Factors Affecting Magnetic Flux Leakage Inspection of Tailor-Welded Blanks

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Abstract

The development of a laboratory-based tailor-welded blank (TWB) inspection system using the principles of magnetic flux leakage (MFL) is presented. The effects of variations in inspection system operating parameters are quantified to allow for optimized system performance. The parameters examined included the applied magnetic field strength, inspection scanning velocity, spatial resolution of acquired signals, specimen end effects, and pole-piece lift-off. The results indicate that this inspection method is relatively insensitive to operating parameters and is, therefore, robust.

List of Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{sample}$</td>
<td>Sampling frequency</td>
</tr>
<tr>
<td>$MFL_{ref}$</td>
<td>Magnitude of signal at reference speed</td>
</tr>
<tr>
<td>$MFL_{pp}$</td>
<td>Magnitude of signal</td>
</tr>
<tr>
<td>$SR$</td>
<td>Spatial resolution</td>
</tr>
<tr>
<td>$V_{scan}$</td>
<td>Scanning velocity</td>
</tr>
<tr>
<td>$% SigRd$</td>
<td>Percentage signal reduction</td>
</tr>
</tbody>
</table>
1.0 Introduction

1.1 Tailor-Welded Blanks

In the automotive industry, car body-parts are formed from pieces of sheet metal known as ‘blanks’. Conventional blanks are typically uniform in thickness, surface finish and formability. A tailor-welded blank (TWB) is composed of two or more pieces, each having its own properties, laser-welded to form a single blank. TWBs enable the ‘tailoring’ of the blank design to meet specific requirements [1]. For example, in the fabrication of a door inner panel, heavy-gauge material can be used adjacent to the load bearing hinges while lighter-gauge material can be located in the area away from the hinges. This results in reduced part weight, reduced vehicle weight and increased fuel efficiency. In 2001, the automotive industry produced 28.8 million TWB units. This number is expected to rise to 90 million units by 2005 [2].

The quality of the weld in a TWB is critical to successful part forming operations. The International Standards Organization (ISO) [3] and the Auto/Steel Partnership (ASP) [1] have developed acceptance guidelines to evaluate the quality of the weld in a TWB. A variety of non-destructive inspection methods have emerged to monitor TWB weld quality as defined by the ISO and ASP guidelines. However, limitations of these methods have prevented widespread adoption of a single preferred method while some manufacturers continue to rely on visual inspection by operators. For a detailed review of these inspection methods the reader is referred to Gartner, Sun, and Kannatey-Asibu [4] and O’Connor, Clapham, and Wild [5]. Gartner et al. provide a detailed review of in-process techniques while more emphasis is placed on post-process techniques in O’Connor et al.
1.2 Magnetic Flux Leakage Inspection

MFL inspection has been used extensively and with great success in the pipeline industry for the past 30 years [6]. During this period, numerous experiments have also been done to develop theoretical models and more recently, finite element models. These models have been used to predict the magnetic flux leakage field from defects in a pipe wall within certain constraints. For a review of relevant MFL theory and experiments, the reader is referred to Mandache and Clapham [7].

In general, when a magnetic field is applied to a ferromagnetic specimen, magnetic flux passes through the material. The flux density is determined by the strength of the applied field and the permeability of the material. In the MFL inspection technique, specimens are magnetized to saturation which is the maximum magnetic flux capacity of a material based on its permeability. Metal loss defects result in a localized reduction in the cross-sectional area of the material. This forces some of the flux to ‘leak’ into the surrounding air, where it is detected by a coil or a Hall effect sensor. Signal analysis is used to relate the leakage signal to the characteristics of the defects.

In 2000, a feasibility study concerning the application of the MFL inspection technique to the evaluation of TWB weld quality was conducted by O’Connor et al. [5]. The study used a rudimentary MFL system to generate and record MFL data from artificial pinholes drilled into the welds of TWBs. The results demonstrated that pinhole defects as small as 0.34 mm in diameter could be detected and a relationship between the magnitude of the defect and the MFL signal was established. In a later study, it was shown that MFL is able to detect naturally occurring weld defects such as pinholes, mismatch, missed welds, lack of fusion and porosity.
This work confirmed that MFL has excellent potential as a practical inspection method for welds in TWBs.

Based on the positive findings of the feasibility study, a new MFL inspection system for an industrial application was developed. Using this system, the effects of operating parameters on the MFL signals were investigated. Operating parameters that were examined include: applied field strength, scanning velocity, sampling resolution, pole piece lift-off, and proximity to specimen edges. This paper describes the features of the newly developed inspection system and the results of the operating parameter studies.

