NEW ACOUSTIC METHODS FOR NONDESTRUCTIVE EVALUATION OF LEATHER QUALITY

by

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ABSTRACT

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. Inferior leather semi-products, such as wet blue, cannot be downgraded earlier or removed before going through many expensive processes (including retanning, fatliquoring, dyeing, drying, staking, milling and finishing). Therefore, developing a nondestructive tester to perform on-line testing of the physical properties of semi-products is very desirable. Recently ARS transferred its knowledge gained over the years to Physical Acoustics Corporation (PAC) and collaborated with the leather industry in order to produce an on-line nondestructive acoustic emission tester. This paper discusses the activities performed by PAC, ARS, and the Seton Company during the Small Business Innovative Research (SBIR) Phase I project "Acoustic Emission for the Characterization of Leather." The main objective of this project was to demonstrate the feasibility of using AE and Airborne UT to assess, characterize, and classify the quality level of various types of leather. The results obtained in this project show that it is feasible to use AE for the evaluation of leather quality during the manufacturing process. A newly designed AE system for the evaluation of leather quality is discussed in this paper. This system, which combines a handheld AE instrument with a rolling sensor probe, offers the potential for testing entire hides in the manufacturing plant. Data could be gathered from different sections of the hide, along different directions with respect to the backbone, and during different stages in the manufacturing process. Finally, we reported a simple method using a mechanical stopwatch as an acoustic wave source. Hits rate were collected when sound traveled though the leather samples. Results show a strong correlation between tensile strength and cumulative hits.

RESUMEN

Actualmente, no hay un método de prueba en la línea de producción para monitorear las propiedades físicas de productos semi-elaborados tales como wet-blue o semi-terminados durante los procesos de la fabricación del cuero. Los productos semi-elaborados como el wet blue de inferior calidad, no pueden ser deseleccionados al inicio o desviados de la línea de producción, sin antes pasar por muchos procesos costosos (que incluyen el recurtido, el engrasado, el teñido, el secado, el estirado, el ablandado y el acabado). Por lo tanto, el desarrollar una prueba no destructiva para realizar durante el procesamiento comprobando las propiedades físicas de productos semi-elaborados, es muy deseable. Recientemente ARS [Servicio de Investigación Agrícola del Departamento de Agricultura de los EEUU.] transfirió sus conocimientos de muchos años a la Physical Acoustics Corporation (PAC) y colaboró recientemente con la industria del cuero para producir un método de ensayo no destructivo

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durante la producción usando un probador de emisión acústica. Este trabajo discute las actividades realizadas por PAC, ARS, y la Seton Company durante un proyecto de innovación para la microempresa (SBIR), durante la primera fase del proyecto "emisión acústica para la caracterización del cuero" [AE]. El objetivo principal de este proyecto era demostrar la viabilidad de usar AE y UT aéreo para determinar, caracterizar, y clasificar el nivel de la calidad en varios tipos de cuero. Los resultados obtenidos en este proyecto demuestran que es factible utilizar AE para la evaluación de la calidad de cuero durante el proceso de fabricación. Un nuevo sistema diseñado de AE para la evaluación de la calidad de cuero se discute en este trabajo. Este sistema, que combina un instrumento manual de AE con un sensor rotativo [ver JALCA Nov. 2005 pg. 440], ofrece el potencial para probar pieles enteras en la planta fabril. Se pueden recopilar los datos de las distintas secciones de la piel, a lo largo de diversas direcciones con respecto al lomo del cuero, y durante diversas etapas en el proceso de fabricación. Finalmente, divulgamos un método simple usando un cronómetro mecánico como fuente de la onda acústica. La cantidad de impactos acústicos fue determinada cuando el sonido atravesaba las muestras de cuero. Los resultados demuestran una fuerte correlación entre la resistencia a la tracción del cuero y los golpes acústicos acumulados.

INTRODUCTION

As with any manufactured product today, leather hides must meet certain quality criteria. Quality control and assurance procedures in the leather industry today require destructive tests to be performed on finished leather in order to determine the material properties. These tests are performed prior to the leather's being made into a final product. Since leather is sold by the square foot, the destructive tests lessen the square footage of the material and therefore infringe on the leather manufacturers' total profit.

