is that energy measurements can be directly related to important physical parameters such as mechanical energy in the emission event, strain rate or deformation mechanisms. Energy measurements also improve the acoustic emission testing results when emission signal amplitudes are low, as in the case of the initial deformation of materials.

Methods and Apparatus

Tensile stress-strain tests and AE data collections were performed simultaneously to study their relationships directly. The tensile tests were carried out using an Instron tensile tester (model 1122) and conducted at 23°C. To obtain acoustic-emission data, a small piezoelectric transducer resonating at 150 kHz (Model R15, Physical Acoustics Corp., Princeton, NJ), 10 mm diameter and weighing 20 g, coated with a film of petroleum grease for more efficient acoustic coupling, was clipped against the leather sample in a tensile tester. Electrical signals emanating from this transducer and from the force transducer of the tensile tester when the sample was stretched were processed with a Model 1220A preamplifier and a LOCAN-AT Model 3140 acoustic emission analyzer (Physical Acoustic Corp.) Each acoustic pulse from an event in the sample caused a damped oscillation to be emitted by the transducer. The analyzer recorded the arrival time of each oscillation pulse, its amplitude, and its energy. Only pulses giving maximum amplitudes greater than 35 dB from the transducer were counted. The energy of the hits, estimated by the "ring-down" method,[9] is proportional to the average area under the rectified pulses, so is determined by the pulse amplitudes and the pulse durations. Since the pulses are

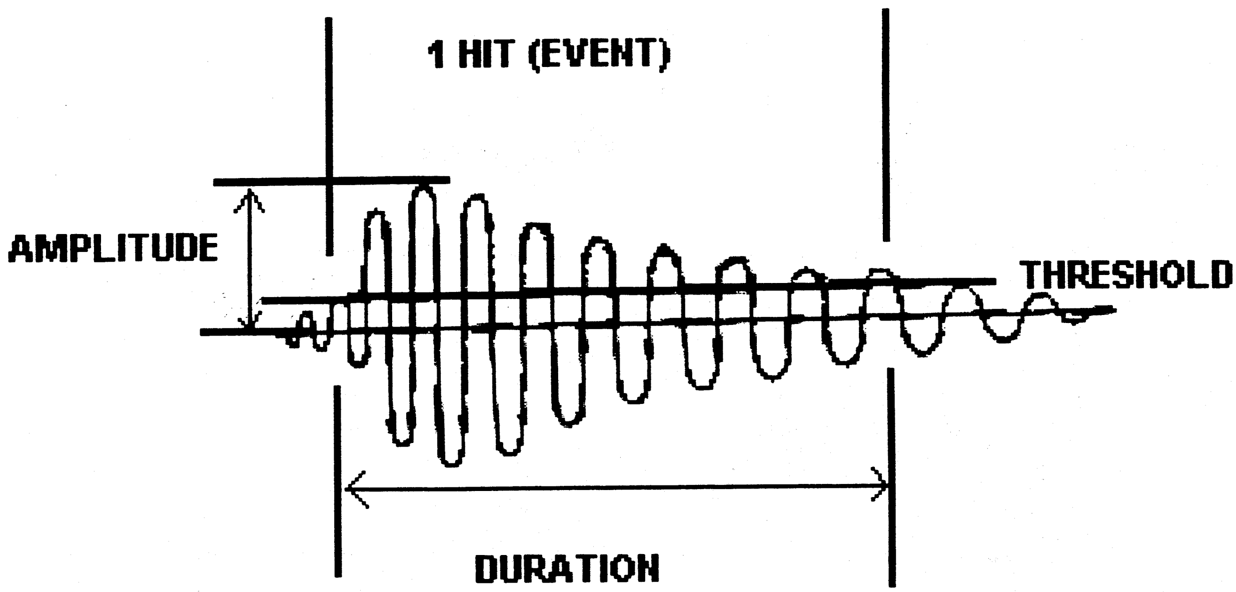

FIGURE 1. — Waveform

highly damped in leather, the durations are always short and increase with amplitudes. Therefore the acoustic energies are correlated with the pulse amplitudes.

Results and Discussion

Acoustic Events (Hits vs Time)

A basic way to graph AE activities is to plot the number of recorded hits or events as a function of time. Figure 2 displays the chronological course of the test, demonstrating the hits vs time profiles during the stress-strain testing of leather for two significantly different tensile strengths. Figure 2a is for a tensile strength of 14 MPa and shows that more hits are generated during the latter part of stretching. In contrast, Figure 2b for the sample having a tensile strength of 21 MPa shows more hits generated in the earlier stages of stretching. However, those AE profiles do not give conclusive insides or hints that can be linked to the changes in tensile strength.

Amplitude Distribution

Figure 3 illustrates the frequency distributions of AE-hit amplitudes during stretching. The amplitude presented here is the peak voltage attained by the AE waveform as illustrated in Figure 1. The stronger leather (Figure 3b) produces hits with higher amplitudes. Observations also show that the stronger leather does not necessarily produce more hits than the weaker leather. Moreover, the hits from weaker leather, as shown in Figure 3a, are more concentrated in the range between 35 to 45 dB. This is in contrast to the stronger leather as shown in Figure 3b, where a more uniform distribution across the 35 to 55 dB range is seen, with a small population located in a higher amplitude region, from 55 up to 70 dB.