2.0 Experimental Methods

2.1 Apparatus

The design of the magnetic circuit and inspection system were based on the rudimentary system used by O’Connor et al. [5]. As shown in Figure 1, the magnetic circuit consists of four Nd-Fe-B permanent magnets (1 cm x 2 cm x 4 cm) placed in a row along the upper center of the assembly. Coupled to the magnets are soft iron blocks in a horseshoe configuration, which direct the magnetic flux down to the specimen. The TWB specimen closes the magnetic circuit with its weld lying transverse to the flux direction. A Hall sensor (Honeywell SS94A1) is used to measure the radial component of the MFL signal. This sensor is supported on the Hall sensor mounting assembly, as shown in Figure 2, which provides spring loading of the sensor against the flat (i.e. non-stepped) surface of the TWB. The pole pieces of the magnet assembly (the soft iron blocks in contact with the TWB specimen) are mounted on wheels. Wheel diameter and position are such that a small gap exists between the pole pieces and the surface of the specimen. Flux density variation is achieved with a backing circuit using a large soft iron plate attached to
the top of the magnet assembly. The plate is hinged on one side and attached to a threaded rod (or screw) on the other. By turning the screw, the position of the plate relative to the magnet assembly is adjusted. The flux level in the magnetic circuit is monitored with a Hall sensor (F.W. Bell BH-700) embedded in an aluminum sheet located between the pole pieces. A photograph of inspection system is shown in Figure 2.

TWB specimens are aligned with and then clamped to a table which is attached to a linear positioning system driven by a stepper motor, as shown in Figure 3. The TWB is located by aligning the weld line with a longitudinal and centred guideline on the surface of the table. Table motion is controlled via command level language with a PC and a motor controller. The position of the table is recorded using a rotary encoder on the stepper motor shaft. A National Instruments 6023E data acquisition card is used for data logging for the rotary encoder and Hall sensor. The Hall effect sensor output, prior to data logging, is filtered using a low pass filter with a cutoff frequency of 1000 Hz to remove unwanted high frequency noise.

Figure 3 also illustrates specimen orientation and motion. The thin side of the specimen is placed on the positive y-axis side with the front edge of the specimen aligned at the home position. Typically, the weld, excluding the heat affected zone, is between 0.5 mm and 1.0 mm in width. Scanning begins with the blank in the home position. The first scan is taken by moving the blank in the positive x-direction along the entire length of the weld. The Hall effect sensor is then translated 0.25 mm in the positive y-direction, and the scan is repeated along the entire length of the weld. These scans are repeated until the full width of the weld has been scanned. MFL profiles of the weld line are generated by compiling data from these scans.

A typical profile resulting from a scan of a weld in a TWB is shown in Figure 4. The defect profile shown in the figure is for a pinhole defect and is characterized by a broad peak. This
peak is usually centered over the weld defect. The length of the peak is dependent on the length of the defect and the amplitude of the signal is dependent on the depth and width of the defect. Further discussion of MFL profiles for various weld defects can be found in Montgomery et al [8].

2.2 Signal Conditioning

To analyze the collected MFL data, the raw signals were digitally filtered using a second order Bessel bandpass filter with corner frequencies of 0.5 cycles/mm and 5 cycles/mm. This process, commonly known as ‘detrending’, removed the DC component of the signal and the low frequency background. In addition, unwanted high frequency noise was eliminated. The 0.5 cycles/mm corner frequency was derived by trial and error while monitoring the signal for distortion. The 5 cycles/mm corner frequency was derived from the Nyquist Theorem that states that the maximum frequency that can be detected in a signal without aliasing is half of the sampling resolution (10 cycles/mm – a result from Section 3.3). To calculate the peak-to-peak value of the defect signal, the scan line from the profile with the largest peak-to-peak value was used (referred to as the peak scan line). Peak-to-peak values were determined after the acquired data had been filtered. Details of the signal processing techniques are discussed in Montgomery et al [9]

2.3 Specimens

A commercial TWB manufacturer provided five specimens for the experiments. The TWBs were welded with an 8 kW CO\textsubscript{2} laser and all specimens were cold-rolled carbon steel. Specimen specifications are summarized in Table 1. The two values in the “gauge” column of Table 1 refer to the thickness of the pieces of sheet metal comprising the TWB. As received from the manufacturer, these specimens contained defect-free welds. Subsequently, one 0.5 mm diameter
pinhole was drilled through the full thickness of the estimated center of the weld line in each specimen. These pinholes, which are similar in size to naturally occurring pinhole defects, act as reference “defects” in this study.