There are currently no methods available that can determine the material properties of leather nondestructively and quantitatively at the different stages of manufacturing. Acoustic methods could potentially be used for on-line nondestructive evaluation (NDE) for monitoring the material properties of leather as a quality control (QC) procedure and therefore avoid damaging and waste of material. In particular, Acoustic Emission (AE) and Airborne Ultrasonics (UT) offer the best potential for on-line monitoring of the leather manufacturing process. If successful these acoustic methods would give the leather industry real time data during the manufacturing process, allowing the differentiation between good and bad hides. This would save the leather manufacturers a considerable amount of money, decrease the use of chemicals, reduce production time, increase the value of the leather, and increase quality. The AE method of nondestructive evaluation (NDE) has been used for many years in a wide variety of applications, including inspection of aircraft and military equipment, civil infrastructure, pipelines and tubes, petrochemical facilities, and industrial systems. Kronick and Thayer initiated a feasibility study into the use of AE for leather characterization.[1] The results of this study showed AE as a promising technique for the assessment of leather properties. More recently, Liu et al. of USDA started research using AE as a QC method related to the different stages of the leather making process.[2-8] Interesting results were obtained from the use of AE to predict the tensile strength of leather by measuring the initial cumulative AE enegy.[3] AE has been subsequently applied in the study of leather tear resistance,[5] liming process,[4] degree of lubrication,[2] and quality of final coatings.[6] Recently, focus was shifted from using a flat sensor to a rotational sensor, thereby making feasible the nondestructive and dynamic measurements of AE quantities.[7, 8] Observations showed an excellent correlation between the softness of leather and the corresponding cumulative acoustic counts. We also used this dynamic method to characterize the grain break of leather. Results showed that the difference in grain break could be determined from the amount of acoustic energy collected from moving the AE sensor over a leather sample laid inside a half pipe. The grain break decreased as the AE energy increased. The higher AE energy is an indication of stiffer leather; therefore, the results revealed that stiffer leather is prone to bad grain break. Data also demonstrated that the thicker samples tended to have poorer grain break. We derived a predictive model that could be very useful for objectively testing grain break using the AE method described in this report. Results also showed a close relationship between the tensile strength and AE energy obtained from testing. In short, these previous studies demonstrated that the softness, tensile strength and grain break could be nondestructively determined by measuring the acoustic quantities with a rotational sensor rolling over the leather. Liu et al. have also extended AE studies to characterize the fracture mechanisms of various green composites (bio-based and bio-degradable).[9-13]

Airborne Ultrasonic (UT) inspection techniques, on the other hand, have been used extensively in the inspection of composite materials and adhesive bonds.[14-17] As this is a non-contact technique, it is an ideal inspection method for leather from hides. Since airborne ultrasonics is very sensitive to surface conditions, it can be used to evaluate leather surface conditions and to locate surface defects such as scars, knife cuts and insect bites. These research results will be described in our future reports.

To investigate the possibility of developing NDE methods based on AE and Airborne UT for QC of leather, the Small Business Innovative Research (SBIR) Phase I project "Acoustic Emission for the Characterization of Leather" was awarded to Physical Acoustics Corporation (PAC) by the USDA for a duration of six months. The Seton Company (Seton) participated in this SBIR as an industrial partner. Seton supplies leather totally for the automotive industry. The main