Acoustic Energy Patterns

We also examined the acoustic energy difference in the response to the change of tensile strength. Figure 4 demonstrates that the acoustic energy increases progressively up to failure. There are higher energy hits at higher deformations. Moreover, it appears that the stronger leather released more acoustic energy than the weaker leather as shown in Figure 4b and 4a respectively. The difference is particularly pronounced in the later stages of stretching toward total fracture of the leather. It should be noted that the acoustic energy described here is an instantaneous acoustic quantity at a particular moment of stretching. Although it shows a clear trend indicating that the stronger leather produces more energetic mechanical waves, a definitive correlation still cannot be fully concluded between tensile strength and acoustic energy.

Acoustic Cumulative Energy

All the AE data presented so far were attained at a particular moment. Figure 5 shows the cumulative energy, i.e., the summation of energy measure since the start of the test, as a function of time. These curves propagate very similarly to those of stress-strain curves. The cumulative energy slowly increased with stretching time until reaching a breaking point. The most significant information obtained from these

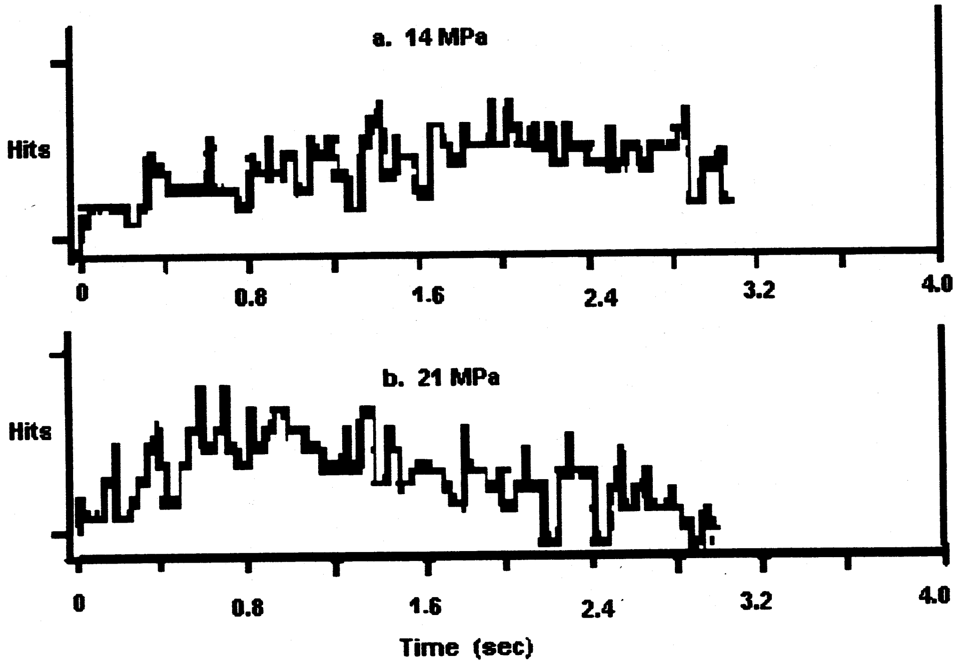

FIGURE 2. — Acoustic Events (hits) History

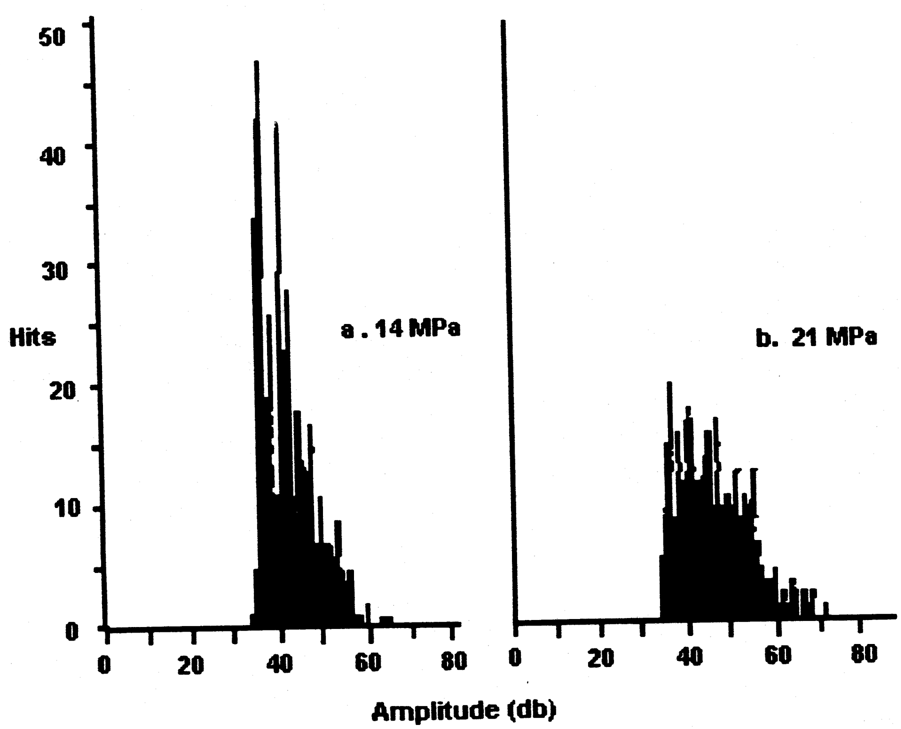

FIGURE 3. — Amplitude Distributions

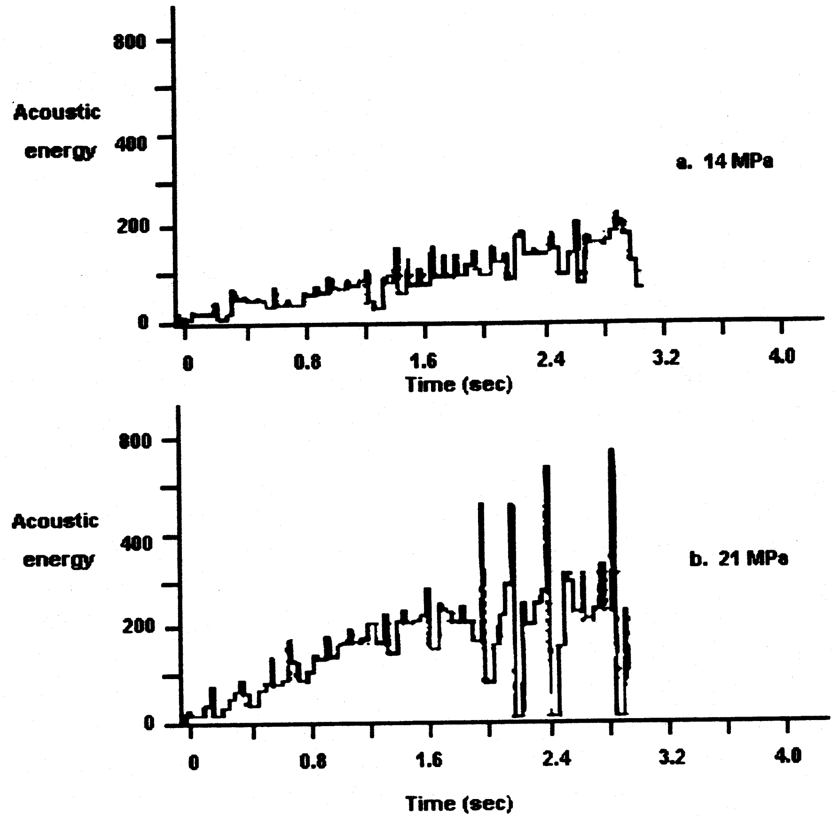

FIGURE 4. — Acoustic Energy vs Time

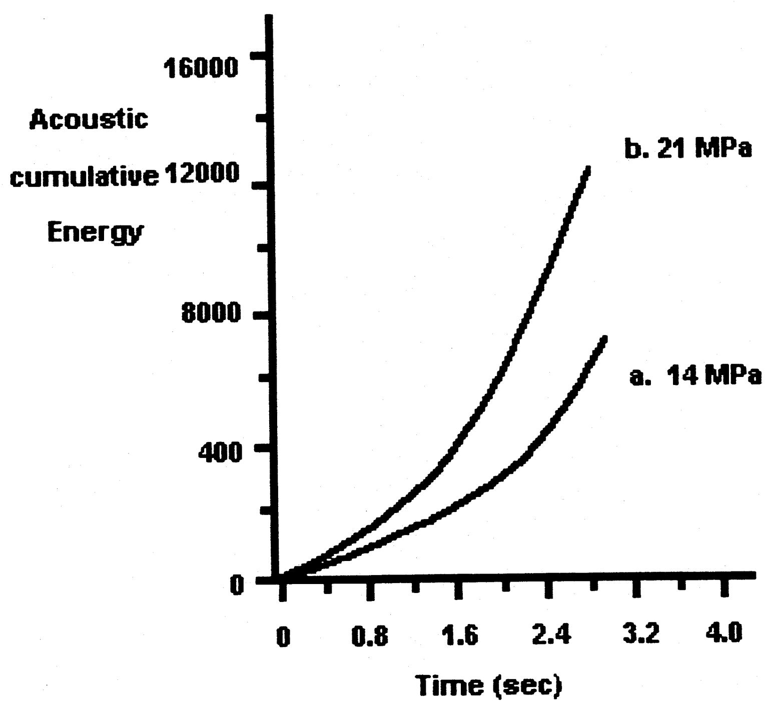

FIGURE 5. — Acoustic Cumulative Energy vs Time

tests is that the stronger leather released higher cumulative energy as demonstrated clearly in the comparison between samples of 14 MPa and 21 MPa.

Relationship Between Tensile Strength and Acoustic Cumulative Energy

To be more systematic and conclusive, we performed tensile tests and AE analysis simultaneously on 16 samples. An experimental design from the technique named "response surface methodology," developed by Box and Hunter for two factors study,[10] was followed to arrange sixteen combination of two independent variables such as strain rate and sampling angles as listed in Table I. SAS statistical software was used to formulate the relationship between dependent variables, including tensile strength and AE cumulative energy and independent variables as mention before. Figure 6 shows a 3-D plot of the tensile strength as a function of strain rate and sampling angle simultaneously. It shows that the tensile strength decreases with strain rate at the beginning; then when the rate reaches around 150 mm/min the tensile strength increases with strain rate. This behavior may be explained by the effects of stress concentration and generation of local heat as discussed in detail in a previous research paper.[10] Leather is known to be a highly anisotropic material and its tensile strength is strongly associated with fiber orientation. Consequently it is dependent on the sample angle. Figure 6 shows that tensile strength maximizes at 0° sampling angle and slowly decreases as the sampling angle deviates from 0°. Samples taken from parallel to back bone direction have the highest tensile strength.