3.0 Sensitivity Studies

There are a number of parameters that can affect the MFL signal for a given defect. In Sections 3.1 to 3.5, the results of five studies are presented in which the sensitivities of MFL inspection to the following parameters were assessed: applied field strength, scanning velocity, signal resolution, specimen end effects, and pole-piece lift-off.

3.1 Applied Field Strength

The effect of applied magnetic field strength on the MFL defect signal is an important issue. Jansen et al. [10] demonstrated that a high magnetization level is the key factor in characterization of defects in pipelines. The purpose of the current study was to determine the relationship between the applied magnetic field strength and MFL signals from a defect in a TWB weld. The range of magnetic field strength in these experiments was determined by the range of the adjustable backing circuit and the permanent magnets. This was measured to be 0.27 Tesla to 0.45 Tesla in the pole piece. These values typically produce magnetic saturation in the blank. Results of a further study investigating a much lower range of flux densities has been published elsewhere [11].

In the first stage of the study, the shape of the MFL signal profile as a function of applied field strength was examined. The scans were conducted at 200 mm/s and with a spatial resolution of 40 samples/mm. Plots of the MFL profiles for specimen 5 at the highest and lowest
applied field strength are shown in Figure 5. Although the extent of the defect in the X and Y directions is similar in both cases, the peak amplitude increases with increasing flux density, since at higher sample flux densities more flux will be forced into the air above the pinhole. These profiles are representative of all the profiles obtained for all of the blanks in this study.

In the second stage of the study, scans were conducted on each specimen for a range of flux densities. Flux densities were measured using the embedded Hall effect sensor with the magnet assembly located at mid-span of the specimen. The scans were conducted at 200 mm/s with a spatial resolution of 40 samples/mm. For each specimen type, the peak-to-peak value of the defect signal from the artificial defect was measured. The flux density in the pole-piece was calculated using the readings from the embedded Hall sensor. Shown in Figure 6 are the results for specimens 2 and 5, which were representative of the results for all specimens. The results indicate a monotonically increasing trend in the peak-to-peak values as a function of applied field strength. This is consistent with the results shown in Figure 5 and also with the explanation that at higher flux densities more flux is expected to be forced into the air in the defect vicinity. Specimen 1 is thinner and therefore will be more highly saturated than specimen 2, hence the larger overall MFL signal.

The difference in magnitude of the peak-to-peak values for the different specimen types is ascribed to differences in the thickness ratios (i.e. ratio of thicknesses of the two sheets of which the TWB is comprised) of the specimens. As the thickness ratio increased, the peak-to-peak value of the defect signal for the artificial defect increased.

It was also determined that for each specimen type, although there was an increase in the peak-to-peak value of the defect signal with applied field strength, there was no significant change in the signal-to-noise ratios of the defect signal [10]. In the context of MFL, noise refers
not to electromagnetic noise but to the small, reproducible variation in the signal due to material variations. These results are consistent with the finding of a numerical study by Altschuler et al. in which it was shown that signal-to-noise ratios for MFL signals from pipeline defects were relatively insensitive to the strength of the applied field [12].

3.2 Scanning Velocity

Relative motion between the magnetic field and the magnetized material induces eddy currents in the magnetized material. These eddy currents generate an opposing magnetic field that reduces the amount of flux and, thereby, the overall applied field in the sample. In the pipeline industry, where inspection speeds reach 8 m/s, the reduction in MFL signals can be as much as 75% [13]. In the TWB manufacturing process, welding and inspection speeds are much lower (typically 150 mm/s) and the geometry (flat plate as opposed to a cylinder) does not encourage significant opposing eddy current fields. The purpose of this study was to determine the effect of scanning velocity on the MFL signals at typical TWB scanning speeds.