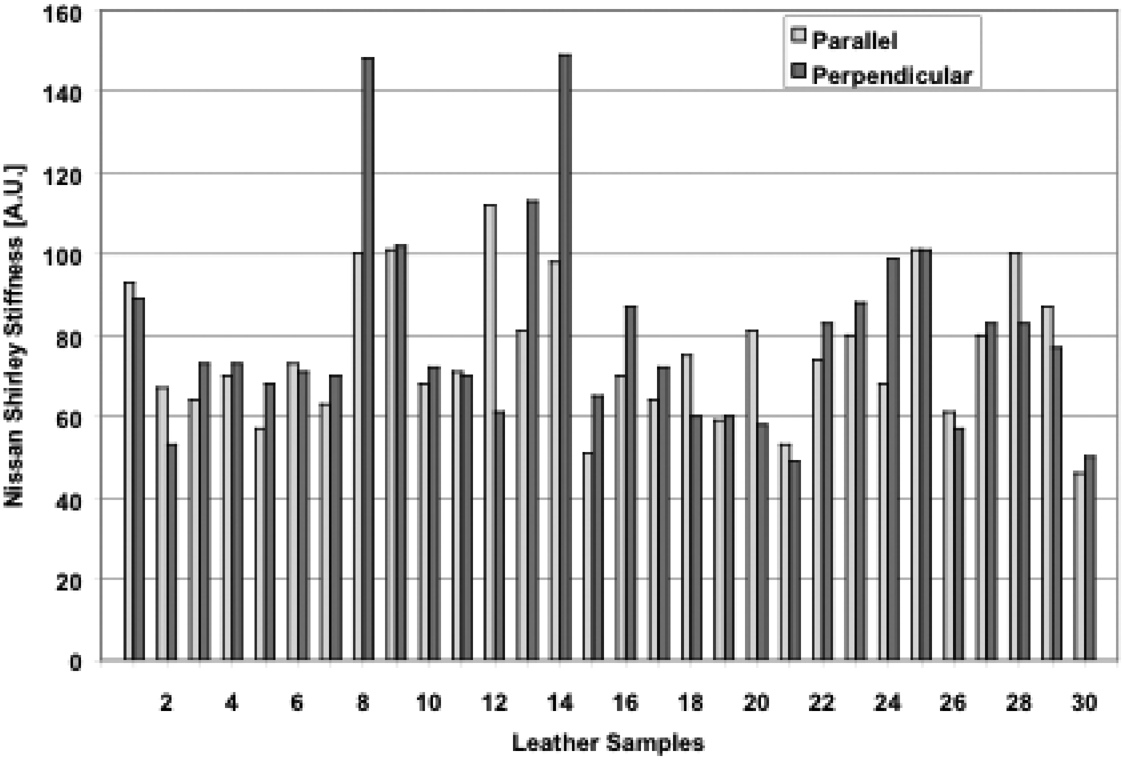

Figure 1: Shirley Stiffness for the 30 samples provided by Seton

objective of this SBIR Phase I project was to demonstrate the feasibility of using Acoustic Emission (AE) to assess, characterize, and classify the quality level of various types of leather.

EXPERIMENTAL

Materials

Seton provided a set of leather samples, consisting of both chrome and chrome-free leather processed from bovine hide. This set consisted of 30 samples of leather covering a wide range of stiffness values (as presented in Figure 1) and surface finishes, and was used to investigate the correlation between stiffness and AE parameters. All thirty samples were rectangular in shape (29.2 cm by 20.9 cm).

The leather stiffness for each sample was measured using the Nissan Shirley Stiffness test method (NSS), which measured the relative stiffness based on ASTM D1388 (Standard Test Method for Stiffness of Fabrics). The NSS values were measured both parallel and perpendicular to the backbone direction of the hides. The NSS measurement results were labeled as parallel and perpendicular, respectively. Bar plots of the parallel and perpendicular NSS values for the thirty samples (the sample number is noted on the horizontal axis) are shown in Figure 1. Sample 8 and sample 30 are drastically different; the former has the highest value, whereas the latter has the lowest stiffness.

Acoustic Emission Generation

In many previous studies performed on leather by ERRC, AE was generated by the fracture of leather samples under tension. However, this is a destructive test that requires the extraction of samples from a leather hide. Most recently, Liu et al. started to exploit a rotational sensor to perform nondestructive testing on leather. In this new investigation, rolling AE sensors were used to produce AE from the leather. The deformation of the leather, as it was squeezed and stretched by the rolling sensors, is accompanied by a rapid movement, relocation, or friction of structural elements such as fibrils, fibers and/or fiber bundles. AE signals are produced, detected by the sensors, and recorded by the AE system if their amplitude is larger than a previously established threshold, which in this case was set at 35dB.

AE Data Acquisition & Database Assembly

A series of AE measurements was performed on the 30 leather samples using newly designed wide-band rolling sensors (RSWD). These sensors, shown in Figure 2(a), have better miniature ball bearings, which greatly increase the smoothness of the rolling barrel and at the same time dramatically decrease the rolling "noise". Two RSWD rolling sensors were attached to an X-Y computer-controlled scanner in order to perform the AE measurements, as shown in Figure 2(b).

Information about the AE signals is obtained by measuring different features such as the amplitude, duration, rise time, AE counts (number of threshold crossings), AE energy (a approximate measure of the AE signal energy), average frequency, percentage of energy in different frequency bands