Interestingly, the sampling angle also imposes the same effect on the acoustic cumulative energy. As shown in Figure 7, the cumulative energy at break also peaks at 0° sampling angle and slowly decreases as the sampling angle deviates from the parallel direction. On the other hand, Figure 7 also shows that an increase in strain rate leads to a monotonous increase in the cumulative energy. This behavior is slightly different from that of tensile strength in the very slow strain rate range, i.e., below 150 mm/min. For a close comparison, we then plotted tensile strength against the corresponding AE energy as illustrated in Figure 8. It is quite clear that there is a correlation between these two physical quantities, showing again that the acoustic cumulative energy increases as tensile strength increases or vise versa. The deviation from the regression line may be attributed to the slightly different responses to the change of strain rate.

TABLE I
Test Conditions

	Strain Rate (mm/min.)	Sampling Angle (°)
1	250	-45
2	200	0
3	100	-45
4	200	0
5	100	45
6	200	0
7	200	0
8	300	45
9	200	64
10	200	0
11	250	0
12	200	0
13	200	0
14	200	-64
15	50	0
16	200	0

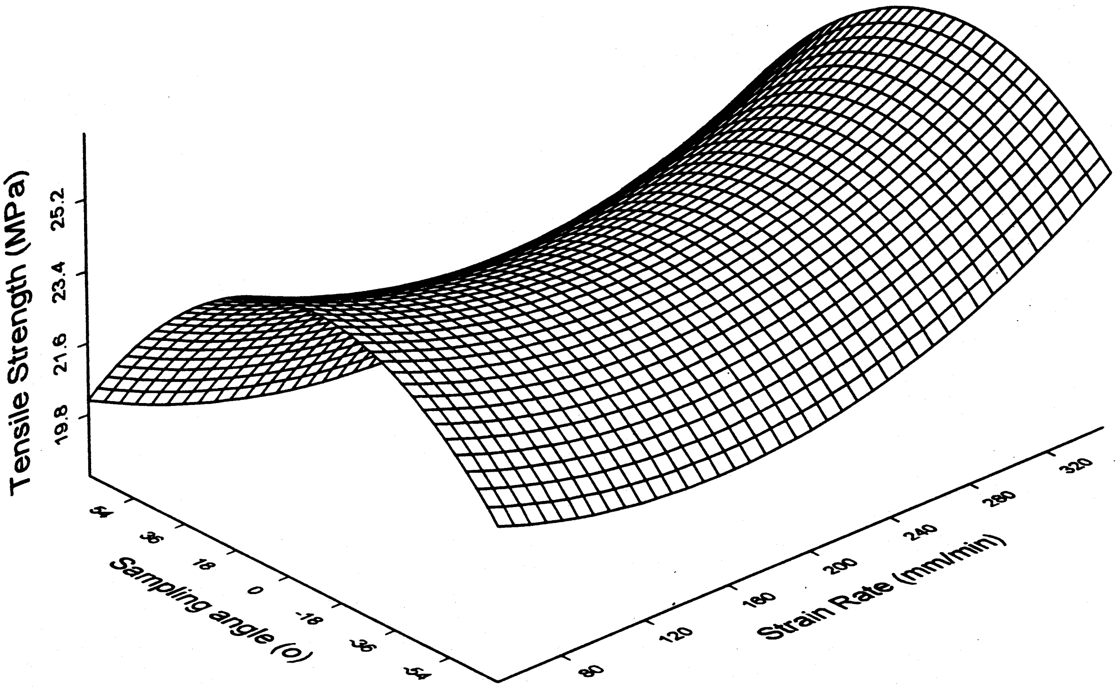

FIGURE 6. — Tensile Strength as a Function of Strain Rate and Sampling Angle

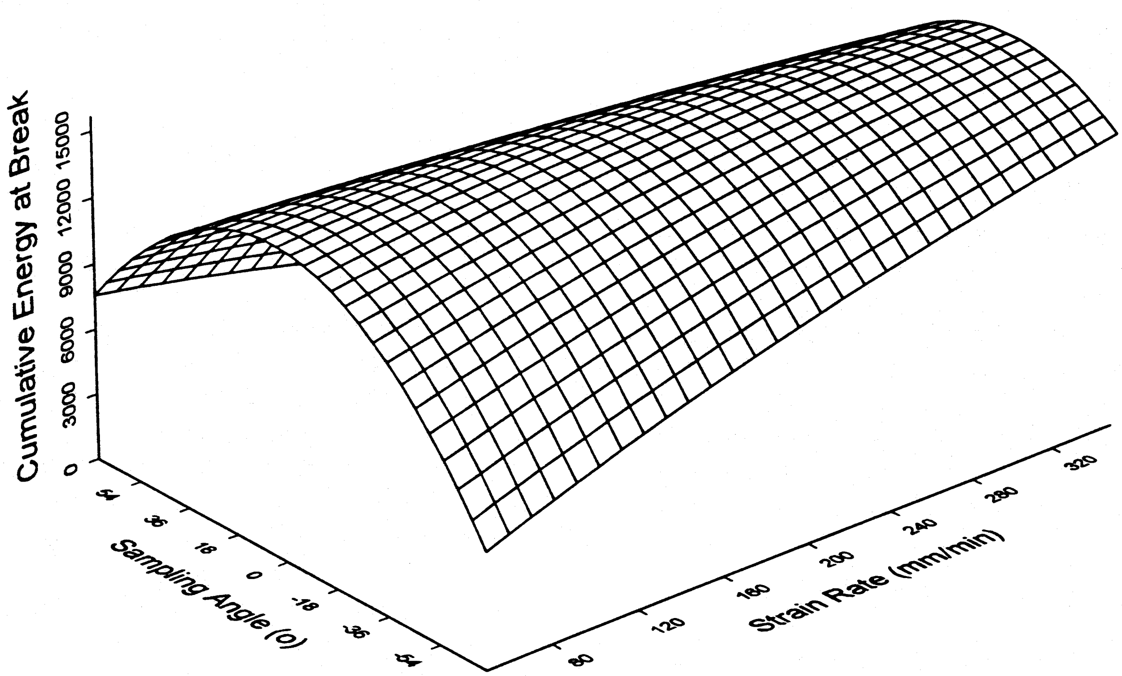

FIGURE 7. — AE Cumulative energy at Break as a Function of Strain Rate and Sampling Angle

