Detection of bond defects in cold roll bonded Al/Al-Sn/Al/steel sheets using Lamb type guided wave EMATs

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Abstract

Rayleigh-Lamb, ultrasonic, guided wave modes were used to detect delamination, embedded steel debris and a brittle intermetallic Al-Fe diffusion bond layer at the interface between clad Al and steel, which were bonded together in a cold roll bonding (CRB) process. Multi-layered samples were produced, with artificially implanted defects of different sizes between the clad Al and steel layer to determine the sensitivity of the guided wave modes to qualitatively indicate the occurrence of defects based on signal attenuation caused by defects. Electromagnetic acoustic transducers (EMATs) were used to generate and detect the guided waves in the pitch and catch technique. Signals were measured in the as rolled and post rolling annealed state to determine the influence of the altered material properties on attenuation and Signal-to-Noise Ratio (SNR). Results show very good sensitivity of the $S_0$ wave mode for delamination and embedded steel debris detection and a relation between attenuation, defect type, size and annealing state. However, detection of the presence of a brittle intermetallic Al-Fe diffusion layer was not possible due to the strong sensitivity to the material properties and thicknesses of the clad Al and steel materials. Micro sections of all samples were examined to explain the observations. The results suggest a promising use of Rayleigh-Lamb guided wave modes for online detection of bond defects in serial production of Al-Sn alloy/steel bimetal strips.

1. Introduction

Al/Al-Sn/Al/steel strips that are for simplicity referred to as Al-Sn alloy/steel bimetal strips are used for engine bearings in the automotive industry due to the ideal hybrid properties of Al-Sn alloy and steel [1]. This work is based on bimetal samples for which the clad Al is cold roll bonded (CRB) to steel. In CRB, the solid state weld is achieved by a substantial and simultaneous plastic deformation of the metals at room temperature [1]. Figure 1(a) illustrates this process. The disadvantage of this technique is a large number of secondary operations and high requirements for the bonding surface
preparation quality [2]. Current industry practice for inspection is destructive testing using a chisel test, peel test, shear test, Erichsen cup test or hot hammer test [1]. Although each technique has specific advantages and disadvantages, they all have in common that only a minor proportion of the produced material is inspected. Figure 1(b) shows a micrograph of the four-layered Al/Al-Sn/Al/steel sheet structure. The cladding layers of the Al-Sn internal core are made of Al-1050 strip. The Al-Sn alloy has a nominal 6% Tin content. The three-layered Al/Al-Sn/Al system is referred to as clad Al, which is cold roll bonded onto the steel free from aligned linear porosity or continuous oxides. The backing is made of a low carbon steel.

Figure 1. (a) Cold roll bonding (CRB) process schematic [3] (b) cross section view of the four-layered Al/AlSn/Al/steel structure

Figure 2 illustrates the frequency of specific flaws which were detected in serial production in a certain period of time. It demonstrates that 71% of the total flaw occurrences are associated with bond defects at the interface between Al-1050 foil and the steel, whilst the interface between Al-1050 and Al-Sn alloy accounts for 10% of the defects. Therewith in total 81% of the flaws that occur in serial production are bond defects.

Figure 2. Pareto analysis of defect occurrence in Al-Sn alloy/steel bimetal strips in serial production

Figure 3(a) illustrates a micrograph of a clad Al to steel bond with delamination that exceeds the critical threshold of 250 μm length. The threshold is based on empirical data. If the delamination exceeds this threshold, then there is a danger that the bond fails in the bimetal engine bearing. In Figure 3(b), a clad Al to steel delamination in a bimetal
half bearing shell is shown which was detected during inner diameter (ID) boring, when the shear forces exceeded the adhesion between the layers. The micrograph in Figure 3(c) shows a delamination between the top Al-1050 layer and Al-Sn alloy. This type of delamination results in visible blisters on the top Al-1050 surface of the bimetal strip, which is shown in Figure 3(d).

Figure 3. Clad Al to steel delamination (a) micrograph and (b) half bearing; Al-1050 to Al-Sn alloy delamination (c) micrograph and (d) Al-1050 strip surface

Considering the difficulty to create a metallurgical bond between two dissimilar metals in the CRB process and the limitations of destructive testing, there is a need for an automated online non-destructive testing (NDT) technique that is capable of inspecting the bond quality of Al-Sn alloy/steel bimetal strips during production. Active thermography and shearography techniques were studied for Al-Sn alloy/steel bimetal strips, with the result that these techniques have limitations that prevent an online application due to the requirement for suitable excitation methods. Furthermore conventional ultrasound bulk wave techniques were investigated. However, bulk wave ultrasound inspection cannot keep up with the desired speed of online inspection, since a two-dimensional scan of the material is required to cover the entire volume [4]. Contrary to this, guided waves require only a one-dimensional scan, which significantly increases the inspection speed. In this paper, Rayleigh-Lamb guided waves that are generated and received with EMATs are used to inspect the multi-layered samples. It is the first time that this technique has been applied to inspect the bond of Al/Al-Sn/Al/steel multi-layered sheets.