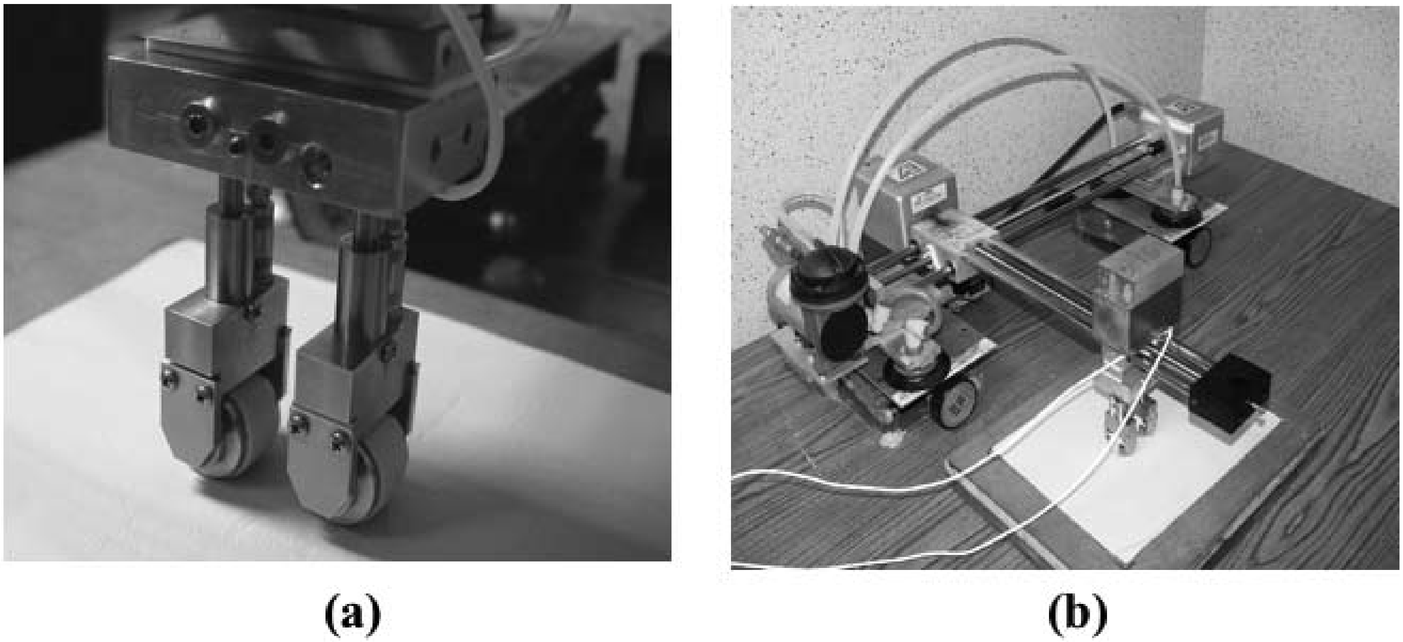

Figure 2: (a) Newly designed RSWD rolling sensors used in the latest round of experiments, (b) X-Y scanner with RSWD rolling sensors used in the AE measurements.

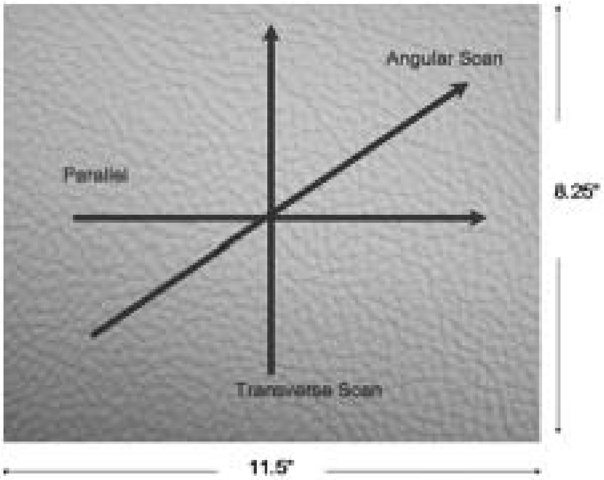

Figure 3: Three different scanning directions performed on the leather samples.

(partial powers), etc. Each of the samples was scanned in three different directions: along the length of the sample (parallel scan), across the width of the sample (transverse scan), and at an angle of 45 degrees between the two perpendicular directions (angular scan), as shown in Figure 3. On each of the samples, and along each direction, a forward and a backward scan pass were performed. The length of the scans were 20.3 cm, 15.2 cm, and 15.2 cm along the parallel, transverse, and angular directions, respectively.

All the scans were performed at a constant velocity of 2.54 cm/sec and constant pressure of 9 N, which was achieved using a computer program and a constant dead weight on top of the rolling sensors, respectfully. The scans were performed on the finished (grain) side and on the flesh (corium) side. In total, 6 scans were performed on each of the 30 samples.

Evaluation of Mechanical Properties of the Leather Samples

In order to have an independent measurement of the leather material properties, rectangular shaped (1 x 10 cm) specimens were cut from the original leather samples and subjected to a destructive tensile test, which provided values of different mechanical properties such as Tensile Strength, Elongation, Young Modulus, Initial Strain Energy, and Fracture Energy. An upgraded Instron mechanical property tester, model 1122, and Testworks 4 data acquisition software (MTS Systems Corp., Minneapolis, MN) were used throughout this work. Tensile strength is the maximum stress in tension that the leather may sustain without breaking. Elongation is defined as the maximum strain. The Initial Strain Energy of leather, defined as the energy needed to stretch the leather to 10% strain, is the area under the stress-strain curve from 0 to 10% strain. It is a physical quantity representing the stiffness of a material. The Fracture Energy is measured as the area under the stress-strain curve divided by the volume of the sample and represents the energy needed to fracture the samples. These properties were measured with a sample length of 5 cm between the two grips. The strain rate (crosshead speed) was set at 25.4 cm/min.

RESULTS AND DISCUSSION

AE Hit Feature Analysis

The signals recorded from each of the samples were processed in real time and several features were extracted from each of the hits detected. The features extracted from the AE signals are listed below: Amplitude, Energy, Rise Time, Duration, Counts, Counts to peak, Average Frequency, Average Signal Level (ASL), RMS amplitude, and Absolute Energy.