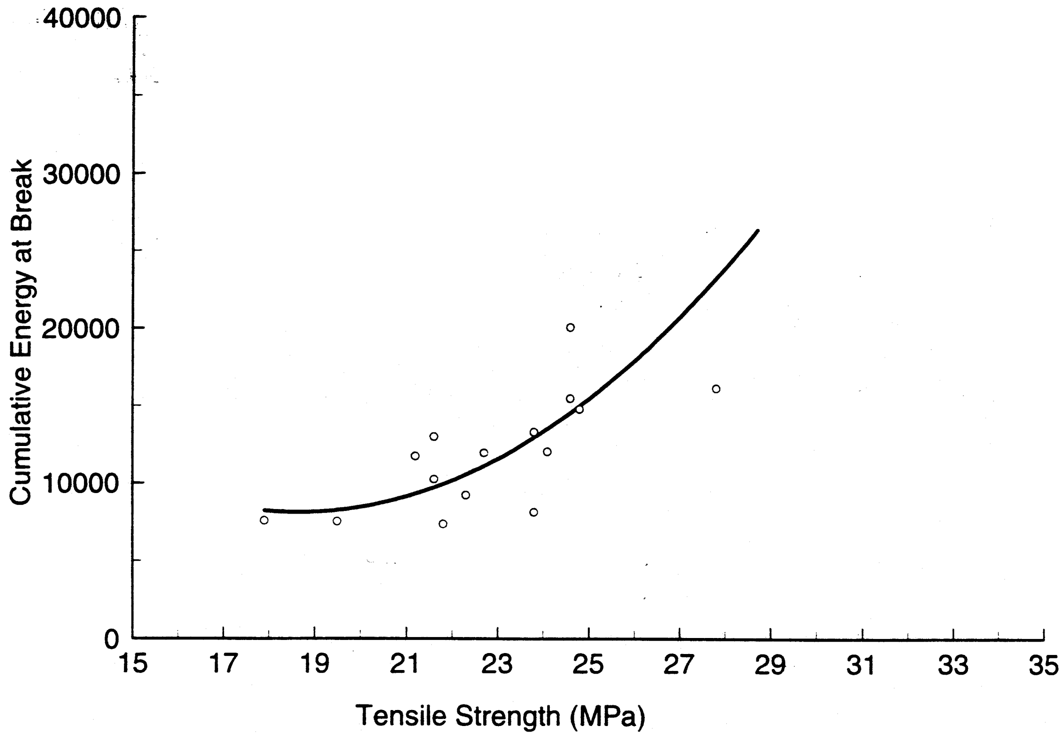

FIGURE 8. — Correlation between Acoustic Cumulative Energy at Break and Tensile Strength

Initial Cumulative Energy vs Acoustic Cumulative Energy at Break

A further investigation was conducted on the initial cumulative energy in response to the change of sampling angle and strain rate. The initial cumulative energy was measured when the leather samples were stretched to 10 percent strain, where the strain remained in the elastic deformation region of leather. Observations showed that these deformations are recoverable once the stress (or load) is released. As shown in Figure 9, the initial cumulative energy behaves very similarly to the cumulative energy at break, as it also peaks at 0° sampling angle and slowly decreases as the angle deviates from the parallel direction. Moreover, as also shown in Figure 9, the initial cumulative energy increases with an increase in strain rate. We then examined the correlation between initial cumulative energy and cumulative energy at break. As demonstrated in Figure 10, the initial cumulative energy is proportional to the cumulative energy.

Initial Cumulative Energy vs Tensile Strength

A correlation is also observed between initial cumulative energy and the corresponding tensile strength, as shown in Figure 11. The implication of this finding is very significant to the design of an AE nondestructive tester to predict the tensile strength. Based on the relationship derived from this study, one may use this tensile stretcher to elongate a leather sample to 10 percent strain and obtain the initial cumulative energy data from an AE analyzer. The tensile strength then can be predicted without damaging or fracturing the leather.

