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LASER-ULTRASONIC INSPECTION OF MG/AL CASTINGS

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ABSTRACT. Laser-ultrasonics is used to assess the metallurgical bond between Mg/Al materials in die-cast Magnesium/Aluminum composite. The acoustic impedances of Mg, Al and air are such that the amplitude of ultrasonic echoes reflected back from a void is many times larger than the amplitude of those reflected back from a well-bonded interface. In addition, the polarity of echoes from a void is inverted compared to that from a well-bonded interface. Laser-ultrasonic F-SAFT is also used for imaging tilted Mg/Al interfaces. Experimental setup, signal processing and results for detecting voids in the Mg/Al interface of cast parts are presented.

INTRODUCTION

In the search for a lighter automotive engine, a Magnesium/Aluminum composite design has been proposed for the single heaviest component, i.e. the cylinder crankcase shown in Fig. 1a. The manufacturing method consists to make the cylinder barrels, the main bearings and the water jacket from a hypereutectic aluminum alloy and to subsequently cast magnesium around it in a die-casting process [1]. A nondestructive technique is required to assess the metallurgical bond between both materials in the part.

This paper presents experiments, signal processing and results for detecting voids at the Mg/Al interface of cast parts, based on the non-contact generation and detection of ultrasound with lasers. Tests have been performed on samples composed of an Al core enclosed in a Mg shell, as shown in Fig. 1b and taken from the bulkhead/main bearing area of the crankcase. The acoustic impedances of Mg, Al and air are such that the amplitude of ultrasonic echoes reflected back from a void is many times larger than the amplitude of those reflected back from a well-bonded interface. In addition, the polarity of echoes from a void is inverted compared to that from a well-bonded interface. These features have been used as signatures of voids. For Mg/Al interfaces tilted with respect to the Mg surface of inspection (see the Al core in Fig. 1c), the laser-ultrasonic data have been processed using a Fourier domain Synthetic Aperture Focusing Technique (F-SAFT). Results obtained using both approaches are presented.

FIGURE 1. a) BMW I6 Mg/Al composite crankcase, b) Mg/Al casting sample with flat-bottom holes to simulate delaminations and c) the Al core of such a sample.

EXPERIMENTAL SETUP AND SAMPLES

In a first approach, the generation of ultrasound is performed by a 100 ns duration, pulsed CO₂ laser in the thermoelastic regime with the part surface covered with removable water-based paint. Scanning is made with large laser spots and a large scanning step size. The detection laser is a highly stable, single-frequency, 60 μ s duration, pulsed Nd:YAG laser. The phase demodulation is performed with a 1 m long confocal Fabry-Perot interferometer. For tilted Mg/Al interface, the ultrasonic wave can be reflected obliquely from the Mg/Al interface to any location on the Mg surface surrounding the laser-generation point. Then, the small ultrasonic displacement of the Mg surface will not be properly detected unless the detection laser spot is either at the right location, or the detection laser spot is large enough. The second approach adopted here is to process the data with F-SAFT, which allows synchronization of the ultrasonic signals scattered back in different directions from each point of the Mg/Al interface. More details about its implementation combined with laser-ultrasonics can be found in Refs. 2 and 3. In this case, the generation of ultrasound is performed in the slight ablation regime from the bare Mg surface (without paint) with a 10 ns-duration, frequency-doubled, Q-switched Nd:YAG laser. Smaller laser spots and a smaller scanning step size are used. The detection laser and the interferometer are kept the same.

