INTRODUCTION

The formability of rolled sheet metal is strongly influenced by the texture of the polycrystalline metal. For steel sheet, it is desirable to have high drawability to make automobile body parts, etc. In addition, material homogeneity is desired; that is, material cut from different parts of a rolled sheet should have the same plastic deformation when subjected to deep drawing.

For the manufacture of automobile doors and panels, variations in formability can cause a problem in automotive press-shop operation. Here blanks are cut from a coil of rolled steel and fed into a production line. After deformation, the material may be moved elsewhere by a robot. Improper formability can thus create two problems: a) a part which must be rejected because it is out of specification; b) a part which cannot be gripped by the robot, causing production line shutdown.

It is desirable to have a nondestructive means of formability measurement which could be implemented in rolling mills and/or press-shop operations to certify that the sheet has the proper formability. Current methods are destructive and cannot be implemented on-line.

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We are exploring the use of ultrasonic techniques for monitoring texture and the resulting formability in rolled sheet. Since texture influences velocity as well as formability, ultrasonics is a natural candidate for formability measurement. Furthermore, advances in ultrasonic devices, most notably the development of the electromagnetic-acoustic transducer (EMAT), now make real-time, on-line monitoring a distinct possibility.

Here we present results of an initial study to demonstrate feasibility of these concepts. We show a good correlation of ultrasonic measurements with (destructive) formability measurements. We address problems associated with use of EMATs, as well as some issues related to technology transfer from lab to production environments.

RELATIONS BETWEEN ULTRASONICS AND FORMABILITY

Stickels and Mould [1] measured Young's Modulus, $E$, on specimens cut at angles, $\alpha$, to the sheet rolling direction. They found that $E(\alpha)$ correlated well with an expression of the form

$$ E(\alpha) = E_0 + E_2 \cos 2\alpha + E_4 \cos 4\alpha. $$

(1)

They also measured the r-value for the same specimens. The r-value is the ratio $\varepsilon_{yy}/\varepsilon_{ZZ}$. Here $\varepsilon_{yy}$ is the strain normal to the loading direction in a uniaxial tension specimen cut at angle $\alpha$; $\varepsilon_{ZZ}$ is the strain in the thickness direction. The r-value is a measure of sheet formability. Stickels and Mould found that the r-value obeyed a relation similar to equation (1):

$$ r(\alpha) = r_0 + r_2 \cos 2\alpha + r_4 \cos 4\alpha $$

(2)

Since $r$ and $E$ have the same functional form, terms such as $r_0$ and $E_0$ should be related. In fact, Stickels and Mould demonstrated good correlations between $r_m$ and $E_m$ ($m = 0, 2, 4$).

These relations form the basis of the "modul-r" technique which is widely used in measuring sheet formability. Measurements of $E(\alpha)$ are made on small specimens cut from the end of a coil of sheet after rolling; quantities such as $r_0$, $r_2$, $r_4$ are determined from the correlations developed by Stickels and Mould [1]. These quantities have the following interpretation [2]: $r_0$ is the average sheet drawability; $r_2$ relates to tendency for two ears to form on deep-drawing; $r_4$ relates to tendency for four ears to form.

The modul-r technique as currently implemented is destructive and cannot operate in real time. We are attempting to develop a method for sheet metal formability which overcomes these limitations.

Since the work of Stickels and Mould, other relations between ultrasonic velocities and sheet metal formability have been developed. Sayers [3] used a Voigt averaging scheme and elements of texture theory to obtain the effective elastic moduli of rolled sheets of cubic metals. He found that the nine elastic moduli of a sheet (which has orthorhombic symmetry on the macroscale) could be calculated from six quantities: the three elastic moduli of the cubic single crystals, and three texture...
parameters called $W_{4m0}$ ($m = 0, 2, 4$). These parameters are defined in Ref. 3. From the orthorhombic elastic constants, Sayers predicted the effect of texture on bulk wave propagation.