2. Experimental procedure

2.1 Wave propagation analysis

Table 1 summarises the material properties related to wave propagation analysis.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Clad Al</th>
<th>Backing</th>
</tr>
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<tbody>
<tr>
<td>Material</td>
<td>Al-1050</td>
<td>AlSn alloy</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>0.04 +/- 0.01</td>
<td>0.51</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.71</td>
<td>3.11</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Poison’s ratio (GPa)</td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>

All layers of the clad Al and steel sheets are assumed isotropic in the simulation of guided wave propagation dispersion curves, which are based on the general theory of elastodynamics [5], represented by a displacement equation of motion (Equation 1):
\[(\lambda + \mu)u_{j,i} + \mu u_{i,j} + \rho f_i = \rho \ddot{u}_i \text{------------------------}(1)\]

\(\lambda\) and \(\mu\) are Lamé’s first and second coefficients and depend on Young’s modulus and Poisson’s ratio of the material in each layer. For the theoretical simulation, the clad Al material is assumed as one layer. The displacement field is \(u\), \(\rho\) is the density and \(f\) is the distributed body force. The coordinate directions are indicated with the indices \(i\) and \(j\), in which \(1\) refers to the direction of wave propagation, \(2\) referring to the direction of wave front, and \(3\) referring to the thickness direction. The Rayleigh-Lamb phase and group velocity dispersion curves in the Al-Sn alloy/steel bimetal system for this study were calculated by Innerspec using the semi-analytical finite element method (SAFE). Each combination of frequency and velocity on these curves represents a theoretically possible test mode. Lamb modes can either be symmetric (S) or anti-symmetric (A) and their propagation characteristics depend on entry angle, excitation and structural geometry [6]. The ideal Lamb mode for inspection should have the following properties: (1) non-dispersive, (2) low attenuation, (3) high sensitivity, (4) easy excitability, (5) good detectability and (6) tool-less selectivity [7]. The simulation combined with the selection criteria, did result in various wave modes that appeared to be good candidates for further laboratory study. In an empirical study with these potential wave modes, the \(S_0\) mode with a wavelength that is lower or equal to the defect size, and a frequency that is efficiently excited in the Al-Sn alloy/steel bimetal sheets was identified, which is reasonably sensitive to the samples with artificially implanted defects.

2.2 Sample preparation

Nine test samples were produced for this study. These were made of 1.55-1.65 mm thick bimetal sheets, consisting of 0.52 mm thick clad Al and 1.08 mm steel after a high level of reduction during CRB. The width of the samples was 211 mm. The samples were produced in a continuous process as strip and then cut into individual pieces, each approximately 800 mm in length. The test samples production process was identical to serially produced material, except that a specific defect was artificially implanted immediately before CRB, which is shown in Figure 4(a) to (h). A template and sieve were used to spread a defined quantity of contaminants, in a thin and even layer on the finished steel surface. Figure 4(a) to (d) show alumina (Al\(_2\)O\(_3\)) powder and (e) to (h) steel debris that was applied. The elongation factor in rolling direction during the CRB reduction was taken into account, thereby the theoretical 2D defect size in the \(X_1-X_3\) sheet plane after CRB were approximately 1x1 mm, 5x5 mm, 10x10 mm and 15x15 mm. Alumina was applied to create an artificial delamination, as it was reported that surface oxides interfere with the creation of nascent metal welds, which establish an effective cold weld [8]. Steel debris was implanted, as it is the most frequently detected impurity in serial production and impairs the bond quality. One sample without artificial defect was produced as a control sample.
2.3 Experimental set up

The guided wave experiment was set up in the pitch and catch configuration as shown schematically in Figure 5(a). The transducers were positioned at the steel side. Both transducers were placed so that the wave path propagated along a direction with shallow angle from normal to the edge of the sheet, in order to eliminate the influence of edge reflection.