Discussion

Before understanding the AE data, one has to review the fine structure of leather. Leather consists of collagen fibers with a very complex structure, a network of interwoven fiber bundles with large spaces unevenly distributed among them. The fibrous structure may be revealed best when leather is fractured, as demonstrated in Figure 12. This is a micrograph of the fractured end of a leather specimen. It has been reported that fiber bundles (20-200 μm) of leather are comprized of very fine element fibers (10 μm), which can further be divided into even finer fibrils (0.01-0.5 μm).[11] The overall tensile strength is a measure of the tensile fracture resistance which is dependent on the mobility of fiber bundles and their degree of interweaving. The mobility leads fiber bundles to align in the direction of the applied force; interweaving affects how strongly those fibers bundles hold together. Another factor that is also very important is the fiber bundle orientation, which is

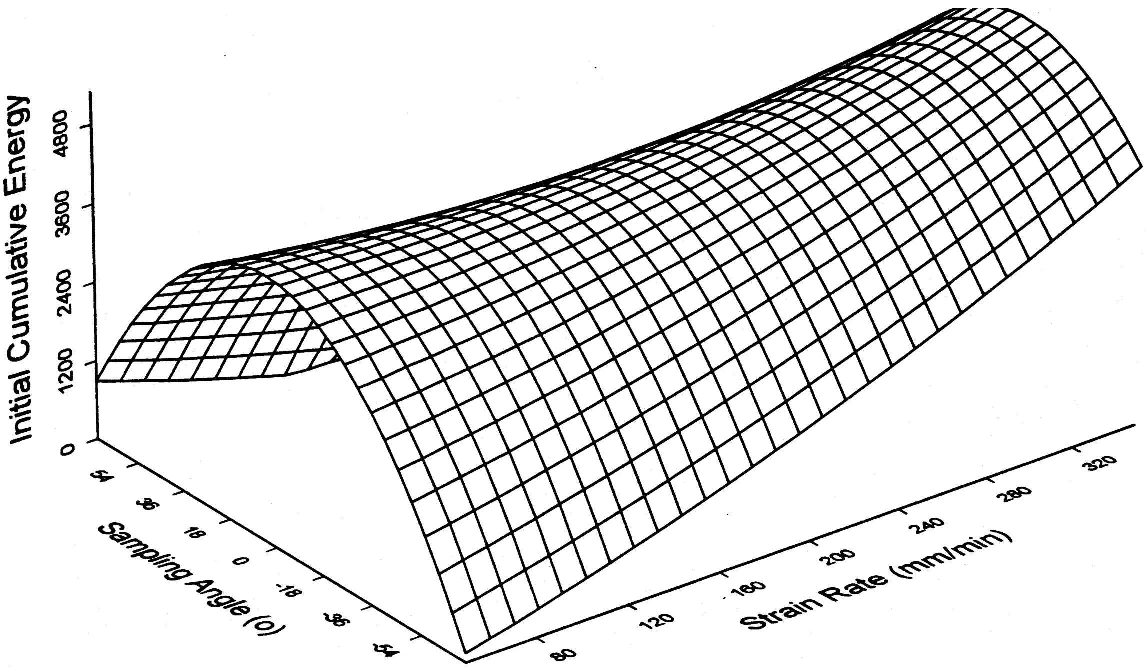

FIGURE 9. — Initial Cumulative Energy as a Function of Strain Rate and Sampling Angle

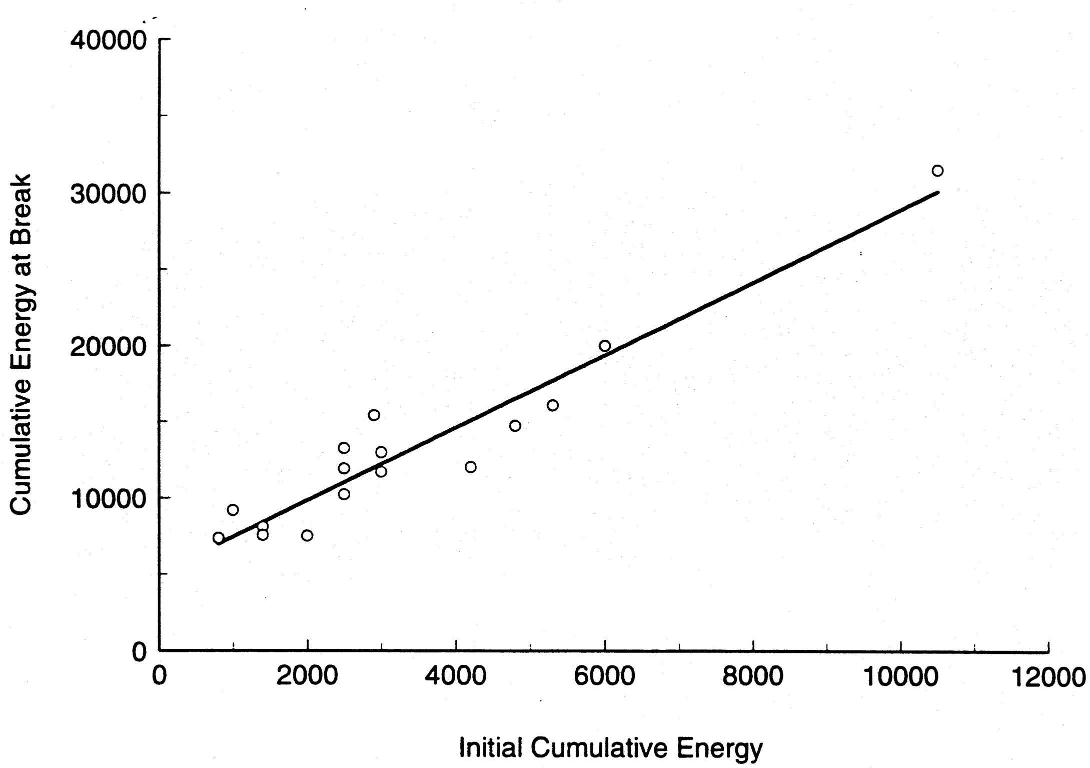

FIGURE 10. — The Relationship between Initial Cumulative Energy and Cumulative Energy at Break