Testpieces of Al alloy and of Mg alloy were first probed to measure the ultrasonic characteristics (velocities and impedances) of these alloys. Through-thickness longitudinal wave velocities, v_L , of 5.80 ± 0.1 mm/ μ s and 6.67 ± 0.04 mm/ μ s were obtained for the Mg and Al alloys respectively. These velocities are quite uniform across the samples, in spite of the important and non-uniform porosity of the Al sample. In void areas, the ultrasonic echoes are reflected by a Mg/Air interface. Assuming material densities, ρ , of 1.74 g/cm³

for Mg and 2.70 g/cm^3 for Al, the reflection coefficients for ultrasonic displacement at the interface (normal incidence) are $r_{\text{Mg/Al}} = -0.28$ for a well-bonded interface and $r_{\text{Mg/Air}} = 1.0$ in the case of a void. Therefore, the amplitude of ultrasonic echoes reflected back from a void is 3.5 times larger than the amplitude of those reflected back from a well-bonded interface. When considering reflection coefficient for obliquely incident waves, a factor of up to 4.0 is attained. In addition, the polarity of echoes from a void is inverted compared to that from a well-bonded interface. These two features (the amplitude ratio of echoes and the polarity inversion) can be used as signatures of voids. In a more thorough analysis, the thin intermetallic layer at the Mg/Al interface could be considered but conclusions are expected to be the same.

Measurements were then performed on two samples of Mg/Al casting composed of an Al core enclosed in a Mg shell. In one Mg/Al casting shown in Fig. 1b, eight flat-bottom holes (two lines of holes with diameters 10, 5, 1, 0.5 mm) have been drilled in the Al part to simulate delaminations. These flat-bottom holes have a depth such that the bottom of the hole is located at the interface of the two alloys. The other testpiece of Mg/Al casting is expected to have some voids at the Mg/Al interface. The inspection is performed from the Mg shell surface in different areas of the two samples.

LASER-ULTRASONIC RESULTS

Results using large laser spots and water-based removable paint

The laser spots sizes were 5 mm and 2.5 mm for the generation and detection respectively and the scanning step size was 0.5 mm. The detection bandwidth extends from 1 to 10 MHz. The lasers repetition rate was 100 Hz and the scanning time for each Mg/Al casting sample was about 5 min. The laser-ultrasonic signals (A-scans) were stored in a PC-computer for later signal processing. The data was first filtered by a 5 MHz high-pass numerical filter and a reference echo was selected from the signals acquired in the well-bonded region. Each A-scan was then cross-correlated with the reference echo. The peak value of the cross-correlation signals was then used to build images. The peak value is defined as the minimum or the maximum value depending on which is the largest in absolute value. A negative value of the cross-correlation means a polarity inversion of the signal with respect to the reference signal.

Fig. 2 shows the image obtained on the testpiece with flat-bottom holes. As expected, a negative value (polarity inversion) is observed for inspection above two of the flat-bottom holes drilled to simulate voids. Two other delaminated regions are also revealed, one at the bottom of the image and one near the semi-circle border. Also, A-scans taken from a well-bonded region and from void regions are shown in Fig. 3. The labels A to D refer to the scan locations shown in Fig. 2. A polarity inversion is clearly seen in Fig. 3 between signal in location A (well-bonded region) and those of the indications B, C and D. In addition, the echo amplitude from a delaminated region is about four times larger than that from a well-bonded region, as expected from the simple calculation in previous section. Another image of the testpiece, not shown here, was built using the maximum echo amplitude. Except for some uncertain features, that image is very similar to that in Fig. 2, with indications of nearly identical dimensions. Then, as predicted, the polarity inversion and maximum amplitude features can be used to detect delaminations. Notice that the dim regions in Fig. 2 indicate very poor SNR. Therefore, the two lines which intersect are regions where the Mg/Al interface is not parallel and for which the ultrasonic signal is not reflected back to the detection laser spot. These blind regions can be

eliminated by changing the scan parameters and by processing the data with F-SAFT, as discussed in the next section.

The image obtained for the other testpiece (without holes) and based on cross-correlation is shown in Fig. 4. A negative value (polarity inversion) is observed in a rectangular region between the bottom and the center of the image which is a clear signature of voids. Also, two regions are found on top of the image but are uncertain. Similar to the testpiece with the holes, the region right above the rectangular delaminated area has a Mg/Al interface tilted with respect to the top Mg surface and is considered using F-SAFT in the next section.