These EMATs were manufactured by Innerspec Technologies Inc. Figure 5(b) is a schematic of the EMAT transducer and its interaction with the bimetal sample. The transmitting and receiving transducers each have a magnet in housing and a meander coil over the magnet pole. Above the magnetic pole, the magnetic field (B) is mainly in the X₂ direction. Eddy currents (J) are induced by the meander coil in the X₁ direction. The Lorentz force (f), which acts on particles in the sample due to the magnetic field (B) and eddy currents (J), is given by Equation 2:

\[
f = J \times B \]

Since the current sent along the meander coil is periodically distributed, the corresponding eddy currents in the steel surface of the bimetal sample generate periodically distributed loading. When the guided wave propagates above the receiving EMAT, the horizontally polarized stress field that it produces interacts with the magnetic field, thus generating currents in the meander coil, which is placed between the bimetal sheet and the magnet. The EMATs used in this study are designed so that
they can transmit and detect guided waves, within a frequency bandwidth from 50 kHz to 6 MHz.

A data acquisition Pentium-based personal computer (PC) running the Windows XP operating system with temate® software and a field-programmable gate array (FPGA) card with high-speed waveform digitizer was used to generate the excitation signal (see Figure 6(a)). This is sent to a Data Input Output (DIO) FPGA interface, which receives trigger signals from the signal conditioning box and FPGA card and distributes them to the tone burst amplifier (see Figure 6(b)). In Figure 6(c), a temate® 2-CH tone burst amplifier with 10KW power is shown that is used to convert the low-voltage power signal into a high-power pulse train, which is required to drive the transmitting EMAT to produce a good signal-to-noise ratio. A remote electronics signal conditioning box (Figure 6(d)) connects the EMAT sensors with the tone burst amplifier and to the DIO interface. It has an analogue-to-digital converter for signal conversion. A specific holder shown in Figure 6(e) was used for all measurements to keep both EMATs perfectly aligned and at a constant distance apart from each other.

**3. Results and discussion**

**3.1 Rayleigh-Lamb guided wave inspection**

An inspection gate between 42 and 46 µs to monitor the amplitude changes was set for the through transmission signal. Figure 7(a) shows the A-scan for a defect free location, for which the gain was adjusted so that the reference amplitude was close to 100%. When the guided wave encounters a delamination or embedded steel debris between the clad Al and steel layer, a large amount of the incident wave energy is converted to radiation energy in all directions, which results in stronger attenuation compared to a defect free location. As a result, the wave energy that reaches the receiving EMAT transducer at the set inspection gate is decreased, which is shown as lower signal amplitude. Figure 7(b) shows an example of a defective sample with embedded 10x10 mm area steel debris for which the sound wave that arrives at the inspection gate between 42 and 46 µs is reduced to 30% amplitude due to the energy loss at the defect. For the selected S0 mode and the size of the artificial defects tested in this study, only signal attenuation was observed. However, for larger delaminations it was observed that the guided wave propagates independently in the clad Al and/or steel plate and a mode conversion may occurs.
The CRBed samples were tested twice, prior and post annealing. This was done to determine if inspection could take place at the CRB production line or, only as a final inspection carried out after annealing. Figure 8(a) shows the B-scan for the defect free sample prior annealing. The gain value was set at ‘0’ to obtain signal amplitude close to 100%. Once the gain was set for the un-annealed reference sample, the inspection parameters were kept the same for all other measurements. Figure 8(b) shows the B-scan for the same defect free sample after annealing. Figure 8(c) shows the B-scan for the embedded 10x10 mm steel debris defect prior annealing and, in Figure 8(d), post annealing. For the reference sample, 175 measurement points were recorded along the sample scan. For the defective samples, the scan was repeated ten times and in each scan the lowest amplitude within the measurement range was recorded.