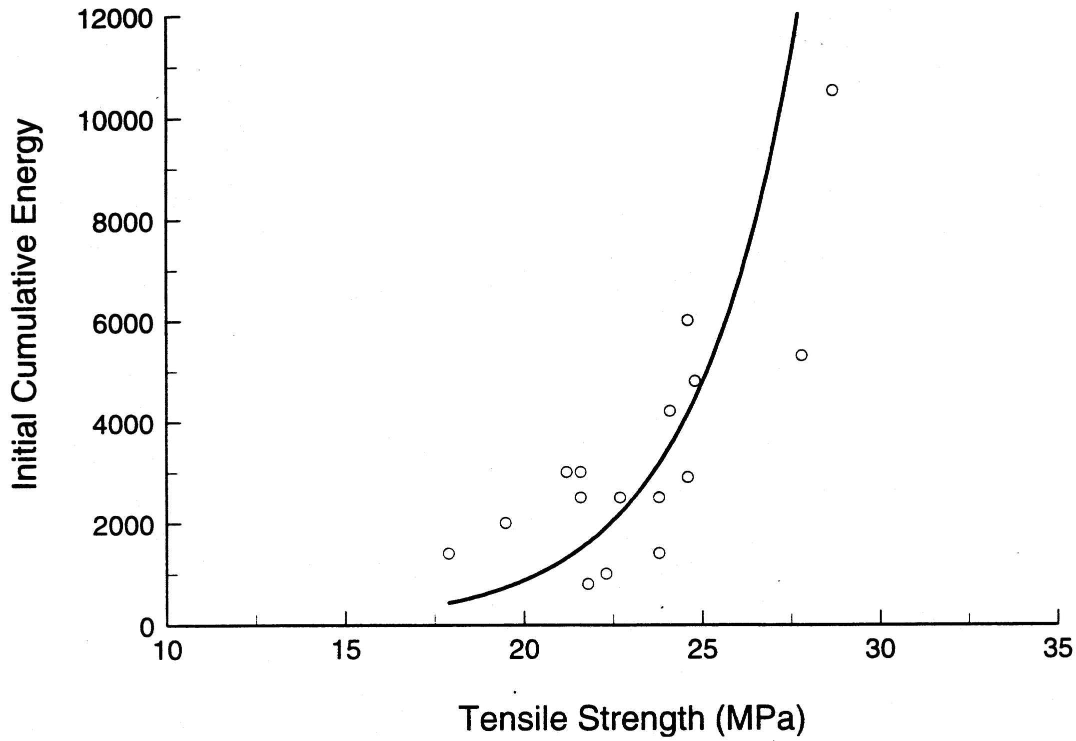

FIGURE 11. — The Relationship between Initial Cumulative Energy and Tensile Strength

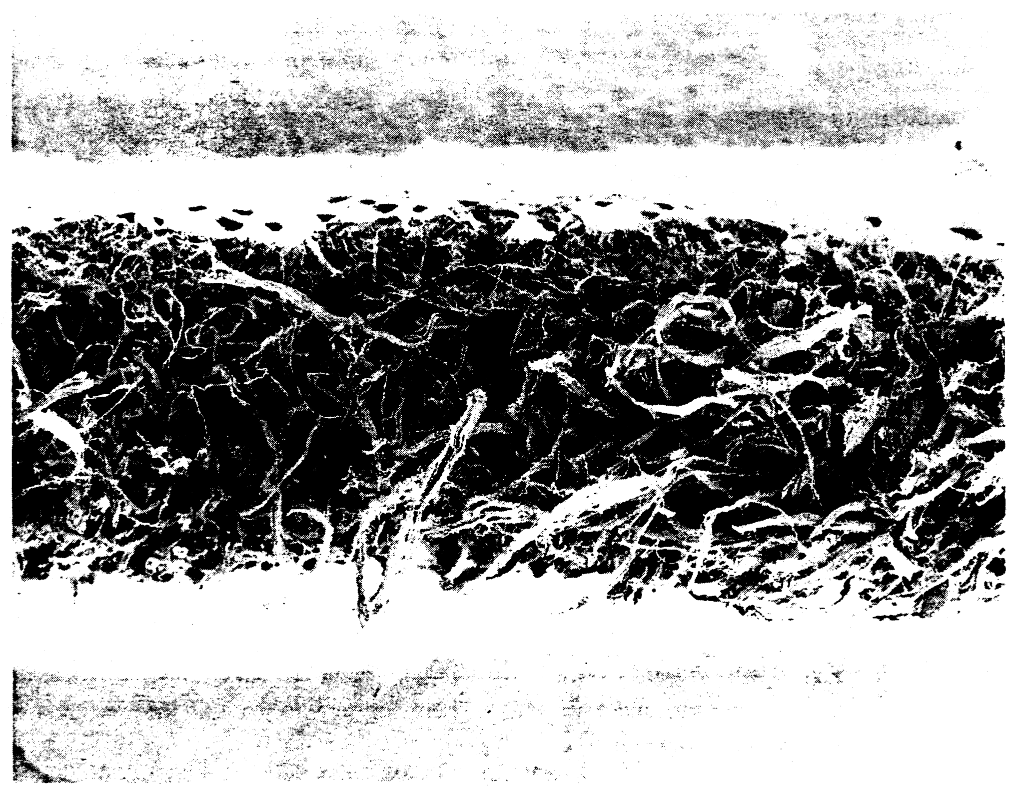
FIGURE 12. — Micrograph of a Cross-section of Fractured Leather

dependent on the sampling angle.[11] On the other hand, AE hits only represent the number of significant deformations or fiber/fiber bundle fractures, which have no bearing on the tensile fracture resistance, i.e., tensile strength. Therefore it is not a surprise that the AE hits do not show a correlation with tensile strength. On the other hand, the results of AE amplitude distributions indicate that the hits with a good uniformity and higher amplitude may implicate higher tensile strength material. The correlation, however, is hardly conclusive and very difficult to represent in a quantitative manner.

