Non-destructive detection of the useful zone in Boron carbide-reinforced metal matrix composites laminated plates

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Abstract

Boron carbide (B₄C)-reinforced metal matrix composites (MMCs) are materials of choice for the manufacturing of radioactive material containers due to their neutron absorption properties. The neutron absorption capacity of this material depends mainly on the density of B₄C particles in the aluminum matrix. The reinforced MMC sheets used to manufacture these containers are produced by a lamination process. The raw sheets coming out of the rolling mill show uneven distribution of B₄C particles between the extremities of the sheets, constituted solely of aluminum (rejection zone), and the interior of the laminated sheet, with the right aluminum / B₄C ratio (useful zone). Detecting the boundary between the useful zone and the rejection zone is a crucial step in the process, as it defines which part of the sheet should be used to manufacture the containers. Determination of this boundary is currently carried out by chemical digestion, which is costly, time-consuming, and provides only localized information. The aim of this work was to develop a non-destructive technique able to detect the boundary between the rejection zone and the useful zone. The approach is based on the difference in acoustic attenuation between rejection and useful zones. More precisely, the ultrasonic parameter used was the amplitude ratio between the backwall and the front wall echo of the sheet when performing a pulse-echo inspection at 20 MHz. The amplitude ratio in aluminum is smaller than in the useful zone containing B₄C, which is more attenuating for the ultrasounds. Two types of scans were performed: 1D linear scan and 2D scan. The linear scan was performed using a conventional probe coupled to the part via a conformable wedge. The boundary between both zones was detected by segmenting the amplitude ratio profile into different sections with constant statistical parameters. The 2D scan was performed with an automated 5-axis inspection system in a water tank using a conventional probe. A map of amplitude ratios was generated, and the useful zone was detected using an agglomerative clustering segmentation. Validation was carried out by comparing the amplitude ratio profile with chemical digestion data from samples taken from these sheets. Experimental validation, performed on sheets with different B₄C densities and thicknesses, showed that amplitude ratio enables a good detection of the boundary and therefore the useful zone.

Keywords: metal matrix composites, ultrasound, non-destructive testing, image processing, segmentation

1. Introduction

The storage and transportation of used nuclear fuel requires the use of containers made from neutron-absorbing materials. One of these materials is an aluminum metal matrix composite (MMC) in which particles of B₄C (boron carbide) are distributed, forming a core surrounded by two layers of aluminum (cladding). This composite material is obtained by stacking a core of aluminum powder and B₄C sandwiched between two aluminum sheets. The areal density (AD) of B₄C in the final material, corresponding to the mass (in mg) of the boron isotope $^{10}$B per cm$^2$ of sheet, determines the neutron absorption capacity of the sheet. The lamination process results in sheets having an outer zone consisting of aluminum with an insufficient proportion of B₄C, and a useful zone in the center with the desired areal density of B₄C. The useful zone is currently identified and cut out based on empirical knowledge of the process, then confirmed by chemical digestion to determine the surface density at the edges of the identified useful zone. However, chemical digestion is costly, time-consuming, and provides only localized information. This process can also result in a significant loss of compliant material.
The aim of this work is to develop a non-destructive technique able to detect the useful zone containing the right proportion of B₄C. This will lead to an optimal cutting of the sheets, saving as much of the useful material as possible.

Various studies [1-4] have so far attempted to establish the links between parameters derived from non-destructive inspection and the properties of MMC-type materials. However, to the best of our knowledge, there are no published studies proposing non-destructive testing (NDT) tools to detect the boundary on boron carbide (B₄C)-reinforced MMC laminates.

The proposed approach is based on the difference in acoustic attenuation between rejection and useful zones. More precisely, the ultrasound parameter used was the pulse-echo amplitude ratio between the backwall and the front wall echo on the sheet. The amplitude ratio in aluminum is smaller than in the useful zone containing B₄C, which is more attenuating for the ultrasounds. Two options are considered for the implementation of the technique: a 1D linear scan from the edge to the center of the sheet, or a 2D scan covering the entire sheet. Segmentation techniques to identify the useful zone have been developed for both options.

2. Material and methods

2.1 Description of the parts

Boron carbide (B₄C)-reinforced metal matrix composites consist of 3 layers: a core of aluminum powder mixed with B₄C particles, enveloped by two layers of aluminum (cladding), as shown in Figure 1.

![Figure 1: Micrography of the useful zone](image)

The manufacturing process consists in superimposing the three layers in an aluminum container, and then compressing them before passing them through a rolling mill. The rolling process results in laminated sheets with external regions containing aluminum, corresponding to the wall of the container and an insufficient proportion of B₄C, and in the center, a useful zone made of the 3 layers described in Figure 1. Figure 2 shows a schematic top view of the laminated sheets, with green representing the useful zone and yellow the aluminum zone to be rejected.