All five specimen types were used for this study. The flux density in the pole pieces and the spatial resolution were held constant at 0.41 Tesla and 40 samples/mm, respectively. The scan velocity was set to 1 mm/s and a multi-pass scan of the weld was taken. The scan was then repeated at the following velocities (mm/s): 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, and 200. Signals were examined as a function of velocity, with particular attention to signal reduction. Signal reduction was calculated using the following equation:

$$\%\text{SigRd} = \left(\frac{MFL_{ref} - MFL_{pp}}{MFL_{ref}}\right) \times 100$$  \[1\]

where $\%\text{SigRd}$ is the percentage of signal reduction; $MFL_{ref}$ is the peak-to-peak value of the defect signal at 1 mm/s; and $MFL_{pp}$ is the peak-to-peak value of the defect signal at a given
velocity. \( MFL_{ref} \) was set to 1 mm/s as this was the slowest speed at which the positioning table could be operated. Note that, “peak-to-peak value”, refers to the difference between the adjacent positive and negative peaks which are typical of a pin-hole defect, as shown in Figure 5.

Figure 7 shows the results for specimens 1 and 2, which are representative of the range of signal reduction that occurred in all specimens. Specimens 1 and 5 showed little or no signal reduction as scanning velocity increased. Specimens 2, 3, and 4 showed reductions of up to 8%. Typically, the majority of the velocity effects occurred below 80 mm/s and the shape of the MFL signals was insensitive to velocity. As expected, the measured signal reductions due to velocity are much smaller than those found in pipelines by Atherton \textit{et al.} [13] since greater reductions are expected for defects in thicker materials.

### 3.3 Signal Spatial Resolution

In MFL inspection of pipelines, sampling of MFL signals is usually performed at a fixed spatial resolution rather than at a fixed temporal resolution because the speed of the inspection tool can vary [14]. Having a high-resolution system increases the amount of data acquired, which in turn increases the ability to characterize defects. However, system designs must optimize the trade-off between increased resolution and superfluous data [15]. The purpose of this study was to find a range of spatial resolutions that maximized signal quality while minimizing the amount of data collected, stored, and analyzed. Spatial resolution was calculated by using the following formula:

\[
SR = \frac{f_{\text{sample}}}{V_{\text{scan}}} \tag{2}
\]
where SR is spatial resolution \([\text{samples/mm}]\); \(V_{\text{scan}}\) is the scanning velocity \([\text{mm/s}]\); and \(f_{\text{sample}}\) is the sampling frequency of the data acquisition system \([\text{samples/s}]\).

All five specimens were used for this study. MFL signals were analyzed in the spatial frequency domain using the FFT (Fast Fourier Transform) technique. In the spatial frequency domain, the frequency is determined with respect to the position rather than time. Shown in Figure 8 is a spectral plot of a highly over-sampled MFL signal (spatial resolution of 40 samples/mm). This plot is representative of the signals for all of the specimens. The largest frequency components of the MFL signal occur at less than 1 cycle/mm. Based on the Nyquist sampling theorem, to avoid aliasing, the sampling frequency should, therefore, be at least 2 sample/mm. However, to ensure that a quality high-resolution MFL signal a factor of safety of 5 was applied and sampling was done at 10 samples/mm. Based on the results of this work, the data acquisition program was modified so that the spatial resolution of the signal was maintained at 10 samples/mm for any scanning velocity.

3.4 End Effects

The purpose of this investigation was to assess the effect of the proximity of a defect to the edge of the TWB. Possible changes in flux density as the pole pieces move off the end of the specimen were also examined.

Specimen 1 was scanned for the full length of the weld line (scan velocity: 200 mm/s, spatial resolution: 10 cycles/mm, pole piece flux density: 0.410 Tesla) after two 1.1 mm diameter holes were drilled in the weld line, 3 mm and 100 mm from the end of the specimen. In this test, the Hall sensor was allowed to run off the end of the specimen onto a small square piece of plate glass, flush with the end of the specimen.
Figure 9 shows the MFL data for this scan of specimen 1. Peaks for the 1.1 mm holes are clearly visible. The large spike in the signal at approximately 380 mm is due to the movement of the Hall sensor off of the end of the specimen. The signal from the 1.1 mm hole closest to the edge is reduced compared to the signal from the 1.1 mm hole 100 mm away from the edge.

This reduced signal from the hole close to the specimen edge is caused by the decreased flux applied to the specimen as a portion of the magnet assembly rolls off the specimen. Although edge effects will not affect the ability to detect defects, they must be considered when making defect size estimations based on the defect signal if the defect is close to the edge of the specimen.