It was expected that the values of the AE features for the hits detected would change significantly from sample to sample as the NSS values did. However, a preliminary analysis of the data, performed using PAC's Pattern Recognition software NOESIS, showed that the AE feature distributions did not change significantly from sample to sample. As an example of this, Figure 4 shows scatter plots of AE Counts vs. Average Frequency, and of Amplitude vs. Duration for sample 30, the one with the lowest NSS, and sample 8, the one with the highest NSS. Figure 4 clearly shows that the data from sample 8 labeled as black dots, and sample 30 labeled as grey diamonds, overlap. Similar results were obtained for the 30 samples regardless of the NSS value.

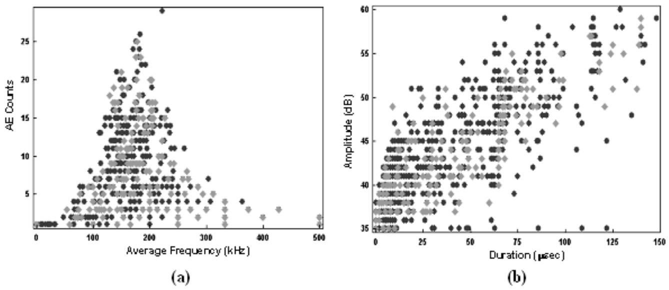

Figure 4: Scatter plots of AE features for sample 30, grey diamonds, and sample 8, black dots. (a) Counts vs. Average Frequency, (b) Amplitude vs. Duration.

Cumulative AE Feature Analysis

As the distribution of AE hits features did not vary significantly from sample to sample we decided to analyze the cumulative values of the AE features for each of the samples. The results from this analysis showed that some of the cumulative values for the AE features varied significantly from sample to sample. As an example of this, Figure 5 shows the cumulative plot of Hits vs. Energy (absolute value) for samples 8 (highest NSS value) and 30 (lowest NSS value). This plot shows that the sample with the highest NSS, samples 8, has the highest accumulation of Hits and Energy.

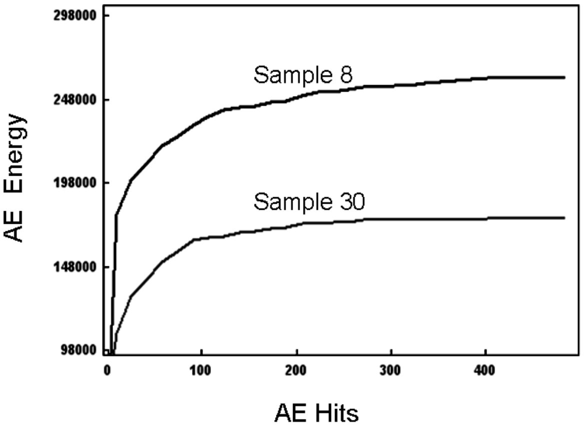

Figure 5: Cumulative plot Hits vs. AE Energy for sample 30 (lowest NSS value) and sample 8 (highest NSS value).

The AE features that show significant variation in the cumulative values are listed below: Number of Hits, Energy, Absolute Energy, Counts, Average Signal Level (ASL), and RMS amplitude. Since one of the main objectives of this study was to use acoustic parameters to determine leather quality, a correlation was sought between the NSS and the cumulative values of the AE features listed above. The NSS parallel, transverse, and average values of the leather samples were compared to the AE features for the parallel, transverse, and angular scans, respectively. This process was repeated for the cumulative values of the AE data obtained for the grain (finished) and corium (flesh) sides of the leather. Data showed that the best correlation between AE data and NSS values obtained from the angular scans on the corium side of samples. The results showed an increase in the cumulative values of AE features when the value of the NSS increases. Statistical analysis using all the data (AE and Shirley Stiffness) provided a good relationship using Weibull Statistics[18] as shown in Figure 6. The average value of NSS in both directions was chosen because, according to Seton, this is the leather quality value reported to most customers.

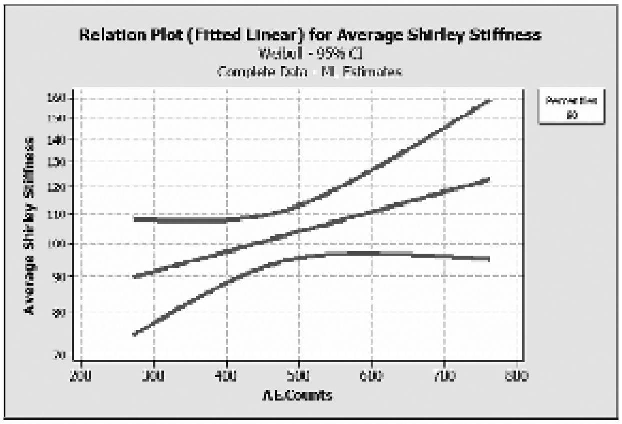

Figure 6: Analysis from Weibull statistics showed a good correlation between AE counts and NSS stiffness values.