These results have been generalized to guided waves in moderately textured plates by Thompson et al. [4,5,6]. The velocities, $V(\alpha)$, of the lowest-order shear horizontal mode (SH$_0$ mode) and lowest-order symmetrical Lamb-wave mode (S$_0$-mode) obey relations of the form:

$$\rho V^2(\alpha) = A + B W_{400} + C W_{420} \cos 2\alpha + D W_{440} \cos 4\alpha .$$  \hspace{1cm} (3)

Here $\rho$ is density, $A$ is the isotropic contribution, and terms depending on $W_{4m0}$ are texture contributions. The constants $A$, $B$, $C$, $D$ depend upon the elastic moduli of the cubic crystals; their exact form depends upon the averaging scheme [4, 5, 6] and the particular mode.

There is also a relation between the $W_{4m0}$ and the $r_m$ in equation (2). For modestly textured sheet of cubic metals, Davies et al. have shown that $W_{4m0}$ is proportional to $r_m$ [2], so that ultrasonic velocities are directly related to formability. We are trying to exploit this relation in our present work on nondestructive formability measurement.

For steel sheet, the formability parameter of primary interest is $r_0 = [r(0^\circ) + r(90^\circ) + 2r(45^\circ)]/4$. This is because steel sheet is typically used in deep-drawing where: (a) a large depth of drawing is desired; and (b) any flashing due to earing will be trimmed from the part. This contrasts with applications of aluminum sheet (for example, beverage cans) where the amount of earing is of primary importance [7].

$r_0$ is related to the texture parameter, $W_{400}$, which is invariant under rotation in the sheet (see Equ. (3)). Thus, $W_{400}$ (and hence $r_0$) must be determined from absolute velocity measurements, if guided waves are used.** Furthermore, we must also know the isotropic contribution, $A$, in Equ. (3). For bulk waves we can avoid the problems of absolute velocity determination by using ratios of different velocity combinations to eliminate the acoustic pathlength; still, we must know the isotropic velocity contribution.

**EXPERIMENTAL RESULTS**

In our present work, we determined velocity (or arrival time) combinations which vary with $W_{400}$ (and hence with $r_0$). We measured these combinations on a set of four plates with known $r$-value over a range typically encountered in automotive applications. The velocity (or arrival time) combinations are listed below:

<table>
<thead>
<tr>
<th>Wave Type</th>
<th>Velocity Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk</td>
<td>$(V_{S1}^2 + V_{S2}^2)/(V_{S1}^2 + V_{S2}^2 + V_L^2)$</td>
</tr>
<tr>
<td>SH$_0$-mode</td>
<td>$T_{SH}(0^\circ) + T_{SH}(45^\circ)$</td>
</tr>
<tr>
<td>S$_0$-mode</td>
<td>$T_{S0}(0^\circ) + T_{S0}(90^\circ) + 2T_{S0}(45^\circ)$</td>
</tr>
</tbody>
</table>

**$W_{420}$ and $W_{440}$ can be determined from the angular variation of velocities; for example, $W_{420}$ depends on $V^2(0^\circ) - V^2(90^\circ)$ for the S$_0$-mode. Thus, $W_{420}$ and $W_{440}$ are determined from relative velocity measurements.**
Here $V_{s1}$ = velocity of shear-wave polarized along rolling direction, propagating through sheet thickness; $V_{s2}$ = corresponding wave polarized perpendicular to rolling direction; $V_L$ = longitudinal wave. $T_{SH}(\alpha)$, $T_{S0}(\alpha)$ are, respectively, the arrival times for shear-horizontal and symmetrical Lamb waves propagating at an angle $\alpha$ to rolling direction.

Bulk wave measurements were made with piezoelectric transducers dry-coupled to the specimens with a special elastomer. The SH-mode measurements were made with two receiving EMATs clamped together; these were connected with a spacer to a transmitting EMAT. This apparatus was rotated by hand and the time for the SH-mode wave to travel from one receiver to the other was measured. This gave better precision than using a single receiver. In contrast we obtained good precision for $S_0$-mode measurements by using a transmitting and single receiving EMAT. These were also connected by a spacer and rotated by hand.