Finally, the acoustic energy data give a more well defined correlation with tensile strength. Leather having better tensile strength shows a more rapid increase in acoustic energy, particularly before the leather is about to break. This agrees with the behavior during a tensile test. As most leather responds to a stretch, the tensile resistance, i.e., tensile stress increases with time until total fracture. This tendency agrees with the fibrous structure of leather. The AE energy reflects the intensity of mechanical waves induced by the vibration of fibers or fiber bundles. Thus, the AE energy is an indication of the magnitude of fiber vibration, which in turn is related to how much elastic energy is released. As tensile stress increases with time, more elastic energy is stored in the leather and accordingly more elastic energy is released when fibers/fiber bundles break. As a result, it is reasonable to expect that the acoustic energy-time profile has a well defined correlation with the tensile strength as demonstrated in Figure 4. However, the acoustic energy shown in Figure 4 is an instantaneous quantity and is a step-wise function of time. The non-smoothness of the curve is due to the fluctuation in released elastic energy during a stretch process. In contrast, the cumulative energy curves, as demonstrated in Figure 5, show a smooth continuity with time. The cumulative energy at each instance has summarized previous energy and becomes independent of history of energy variation or changes. Another advantage of using a cumulative AE quantity is to magnify the increase in AE energy due to an increase in the tensile stress as demonstrated in Figure 5. A fruitful outcome is clearly shown in Figure 8, the correlation plot of tensile strength vs cumulative energy at break. The physical meaning of this correlation is that the total elastic energy released by stretching leather to a breaking point is proportional to the fracture resistance, i.e., tensile strength. The rationales of this correlation may come from Hooke's law and will be discussed in greater depth later.

For nondestructive testing, the AE data must be collected from early stretching regions without inducing a non-recoverable deformation or fracture. Therefore, the results as shown in Figure 8 are not sufficient enough to be a basis or groundwork for developing a nondestructive AE tester for predicting tensile strength. Since the AE energy is associated with the elastic energy released during deformation or stretching, it should be proportional to the displacement of samples according to Hooke's law[12,13] and consequently, proportional to the time of stretching or the degree of stretch (strain). Therefore, one may expect that a close relationship may exist in cumulative energies between the initial deformation and final breaking points, as demonstrated in Figure 10. Ten percent strain is a recoverable deformation for most leather, and that strain produces sufficient detectable AE signals. As a result, the initial cumulative energy at 10 percent strain was used to correlate to final cumulative energy. This hypothesis was confirmed by the excellent correlation shown in Figure 10 between the cumulative energy and the initial cumulative energy at 10 percent strain. A further encouraging finding is shown in Figure 11, which demonstrates a fair correlation between tensile strength and initial cumulative energy. As mentioned earlier, the implication of this finding is an essential basis to the feasibility of the design of an AE nondestructive tester to predict the tensile strength. Based on the relationship derived from this study, one may use this tensile stretcher to elongate a leather sample to 10 percent strain and obtain an initial cumulative energy pattern using an AE analyzer. The tensile strength can then be predicted without damaging or fracturing the leather.

A question that may be raised is whether one can predict final tensile stress, i.e., tensile strength from initial stress for example at 10 percent strain. If the answer is positive, then the AE method may be unnecessary, and a simple tensile stress-strain measurement may serve the same purpose. However, the answer is negative if one considers the difference between elastic and viscoelastic behavior. The tensile behavior of leather can be related to the viscoelasticity of the leather, in that besides the elasticity, the viscous component or viscosity plays an important role in determining the stress-strain curve even at the very beginning of deformation as discussed in our previous paper.[14] However the tensile strength is the ultimate stress measured at breaking. It has little to do with the viscosity of leather; instead, it is largely determined by the elasticity of leather at the breaking moment. Consequently, there is no direct relationship between tensile strength and initial stress.

On the other hand, AE is only associated with the elasticity of leather. Both the initial cumulative energy and final cumulative energy are released by elastic waves; thus they are associated with elastic properties. In contrary, the initial stress or the stress-strain curves are associated with viscoelasticity. Therefore, one cannot predict the tensile strength from the initial tensile stress.

Conclusions

This investigation has demonstrated that a correlation exists between the tensile strength of leather and the cumulative acoustic energy released from the initial stretching. This correlation provides an essential base facilitating the possible design of a portable leather stretcher equipped with an acoustic sensor, which would allow the prediction of tensile strength by measuring the cumulative acoustic energy during initial stretching without breaking or damaging the leather. The success of this research project will possibly produce an AE tester, providing the leather industry with a nondestructive way in which to monitor the quality of leather at each intermediate leather-making stage. As a result, tanners would be able to adjust their leather-making processes accordingly to yield high quality leather.

Acknowledgments

The authors wish to thank Dr. Paul Kronick for advice on the use of the acoustic analyzer. We also thank Dr. Peter H. Cooke for the SEM micrographs. Particular appreciation is extended to Drs. James Shieh and David Coffin for their invaluable suggestions.