![Figure 2: Illustration of a laminated sheet (top view)](image)

The non-destructive methods developed to detect the useful zone have been validated on 6 different products families (A to F) corresponding to different combinations of B₄C content and sheet thickness.
2.2 Experimental setup

The aim of this work is to develop an industrial detection method of the boundary. Two scanning approaches are considered for its deployment. A first one will consist in performing an ultrasound scan of the complete laminated sheet using an automated inspection system, followed by detection of the useful zone on a 2D map. This approach can be implemented on an automated production line. It is reproduced in the laboratory by inspecting the sheet in an automated 5-axis ultrasonic inspection system (using an immersion tank). The second approach consists of a manual linear scan performed by an operator starting at the edge of the sheet and moving towards the center (useful zone). This manual approach can be easily implemented by integrating an NDT station to the current production line. The experimental setups corresponding to these two approaches are described in sections 2.2.1 and 2.2.2.

2.2.1 Automated scan in immersion (2D)

The automated approach is carried out in a 5-axis ultrasonic immersion system. The sheets to be inspected are placed at the bottom of the tank. Ultrasonic inspection is then carried out in pulse-echo mode at zero-degree incidence, in immersion, using a conventional 20 MHz frequency probe. Other frequencies lower than 20 MHz have been used before, but the 20 MHz frequency provides the highest contrast between the useful and rejection zones in terms of attenuation. Data acquisition is performed by the Topaz 32/128 PR ultrasonic instrument (ZETEC). The distance between the probe and the sheet (or water column) at each scan point is set at 35 mm, in order to place the sheet at a near-field distance, thus obtaining a better-quality signal. The beam diameter at near field distance is approximatively 1 mm. The probe follows a trajectory that covers the entire sheet with 1 mm resolution, keeping a constant distance of 35 mm with the part and ensuring a normal incidence of the beam [5]. At each probe position, the A-scan signal is recorded, including the front wall echo, the backwall echo and its repetitions. The detection of the front wall and backwall echoes for each A-scan is done using two numerical gates (Figure 3).

![Typical A-scan acquired on the sheet with two gates located on the front wall echo and the backwall echo](image)

The parameter used to differentiate the useful zone from the rejection zone is the amplitude ratio, defined by:

\[ R = 20 \log_{10} \left( \frac{A_2}{A_1} \right) \] (1)
Where \( A_1 \) et \( A_2 \) refer respectively to the front wall echo and backwall echo amplitudes. This ratio is directly correlated with the acoustic attenuation through the thickness of the material, allowing thus to differentiate the useful zone containing the right proportion of B\(_4\)C from the rejection zone.

2.2.2 Manual linear scan in contact (1D)

The second implementation approach consists of a manual linear scan using a conventional 20 MHz probe coupled to the MMC sheet via a conformable wedge from IMASONIC. A probe-holding system has also been designed to guide the linear scan and improve its movement stability. The position of the probe is encoded by a wheel encoder attached to the conformable wedge. Acquisition is performed using a GE KrautKramer USN 60 ultrasound instrument.

2.3 Methods

2.3.1 Correlation between UT parameters and chemical digestion

The first step was to confirm the correlation between the ultrasound parameter \( R \) (cf. Equation (1)) and the areal density. The scan carried out in the 5-axis ultrasonic immersion system generates a 2D map of the amplitude ratios. Figure 4 shows an example of such a map for a portion of the sheet and a specific family. The map shows 2 zones: zone 1 consisting of aluminum and a certain proportion of B\(_4\)C, and zone 2 which contains the desired proportion of B\(_4\)C. Based on this map, a stripe of chemical digestion samples was drawn along the vertical axis (see Figure 4 b)). Eight, and twenty samples extracted from the 350 mm stripe lie in zones 1, and 2 respectively (Figure 4 a)).

![Figure 4: a) Amplitude ratio map for family D coupon b) sheet coupon](image)

Figure 5 compares, for all product families, the AD obtained by chemical digestion with the average R ratio estimated on all pixels of the corresponding digestion sample. In zone 1, composed of aluminum and a small proportion of B\(_4\)C, the AD is close to zero and the amplitude ratio is at a first level (lower attenuation). In zone 2 the AD increases and stabilizes at its target value and the amplitude ratio drop and stabilizes at a smaller value (higher attenuation). The proportion of B\(_4\)C in zone 2 is greater than in zone 1. B\(_4\)C particles entrapped in the aluminum
matrix causes additional attenuation, so greater amplitude loss is expected in this zone. This is confirmed by the decrease in the amplitude ratio between zone 1 and zone 2.