Figure 9 plots the median, the quartiles, and outliers of the amplitude prior and post bimetal annealing that was measured for the reference and all defective samples. For the reference sample as well as the defect free areas surrounding the artificially implanted defects, the amplitude after annealing increased by approximately 50% compared to the un-annealed state, suggesting that post rolling annealing results in lower attenuation. Figure 9(a) shows the alumina induced delamination results. The larger the delamination, the less wave energy arrives at the receiving EMAT. The energy loss at the smallest 1x1 mm defect is significant, and the received energy for larger delamination sizes is of the same magnitude. Post rolling annealing has no noticeable effect on attenuation when the clad Al and steel layers are delaminated. Figure 9(b) plots the measured amplitude for samples with embedded steel debris. It was again observed that the larger the embedded steel debris defect is, the stronger is the attenuation, however there is a stronger dependency between defect size and attenuation compared to delamination defects. Furthermore, post annealing noticeably reduces attenuation for embedded steel debris up to 5x5 mm size.
For automatic online strip inspection, it is necessary to set an alarm threshold, which classifies the material as defective if the amplitude falls below the threshold. Any variation in signal amplitude due to local material property changes, external factors or noise should not cause false alarms. A Signal-to-Noise Ratio (SNR) of minimum 2 is required based on empirical data for reliable defect detection. The calculated SNR values prior and post annealing for the delamination and embedded steel debris defects are summarised in Table 2. Taking into account the required minimum SNR and the obtained measurement data, at least 1x1 mm delaminations and 5x5 mm rolled-in steel debris are likely to be detected using an online inspection. Despite reduced attenuation resulting from annealing, the results suggest that online inspection can be done either prior or post annealing, as the post annealing effect on the SNR is negligible.

### Table 2. Statistical and SNR sample data

<table>
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<th>Measurement</th>
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<th>Delamination defect</th>
<th>Embedded steel debris defect</th>
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<tr>
<td>Size</td>
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<td>5x5 mm</td>
<td>10x10 mm</td>
</tr>
<tr>
<td></td>
<td>15x15 mm</td>
<td>1x1 mm</td>
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</tr>
<tr>
<td></td>
<td>10x10 mm</td>
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<td>Annealing</td>
<td>prior</td>
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<td>N</td>
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<td>144.1</td>
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<tr>
<td>std(σ)</td>
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<td>2.9</td>
<td>2.4</td>
</tr>
<tr>
<td>SNR</td>
<td>-</td>
<td>4.0</td>
<td>5.9</td>
</tr>
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</table>

### 3.2 Effect of defects on attenuation

Microsections of the test samples were taken to ascertain that the nature of the artificial defects is similar to real defects in regards to the defect type, location, size and orientation, which influence the amount of sound energy that is reflected, when the guided wave path encounters a defect. Furthermore the different attenuation for delamination and embedded steel debris defects need to be explained. An optical microscope with 100x and 200x magnification was used to inspect the bond line. The cross sections were taken in the \(X_1\)-\(X_2\) rolling direction plane. Figure 10(a) is a micrograph of the reference sample, which was used to obtain the reference amplitude. The bond line is free from aligned linear porosity, continuous oxides and delamination, which confirms that the reference amplitude corresponds to a flawless sample. The Al-1050 to steel delamination in Figure 10(b) is caused by a thin alumina layer while Figure 10(c) illustrates a real delamination from serial production. In both cases, the continuous delamination spreads about 800 µm in the rolling direction until good bonded areas separate it from other delaminations within the area of the artificially
implanted defect. Figure 10(d) shows embedded steel debris between the Al-1050 and steel layers, which was artificially implanted. In Figure 10(e), embedded steel debris that was found in serial production is shown. In both samples, the length of the embedded steel debris exceeds 1000 µm in the rolling direction and continues throughout the area, in which the defect was artificially implanted. It appears that in both cases the steel debris is bonded to the Al foil, but not to the steel layer. The microscopic assessment of the samples suggests that the artificially implanted defects have similar characteristics compared to real defects, which were randomly found in serial production, and therefore their ultrasound wave reflector properties should be representative of real defects. When comparing delamination with embedded steel debris defects, in the real as well as artificially implanted case, the void volume of delamination is clearly larger and continuous in the rolling direction, which explains why the reflected ultrasound wave energy is stronger for the debond type defect compared to the embedded steel debris defect. When the ultrasonic guided wave reaches a debond type defect, the behaviour of the wave changes, causing destructive interferences that are responsible for the amplitude drop shown in the previous results. For the embedded steel debris, the layers are in physical contact, and therefore only a smaller proportion of the ultrasound wave energy is reflected when the wave passes through the interface. The amplitude increase after annealing for the 1x1 mm and 5x5 mm steel debris samples suggests that no voids exist for small areas of embedded steel debris, and therefore the post rolling annealing causes the same attenuation alteration in these defective samples like in the reference sample.