FIGURE 2. Laser-ultrasonic image of the Mg/Al testpiece with flat-bottom holes covered with removable water-based paint. The image shows the peak value of the cross-correlation with a reference echo taken in the well-bonded region.

FIGURE 3. Ultrasonic signals (A-scans) taken from a well-bonded region (A) and from delaminated regions in the different scan locations shown in Fig. 2.

FIGURE 4. Laser-ultrasonic image of the Mg/Al testpiece with expected delaminations covered with removable water-based paint. The image shows the peak value of the cross-correlation with a reference echo taken in the well-bonded region.

Results using F-SAFT processing

To visualize flaws in Mg/Al testpiece for both parallel and tilted interfaces, laser-ultrasonics was coupled with F-SAFT. The laser spots sizes were 0.3 mm and 0.2 mm for the generation and detection respectively and the scanning step size was 0.2 mm. The frequency bandwidth was between 1 and 20 MHz. The scanning was performed in different areas of the two testpieces of Mg/Al casting shown in Fig. 5. The signals obtained in each area were stored for later processing with the F-SAFT algorithm. To visualize delaminations, only the maximum amplitude is used since the polarity inversion was found difficult to capture after reconstruction for a Mg/Al interface located near below the scanned surface.

Fig. 6 shows SAFT images obtained from scanning an area of 40 mm x 30 mm on top of the testpiece with flat-bottom holes (see Fig. 5a). In the left figure, the two flat-bottom holes of diameters 1 and 5 mm included in the scanned area and drilled to simulate delaminations are clearly observed at a depth of 1.2 mm. However, the hole of diameter 0.5 mm also included in the scanned area is not detected. One reason could be that this hole is below the Mg/Al interface. Also, notice that only the 5 mm hole was detected using the previous approach. In the right figure, a void region is revealed at a depth of 1.7 mm near the semi-circle border, with dimensions similar to those in Fig. 2.

Fig. 7 shows SAFT images obtained from scanning an area 40 mm x 15 mm on the same testpiece where the Mg/Al interface is non-parallel, corresponding to a region in bottom right (see Fig. 5a). As in previous figures, the images in a) and b) are C-scans (sub-surface planes) taken at depths of 8.2 and 9.7 mm respectively. The image in c) is a B-scan (cross-section at location indicated in a) and b)) which shows the curved Mg/Al interface as well as the depth of the two C-scans. Notice that a similar view of the Mg/Al interface was not possible with the previous approach using large laser spots. In Fig. 7b, the two flat-bottom holes of diameters 10 and 5 mm included in the scanned area are observed at a depth of 9.7 mm where the interface is almost flat and parallel to the scanned surface. In Fig 7a, corresponding to a depth of 8.2 mm, a horizontal line of variable amplitude is observed. This line is the intersection of the curved Mg/Al interface with the observation plane (parallel to the scanned surface). Along this intersection line, we believe that the darker regions are indicative of delaminated areas.

FIGURE 5. Scanned areas for F-SAFT processing on the two Mg/Al casting samples.

FIGURE 6. SAFT images on top of the Mg/Al testpiece with flat bottom holes showing a) the 1 and 5 mm diameter holes and b) the delaminated area 0.5 mm deeper.

FIGURE 7. SAFT images of the Mg/Al testpiece with flat-bottom holes in a region having Mg/Al interface non-parallel to the surface. The C-scans a) and b) are taken at depths indicated in the B-scan c).