Figure 7 is a 3-D surface response plot of stiffness (NSS value) as a function of AE count and thickness for the 30 samples. The response surface (shown as a mesh screen plane in Figure 7) is constructed based on the linear regression model shown in Equation 1, which relates the stiffness, AE count, and thickness into a linear relationship:

$$\text{Stiffness} = 58 + 10.12 \times \text{Thickness (mm)} + 1.56 \times \text{AE count } (10^3 \text{ counts}) \qquad (1)$$

The black dots in Figure 7 are the data points for the 30 samples. As demonstrated in Figure 7, the data fit this regression model rather well. This figure shows that the stiffness increases with AE counts and thickness of the samples. The higher AE count is an indication of stiffer leather; therefore, the results revealed that stiffer leather can be predicted by measuring the AE count. Figure 7 also demonstrates that thickness has some degree of effect on the stiffness; the thicker samples tend to have a higher bending rigidity, consequently higher NSS stiffness. In summary, Equation 1 gives a predictive model that could be very useful for nondestructively testing stiffness using the AE method described in this report.

Analysis of the Signals Frequency Content

In addition to the AE features discussed and analyzed in the previous section, the waveforms from signals captured in each of the samples were digitized and frequency signal features were extracted in real time. A typical AE waveform produced in a leather sample and its power spectrum are shown in Figure 8.

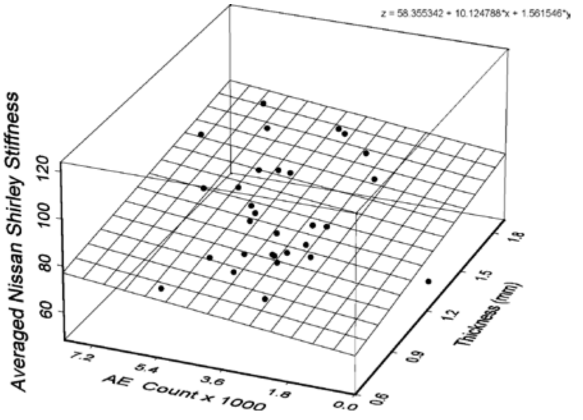

Figure 7: 3-D plot of NSS as a function of thickness and AE count.

The frequency features extracted from the AE signals were: Frequency Centroid, Peak Frequency, and Partial Powers.

It was expected that the frequency features of the AE signals would change dramatically from the softer to the stiffer samples. However, as in the case of the time features, discussed previously in this report, the frequency feature distributions for the 30 samples overlap. As an example of this, Figure 9 shows the histogram distribution of Peak Frequency and Frequency Centroid for samples 8, the one with the highest NSS, and Sample 30, the one with the lowest NSS. The distributions are very similar and the main difference between them is in the number of hits produced by the two samples. As observed in Figure 5, sample 8, produced more hits than sample 30. Based on this result, the frequency features would not be very useful in determining the leather quality.

In summary, the results from analysis of the AE data indicate that the features of the AE signals do not lump together in segregated clusters where each one corresponds to a sample or a group of samples with similar NSS values. On the contrary, it is observed that the AE data are dispersed and show a large overlap between samples. However, it was observed earlier that the cumulative values of some AE features correlate very well with the values of NSS, as shown in Figure 6 and Figure 7. In particular, cumulative AE Count shows the best correlation with the NSS values.

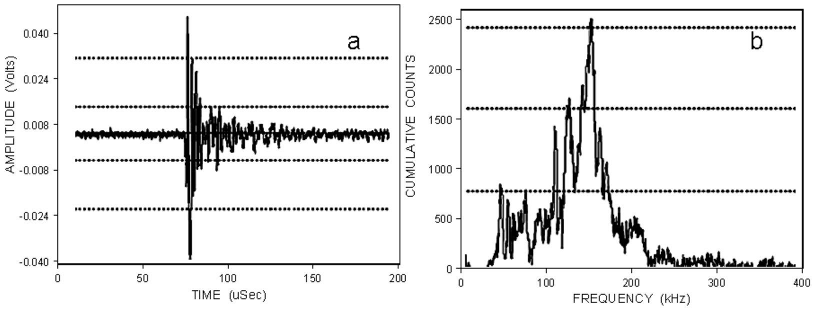

Figure 8: Typical AE signal produced in leather: (a) Waveform and (b) Power Spectrum.