![Figure 5: Correlation between R and AD](image)

This link between the $R$ parameter and AD was confirmed for all 6 product families. Detecting the useful zone (stable AD) thus comes down to identifying the zone where the amplitude ratio stabilizes.

2.3.2 Segmentation of the 2D map

The amplitude ratio map presented in Figure 4 shows that two regions can easily be distinguished. However, in order to automatically identify the different zones, a processing workflow is applied to this map. The map is first smoothed by means of a Gaussian filter to harmonize the color tones for the different zones and thus eliminate the effect of noise. Next, the segmentation of the different zones is carried out using an agglomerative clustering algorithm implemented in Python using the Scikit-learn library [6]. This segmentation method groups similar data into clusters by constructing an ascending hierarchy of clusters. The algorithm is parameterized by the number of regions to be segmented, the type of linkage and a connectivity matrix. This connectivity parameter imposes a spatial constraint on the segmentation process ensuring that only neighboring pixels are merged together. The chosen linkage Ward minimizes intra-cluster variance during merging, thus favoring the segmentation of homogeneous areas.

2.3.3 Segmentation of the amplitude ratio profile

The manual scan implementation of the technique provides a 1D profile of the amplitude ratio $R$ as a function of distance from the edge of the sheet. Since attenuation in the aluminum is lower than in the useful zone, the amplitude ratio changes from a smaller to a larger value as it from the edge to the center of the sheet. The profile of the amplitude ratio as a function of distance from the edge consists of a decrease from a first level corresponding to the rejection zone, to a second level corresponding to the useful zone. The ratio profile is first smoothed using a median filter of size 31, to attenuate the effects of noise and local peaks due to defects.
in zones 1 and 2 of the sheet. The amplitude profile is then segmented using the change point detection algorithm, a method for detecting abrupt changes in a given statistical parameter of a signal [7]. The algorithm consists in partitioning the signal into sections, estimating the statistical parameter for each section and then optimizing the partitioning so as to minimize the error between each sample and the statistical parameter of the section to which it belongs. In the case of a signal with two segments, and using the mean as the statistical parameter, segmentation involves determining the index $k$ that minimizes the residual error $J$:

$$J = \sum_{i=1}^{k-1} \left( R_i - \frac{\sum_{m=1}^{k-1} R_m}{k-1} \right)^2 + \sum_{i=k}^{N} \left( x_i - \frac{\sum_{m=k}^{N} R_m}{N-k+1} \right)^2$$

Where $R_1, R_2, ..., R_N$ refers to the sequence of the amplitude ratio profile.

3. Results

3.1 Segmentation of the 2D maps

Segmentation has been carried out for the 6 product families. The segmented maps are shown in Figure 6. The area delimited by the red border is used to extract the useful zone from the sheet map.

A safety margin can then be applied to the detected boundary to define the cutting line.
3.2 Segmentation of the data obtained by the 1D manual scan

Segmentation has been carried out on the amplitude ratio $R$ for the 6 product families. Figure 7 shows the smoothed amplitude ratio segmented into two portions, for all the product families.

![Figure 7: Segmentation of the profile for the different families](image)

The amplitude profiles clearly show two levels, corresponding to the rejection zone and the useful zone. Some drops in the amplitude ratio can be noticed outside of the boundary zone. They are due to various inhomogeneities in the sheet. However, the algorithm still succeeds in segmenting the profile into two portions, allowing the useful zone to be identified. As with the first approach, a safety margin can be applied to the detected boundary to define the cutting line. It has been noted that the position of the detected boundary corresponds to that obtained by chemical digestion, which makes the ultrasonic approach a very good candidate for the replacement of destructive methods.

3. Conclusion

This paper presents a method for detecting the useful zone in laminated aluminum and Boron Carbide sheets. The method is based on the difference in acoustic attenuation between the edge of the sheet made solely of aluminum, and the useful zone made of aluminum and boron carbide. This attenuation is characteristic of the zone and can be indirectly measured by calculating the ratio of the amplitudes of interface successive echoes. Two options were considered for the industrial deployment of this method: a manual 1D linear scan in contact and a 2D automated scan in immersion. In the case of the 2D scan, the useful zone is automatically segmented using an agglomerative clustering algorithm. In the case of the 1D scan, segmentation is performed using the change detection point signal processing method. The methods have been validated through several trials and on six product families, giving reproducible and valid results. It should also be noted that the detection of the useful zone was carried out using compliant sheets. In the case of drifts in certain design parameters (porosity, B$_4$C rate, etc.), the pattern of the amplitude ratio $R$ may be affected. The robustness of the
algorithm to various types of design parameter drift should therefore be evaluated. Another avenue of study will be to establish a correlation between measurable ultrasonic parameters and the amount of boron carbide in the sheet to achieve an ultrasonic quantitative measurement of the B₄C areal density.

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References