For the testpiece without holes, Fig. 8 shows SAFT images obtained from scanning an area 30 mm x 25 mm where the Mg/Al interface is non-parallel (see Fig. 5b). The C-scans in a) and b) are taken at depths of 3.6 and 6.6 mm respectively, indicated on the B-scan in c) and showing the curved Mg/Al interface. A similar view of the Mg/Al interface was not possible with the previous approach using large laser spots. Notice that the interface is almost flat and parallel to the scanned surface at a depth of about 6.5 mm. Both C-scans show an amplitude change on the right indicative of a delaminated area, even along the tilted Mg/Al interface. In Fig 8a, an horizontal line with two different amplitudes is observed as an indication of delamination. As already mentioned, this line is the intersection of the curved Mg/Al interface with the observation plane. Also, the indication found is in agreement (at least for the flat interface area) with that observed in Fig. 4 using large laser spots.

FIGURE 8. SAFT images of the Mg/Al testpiece with expected delaminations in a region having Mg/Al interface non-parallel to the surface. The C-scans a) and b) are taken at depths indicated in the B-scan c).

FIGURE 9. SAFT images of the Mg/Al testpiece with expected delaminations in a region having non-parallel Mg/Al interface. The C-scan a) is obtained from a large range of depths and a B-scan is shown in b).

To improve the visualization of the indication, Fig. 9a shows a C-scan obtained using the maximum amplitude feature throughout a wide range of depths. This is one approach to follow the curved Mg/Al interface as repeated in the B-scan in Fig. 9b. From the C-scan, one can see a strong amplitude on the right for the delamination area which follows in part the curved Mg/Al interface. Also, a clear polarity inversion is found in the signals after SAFT reconstruction between a well-bonded region and a delamination. This feature could be used as well for imaging but this is possible only when the Mg/Al interface is deep enough, without the interfering contribution from the surface signal.

CONCLUSION AND PERSPECTIVES

The present study clearly shows that the laser-ultrasonic technology can be used for on-line assessment of the bonding of Mg/Al cast parts. Ultrasonics is well known to be a superior technique for detecting delaminations and is widely used for this reason in the aerospace industry. Laser generation and detection provides the additional flexibility and reliability for testing non-planar or complex geometries. However ultrasonics works by scanning a transducer (or its optical equivalent) and tends to be slow. For this reason two approaches have been explored in this work. First, the fastest one uses large spot interrogation and was shown to provide reliable assessment when the Mg/Al interface is essentially flat and parallel to the scanned surface. This approach is generally not appropriate for tilted or curved interfaces. For this case, we have shown that interrogation with a dense array of smaller spots coupled to a numerical reconstruction imaging technique (F-SAFT) could provide reliable information on the interface condition.

This work was intended to be a first basic demonstration of the technique for this application and was limited in scope. For future work, on the hardware aspect, the use of an UV laser could be considered in the large spot interrogation mode that will blast off the surface its natural contaminants and produce the same effect as the CO₂ laser used with the removable paint. Note that, although painting of the metal with a water-based removable paint requires an additional operation, it is used in conjunction with already mature technology well developed for aerospace applications and may be ultimately judged cost effective. On the software aspect related to F-SAFT processing, extension of the polarity detection mode to shallow interfaces and interface tilt are improvements that may be considered. SAFT could also be extended to a complex shape surface by taking into account the inspected surface profile measured with an optical surface profiler, as reported previously [4].

REFERENCES

1. Baril É., Labelle P., Fischersworring-Bunk A., "AJ (Mg-Al-Sr) alloy system used for new engine block", *SAE 2004-01-0659* (2004).
2. Lévesque D., Blouin A., Néron C. and Monchalain J.-P., *Ultrasonics*, **40**, 1057-1063 (2002).
3. Blouin A., Lévesque D., Néron C., Drolet D. and Monchalain J.-P., *Optics Express*, **2**, 531-539 (1998).
4. Campagne B., Lévesque D., Blouin A., Gauthier B., Dufour M., Monchalain J.-P., "Laser-ultrasonic inspection of steel slabs using SAFT processing", in *Review of Progress in Quantitative Nondestructive Evaluation Vol. 21A*, eds. by D.O. Thompson and D.E. Chimenti, AIP Conference Proceedings, New York, 2002, pp. 340-347.