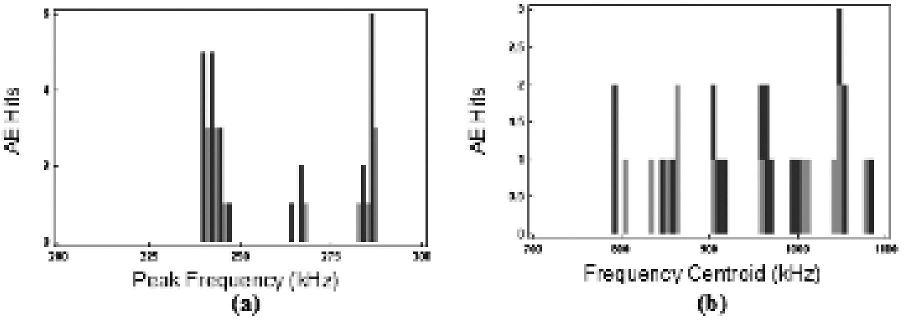

Figure 9: Distribution histograms of AE frequency features for sample 30, grey, and sample 8, black: (a) Peak Frequency, (b) Frequency Centroid.

Figure 10: A newly designed portable AE system for the evaluation of leather quality: (a) Pocket AE-1 system proposed to be the system platform, (b) Prototype rolling sensor to be used in leather evaluation.

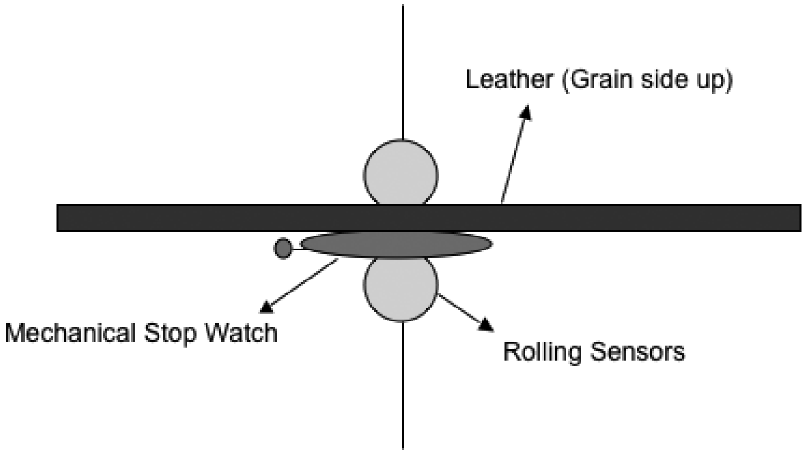

Figure 11: Schematic of Clock Tests.

Design of a Portable AE System

Through the course of this research, a portable AE system was designed to implement the AE method for evaluating leather quality. The Pocket AE-1 Acoustic Emission system functions as the platform. The Pocket AE-1 is a computerized hand-held instrument for AE testing. This system can perform traditional AE feature extraction based AE signal processing, as well as advanced waveform based acquisition and processing. A preliminary version of this system is shown in Figure 10(a). A rolling sensor probe, like the one shown in Figure 10(b), could easily be adapted to work with the Pocket AE-1. Because of its portability and simplicity of use, the combination of a rolling sensor probe and the Pocket AE-1 would be ideal for testing entire hides in the manufacturing plant. Data could be gathered from different sections of the hide, along different directions with respect to the backbone, and during different stages of the manufacturing process.

The data collected from this testing could then be processed in real time in the Pocket AE-1 system and compared to values of leather quality predicted by the correlation developed using the data gathered during this study and refined using leather samples with similar characteristics, as recommended above.

Predicting Tensile Properties via an External Sound Source

All the reported AE waves or signals so far originated from the collagen fibrous material—leather itself, when under external stress. We are also interested to know if sound waves created from an external source, such as a mechanical stopwatch, will be able to probe or predict the physical properties of leather, therefore providing an alternative nondestructive method for the evaluation of leather properties. In this case, leather functions as a sound medium where the sound waves travel through a leather specimen, which are then detected by an AE sensor. The quantities of AE signals could then be a function of the leather properties. In these experiments, the leather was conditioned at 21°C and 65% RH in a constant temperature/humidity room. A schematic of the set-up is pictured in Figure 11. A mechanical stopwatch was placed face up in between the two sensors, with the leather samples, grain side up, facing the top rolling sensor. The AE signals were collected for 240 seconds and the cumulative acoustic hits, counts, and energy were recorded and put into a spreadsheet. A regression analysis was performed on the data and some correlations were found.