A typical result from our measurements is shown in Fig. 1. In all cases, we see a linear variation of ultrasonic parameters with the average formability, $\bar{r}$ ($\bar{r} \equiv r_0$; $\bar{r}$ is the convention commonly used in the sheet metal industry). Consequently, each technique satisfies a necessary condition for its use as a formability measurement method.

We assessed each technique as to its practical implementation in an industrial environment such as a press-shop. The bulk-wave method evaluates formability in a local sense; i.e., directly under the transducer apertures. For formability measurement across the sheet width, a large array of transducers would be required.

![Figure 1](image.png)

Fig 1. Comparison between $\bar{r}$ and average arrival time of $S_0$-mode
The SH$_0$-mode measurements were made with a periodic array of permanent magnet EMATs. We found that the precision of our arrival time measurements was about 35 ns, which contrasted with a precision of about 15 ns with the same apparatus used on aluminum sheet. We attribute the poorer precision to magnetic effects, which are discussed later.

The $S_0$-mode measurements had a better precision (about 10 ns or better); for measurements reported here, we estimate that $\bar{r}$ can be determined with an accuracy of about 0.05. Since the $S_0$-mode is dispersive, in general, we must know the plate thickness, or operate at low frequencies (wavelength $\gg$ plate thickness) where the phase velocity approaches its asymptotic limit [8].

There is another method of obtaining $\bar{r}$ from $S_0$-mode measurements. In general, the $S_0$-mode is dispersive, and for an isotropic plate,

$$\rho V_{\text{LIM}}^2 = E/(1 - \nu^2),$$

where $V_{\text{LIM}}$ = low-frequency limit of phase velocity and $\nu$ = Poisson's ratio. We assume that $E$ can vary with direction, $\alpha$, but that no other corrections are required to Eq. (5). Then we have a procedure for determining $E_0 = \bar{E} = (E(0^\circ) + E(90^\circ) + E(45^\circ) + E(-45^\circ))/4$; the average Young's modulus, $E$, is related to $\bar{r}$ through the correlations established by Stickels and Mould [1].

To determine $\bar{E}$, it was necessary to: (a) develop a method for obtaining the absolute velocity $V$; (b) measure $V(\alpha)$ for $\alpha = 0^\circ, 90^\circ, \pm 45^\circ$; (c) determine $V_{\text{LIM}}$ from $V$, using the dispersion relationship [8]; (d) determine $E(\alpha)$ from Eq. (5).

The results are shown in Fig. 2. The solid line is the best fit to the data of Stickels and Mould [1], and the open circles are the $S_0$-mode data points. These data are plotted as follows. $E$ is determined for each plate from ultrasonic measurements as described above. The $r$-value is the known (destructive) value. Thus, the abscissa and ordinate are determined and plotted. Referring to the data in Ref. 1, we found that the ultrasonic data fall well within the scatter of the data of Ref. 1. From this, we conclude that the EMAT $S_0$-mode measurements give results comparable to the modul-r technique, which uses the solid line of Fig. 2 to relate $\bar{E}$ to $\bar{r}$.

![Fig 2. Comparison of ultrasonic results (open circles) with curve used in modul-r method (solid).](image)
All of our measurements were made in the static mode; that is, with the transducers placed and rotated on plates at rest. In our proposed applications (rolling mill, press-shop operation), plates would pass underneath an array of EMATs which would measure e.g. $T_{s0}(0)$, $T_{s0}(45^\circ)$, $T_{s0}(90^\circ)$. While EMATs have the attractive feature of being noncontacting, there are certain problems which can arise because of their transduction mechanisms. We have addressed several of these problems and potential solutions in our current research.

EMATs typically produce signals which are much smaller (for given electrical input) than a comparable piezoelectric device. They typically generate microvolt signals on reception, so the signal-to-noise ratio becomes a critical problem. While EMATs can operate without touching the specimen, the signal degrades exponentially with liftoff. Furthermore, for magnetic materials, signals can be generated both by magnetostriction and the Lorentz force mechanism [9]; in nonmagnetic materials, only the latter is present. The signals generated by these transduction mechanisms are generally out of phase; they depend on magnetic field strength and also magnetic properties of the sheet [9]. This can lead to arrival time variations which depend on the magnetic state and not on formability.