![Figure 10](image)

**Figure 10. Optical micrographs:** (a) reference sample, (b) artificial 5x5 mm delamination, (c) natural delamination, (d) artificial 5x5 mm embedded steel debris and (e) natural embedded steel debris

### 3.3 Effect of post rolling annealing on attenuation

For the reference sample an amplitude increase of 50% after post rolling annealing was observed. This can be explained by analysing structural changes in the materials. During
rolling, the grains become elongated and flattened, which changes the grain aspect ratio. Figure 11(a) shows the elongated grain structure in the rolling direction, and Figure 11(b) the flattened grain structure in the transverse direction. These micrographs were captured prior to annealing. The elongated grain boundaries lead to elastic scattering of the ultrasound wave and consequently increased attenuation [9]. During post rolling annealing, the grain structure of the work hardened clad Al is recrystallized and diffusion between the steel and Al-1050 layer takes place to enhance the metallurgical bond. Figure 11(c) shows the recrystallized grain structure in the rolling, and Figure 11(d) in transverse direction, which were captured post annealing. The difference in the grain structure is apparent. The recrystallized grain structure reduces the elastic scattering, hence the transmitted energy of the ultrasound wave increases, which explains the amplitude increase. During CRB, the grain structure of the steel is also elongated, however the annealing temperature is too low to recrystallize the steel grain structure, and therefore, the steel does not make a difference to the signal attenuation of the bimetal system.

**Figure 11.** Optical micrographs: Al-Sn alloy (a) elongated structure in rolling direction and (b) flattened structure in transverse direction prior to annealing, (c) recrystallized structure in rolling direction and (d) transverse direction post annealing (Etchant: Wecks)

If the solution heat treatment or annealing time is exceeded, there is the risk of the formation of a brittle intermetallic layer that forms at the bond line. Three intermetallic phases $\text{Al}_2\text{Fe}$, $\text{Al}_3\text{Fe}_2$ and $\text{Al}_{13}\text{Fe}_4$ exist when the steel diffuses into the aluminium layer,
as Fe has a high solubility in Al [10]. Plant internal trials concluded that 3-5 \(\mu m\) thick intermetallic layer is detrimental to the bond, even though this thick layer only forms at enhanced solution heat treatment temperatures and/or times. A sample with about 5 \(\mu m\) thick Al-Fe intermetallic layer was produced and inspected with the same experimental setup. As a result, the guided wave that interrogates the entire plate could not detect the presence of the brittle intermetallic layer, as there was no measurable amplitude difference compared to a normally solution heat treated bimetal sample without Al-Fe intermetallic layer. Lowe et al. [11] studied the bond inspection of diffusion bonded titanium sheets, which have no evidence of a bond line in the perfect bonding case, but if oxygen or nitrogen is present at the bond line during the high-temperature bonding process, an unwanted brittle titanium phase layer forms. Their study was concerned with the detection of the presence of the unwanted layer. It was concluded that the Lamb wave technique was not applicable for the detection of the unwanted intermetallic layer, due to the strong sensitivity to the material properties and thicknesses of the materials and insensitivity to the bond line layer. The Al-Sn alloy/steel dispersion curves are practically only influenced by the properties of the clad Al and steel materials and are insensitive to the embedded layer. This leads to the conclusion that diffusion between the clad Al and steel, such as the 5 \(\mu m\) thick brittle Al-Fe intermetallic layer, has no measurable influence on the sound attenuation. Therewith the decreased attenuation observed after annealing can be primarily attributed to the recrystallization of the clad Al grains.

4. Conclusions

Rayleigh-Lamb wave modes for Al-Sn alloy/steel bimetal were calculated with the SAFE method and, among them, a \(S_0\) mode that is efficiently excited in the Al-Sn alloy/steel bimetal system was selected in an empirical study, using defect free and defective samples. A sample production technique was developed to produce artificially implanted defects, which have ultrasound properties that are comparable to real defects. The selected \(S_0\) wave mode is reasonably sensitive to the artificial defects and measurements results exhibit good repeatability. An explanation for the attenuation change in defect free samples was provided, which is that quasi equiaxed grains produced by post rolling annealing cause less elastic scattering than elongated grains that are present in the clad Al prior to rolling annealing. It was also found that Rayleigh-Lamb wave modes are insensitive to diffusion between the clad Al and steel layers. It was observed that amplitude attenuation depends on the type and size of the bond defect. Based on a required SNR of 2, the results suggest that under serial production conditions, delaminations with approximately 1x1 mm area and embedded steel debris with 5x5 mm area or larger can be detected. The measured SNR prior and post rolling annealing suggests, that inspection could be done online either during production before post rolling annealing, or as final inspection after post rolling annealing. The guided wave inspection technique is capable of inspecting 100\% material volume at the required line speed. The study results provide encouraging signs that the investigated inspection technique can be applied in serial production of Al-Sn alloy/steel bimetal strips.
Acknowledgements

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References