3.5 Pole Piece Lift-off

It is important in automotive applications that the scanning process does not mark the surface of the TWB. The effect of increasing the distance between the specimen and the magnet pole pieces to reduce the potential of damaging contact was, therefore, investigated. Pole-piece lift-off was accomplished using wheels that provided a specified clearance from the TWB surface. Consideration was given to the level of applied field as the lift-off between the specimen and the pole pieces increased. This study examined the effect of lift-off distances from three sets of wheels giving three gap distances: 0.25 mm, 0.5 mm and 1.13 mm.

MFL data was collected using specimen 5 for each set of wheels under two circumstances: (1) The flux in the pole pieces was maintained constant at 0.410 Tesla by adjusting the backing circuit position for each set of wheels. (2) The backing circuit position was held constant while the wheel sets were changed. For both methods, the peak-to-peak value of the defect signal was
determined and compared for each wheel set. The scanning velocity was 200 mm/s and the spatial resolution of the acquired signals was 10 samples/mm.

The results of the lift-off tests are summarized in Table 2. For the tests at constant flux, the changes in peak-to-peak values were insignificant for lift-offs of 0.50 mm and 1.13 mm. In both cases, MFL peak-to-peak values were calculated to be 107 gauss. The lift-off of 0.25 mm resulted in contact between the TWB and the pole pieces and this data was, therefore, disregarded. For the case where the backing circuit position setting was held constant, decreasing the lift-off distance from 1.13 mm to 0.5 mm caused an increase in the peak-to-peak value of the defect signal of 4.7%.

Based on the results of this study, the 0.50 mm lift off wheel set was chosen for the MFL inspection system in this application. It provided increased magnetization from the 1.13 mm wheel set but did not mark the specimen like the 0.25 mm wheel set.

4.0 Conclusions

The MFL inspection method had been shown to be relatively insensitive to variations in operating parameters over the ranges studied. Peak-to-peak defect signals increase as the applied field strength increases but signal-to-noise ratios are relatively unaffected. The effect of scanning velocity on MFL signals was less than 8% over a wide range of velocities. Between 80 mm/s to 200 mm/s the incremental reduction in the signal was less than 1%. The sampling resolution study determined that the components of interest occur at spatial frequencies of less than 1 cycle/mm, a resolution that is easily achieved at typical welding speed using even the
most basic of data acquisition equipment. The pole piece lift-off study found that proper magnetization of the specimen could be maintained with a gap which is large enough that contact between the pole pieces and the specimen does not occur. Lastly, defects were detected over the full length of the weld seam, although signal magnitude decreases at the edges of the blank. In conclusion, this study has shown that MFL inspection of TWBs is a robust method which is not adversely influenced by small variations in the inspection process parameters.
References


http://www.battelle.org/pipetechology/MFL/MFL98Main.html
Table 1: TWB specimen characteristics

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Gauge (mm)</th>
<th>Coating</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.8 / 1.0</td>
<td>Galvanized</td>
<td>Shock tower</td>
</tr>
<tr>
<td>2</td>
<td>2.0 / 1.5</td>
<td>Galvanized</td>
<td>Side rail</td>
</tr>
<tr>
<td>3</td>
<td>1.5 / 1.0</td>
<td>None</td>
<td>Door inner</td>
</tr>
<tr>
<td>4</td>
<td>1.6 / 0.75</td>
<td>Galvanized</td>
<td>Door inner</td>
</tr>
<tr>
<td>5</td>
<td>1.8 / 0.85</td>
<td>Galvanealed</td>
<td>Door inner</td>
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Table 2: Effect of pole-piece lift-off

<table>
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<tr>
<th>Pole-piece lift-off (mm)</th>
<th>Defect Signal Strength (gauss)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Constant applied flux</td>
</tr>
<tr>
<td>0.25</td>
<td>N/A - surface contact</td>
</tr>
<tr>
<td>0.5</td>
<td>107</td>
</tr>
<tr>
<td>1.25</td>
<td>107</td>
</tr>
</tbody>
</table>
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Figure 1 - Schematic drawing of magnet assembly.

Figure 2 – Photograph of MFL test rig.

Figure 3 – Schematic drawing of MFL test rig (DAQ = Data Acquisition Equipment)

Figure 4 – MFL profile for a typical weld line showing a defect.

Figure 5 - MFL profiles for specimen 5 at the highest (0.45 T) and lowest (0.27 T) applied field strengths measured in the pole pieces.

Figure 6. The peak-to-peak defect signal versus applied field strength for specimens 2 and 5 (Note: TR is Thickness Ratio).

Figure 7 - Peak-to-peak signal reduction as a function of scanning velocity for specimens 1 and 2.

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Acknowledgements

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