These problems have been at least partially solved. EMAT systems having a good signal-to-noise ratio have been constructed using an S-mode EMAT which has an Nd-Fe-B permanent magnet for the Lorentz force generation. The EMAT was driven by a current pulser which can deliver up to 140 A into a 1 Ω load at 500 kHz. The pulser is based on MOSFET technology, and, for these high currents, has a pulse repetition rate of about 100 Hz. The signal was received by a second S-mode EMAT about 20 cm from the transmitting EMAT. The received signal was amplified by a low-noise, narrow-band (50 kHz) amplifier with gain adjustable up to 80 dB.

We have also measured the effects of liftoff on signal amplitude; the results for two different drive currents are shown in Fig. 3. Assuming an acceptable signal-to-noise ratio is about five, we see that we can work with liftoffs as large as 2 mm. This clearance should be adequate for our contemplated applications, such as rolling mills and press shops.

We have studied the effects of dual transduction mechanisms, using two types of sheets with different thermomechanical treatments and different alloy content. In both types, we were able to generate signals by magnetostriction at low magnetic field strengths. In this case, the magnetic field which causes magnetostriction is the dynamic field due to the current in the EMAT; we removed the permanent magnet which provides the constant magnetic field for the Lorentz force transduction.*** The strength of the magnetostriction signal was approximately constant in one type of sheet, but varied markedly from place to place in the second. At the least, this indicates that it would be best to design our EMAT systems to work on the Lorentz force transduction mechanism, which is subject to less variation in signal amplitude.

***There can also be Lorentz force generation due to interaction of the dynamic magnetic field and the eddy current. If present, this signal will have twice the frequency of the drive current. We took the FFT of our received signals and saw no spectral components at twice the rf of the pulser.
It is known that magnetostrictive generation is a maximum at one (or more) low magnetic field strengths. We know that our permanent magnet has a field of more than 5 kG [10] which for thick sheet should essentially saturate the magnetic material, causing negligible magnetostriction.

We replaced our permanent magnets and made repeated measurements in various locations to determine arrival time precision. We typically found precision of order 10 ns, which was somewhat poorer than in aluminum. We attribute the increased variability in arrival time to magnetic effects. For thin sheet, the magnetic field may not be high enough to achieve saturation, due to demagnetization. However, for our system the resulting arrival time uncertainty of 10 ns is well within the uncertainty needed to resolve \( F \) to within 0.1 or better.

Another potential problem is Barkhausen noise, generated by rotation of magnetic domains in ferritic steel sheet. We expect this problem to be more pronounced for the SH-mode EMATs, which are periodic arrays of permanent magnets and hence have alternating polarity of the magnetic field. The \( S_0 \)-mode EMATs have only a single magnet and hence should be less susceptible to Barkhausen noise.

A simple experiment was performed to test sensitivity of the \( S_0 \)-mode EMAT system to Barkhausen noise. We compared photos of oscilloscope traces taken for two cases: a) the EMATs at rest; b) the EMATs rapidly scanned by hand back and forth across the sheet. There was no noticeable difference in the photos. A possible explanation is that any Barkhausen noise is outside the bandpass of our narrowband electronics (500 ± 50 kHz).
CONCLUSION

All ultrasonic parameters measured showed a good correlation with $F$. $S_0$-mode EMATs were also used to obtain a correlation of $E$ with $F$ which was as good as the data used for the modul-$r$ method. It appears that $S_0$-mode EMATs will be the transducers of choice for industrial applications. $S_0$-mode EMATs gave better velocity measurement precision. They should also be less susceptible to Barkhausen noise than $SH_0$-mode EMATs.

Some problems affecting technology transfer were addressed. EMAT systems with good signal-to-noise and liftoff tolerance was constructed. The rate of data acquisition (velocity measurements) may be adequate for on-line application, especially in a press shop.

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REFERENCES