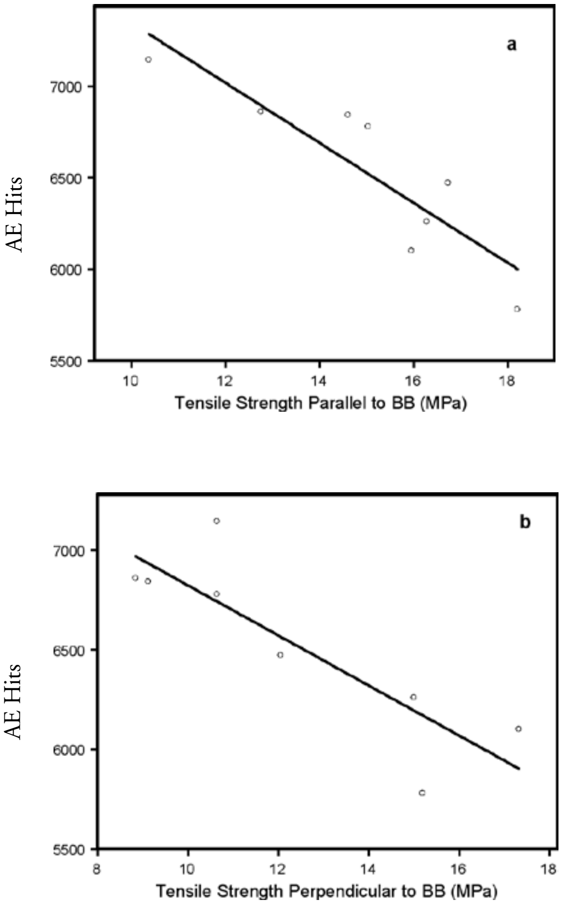

Figure 12: (a) Hits vs Tensile Strength P to BB,
(b) Hits vs Tensile Strength T to BB.

There was a linear correlation between AE hits and Tensile Strength in both the parallel and perpendicular directions to the backbone. This can be seen in Figures 12 and 13. The correlation is negative and shows a lower amount of hits correlates with a better Tensile Strength. The correlation for the hits versus tensile strength in the parallel direction is -0.88 and in the perpendicular direction it is -0.86 (Figure 12). This may be ascribable to the packing degree or apparent density of the leather, in which the stronger leather is denser with a greater three-dimensional woven structure, thus causing the mechanical waves emanated from the stopwatch to attenuate faster in the stronger leather and transfer less sound to the AE sensor.

This is also apparent in the Fracture Energy graphs, Figure 13, in which there is a negative correlation between Hits and Fracture Energy. A higher number of hits for these samples indicated the leather had a low Fracture Energy. The correlation coefficient for the Fracture Energy versus Hits in the parallel direction was -0.88 and in the perpendicular direction it was -0.70. For a natural material, such as leather with many intrinsic variations between samples, this is in fact a very good correlation.

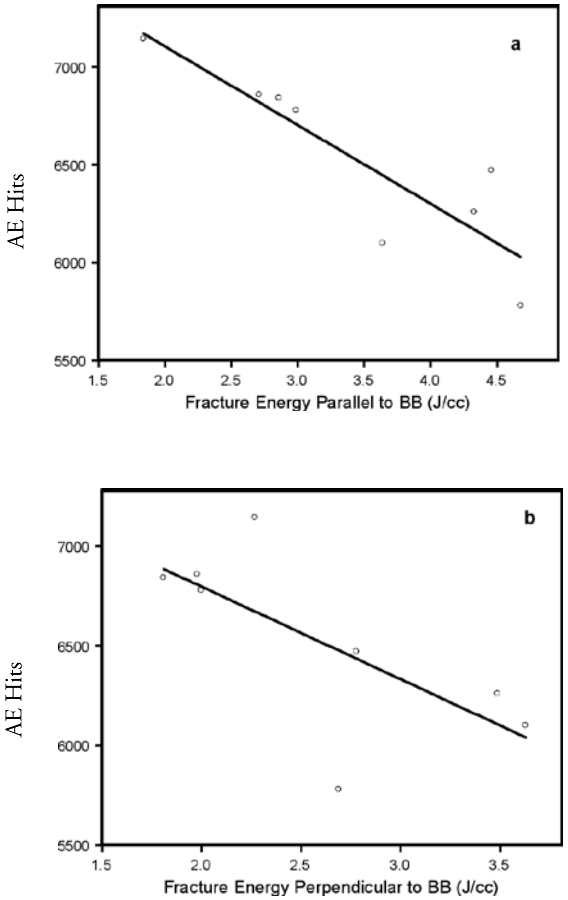

Figure 13: (a) Hits vs Fracture Energy P to BB,
(b) Hits vs Fracture Energy T to BB.

CONCLUSIONS

AE is a feasible method to evaluate the quality of leather as demonstrated by our Phase I SBIR and Cooperative Research and Development Agreement (CRADA) with Physical Acoustics Corp. and Seton Co. The cumulative AE Count recorded over a local area of a leather hide can be used to evaluate leather stiffness. Additionally, by using a mechanical stopwatch we showed that tensile strength and Fracture Energy both correlated to the acoustic emission quantities. We will investigate a better sound source and will use it in the future for the AE signals. In a following report, we will present research results on Airborne UT that showed some encouraging applications to testing leather properties nondestructively, particularly for surface defects on the leather grain or corium.

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