Frequency Effects in High-Frequency Pulse-Echo Ultrasonic Imaging of Titanium Metal Matrix Composites

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Abstract. Inspection of titanium matrix composites (TiMMCs) is required during manufacture, to ensure that defects are found before the material is incorporated into complex structures. The manufacturing process involves lay-up of fibres followed by Hot Isostatic Pressing. Individual fibres must remain in alignment and with precise separations in order to maintain the mechanical properties of the material. Finding defects at an early stage would considerably reduce production costs.

We previously reported the use of high frequency ultrasound in pulse-echo mode for experimental investigations of single layer long-fibre silicon-carbide reinforced titanium structures. Individual fibres 100 μm diameter could be imaged in the frequency range 35-80 MHz.

The present work extends the technique to multi-layer TiMMC structures. C-scan images were produced in which individual fibre layers have been resolved, and titanium matrix-rich regions have been identified. Using full-waveform capture and post-capture analysis, it was found that the frequency spectrum of the reflected pulse varies with the depth in the structure from which it has been reflected. Such effects are expected where the wavelength is close to the fibre spacing. The sensitivity of the frequency spectrum to these “phononic crystal” effects in the TiMMC can be used to determine the quality of the structure.

1. Introduction

Strength, higher temperature resistance, and a low weight factor are some of the attractive material characteristics of titanium metal matrix composites (TiMMCs) that make them a promising competitor to conventional metal alloys. TiMMCs are used to reinforce complex components such as turbines found in aerospace applications.

TiMMCs are produced by a well established process known as Hot Isostatic Processing (HIP). The materials are subjected to high pressure and temperature is applied in an inert medium such as Argon or Nitrogen. HIP intends to eliminate porosity and voids in order to produce reduced weight components, extended service life and reliability of a product and overall a reduction in total production costs [2, 3]. Currently, there is not any standardised test method for inspecting TiMMCs manufactured using HIP for anomalies like fibre misalignment or matrix rich regions.

We have investigated ultrasonic immersion testing of TiMMCs using scanned high frequency polymer probes. The TiMMCs contain layers (plies) of silicon carbide fibres (diameter 100 μm) cored with tungsten (diameter 15 μm) and embedded in a titanium matrix. The average centre-centre fibre spacing is 160 μm. Fig. 1 shows the relationship between the intended ultrasonic inspection frequency and the wavelength of propagation expected through a TiMMC specimen. In particular, the wavelength in TiMMC for the nominally 80MHz probe is close to or below the centre-centre fibre spacings.

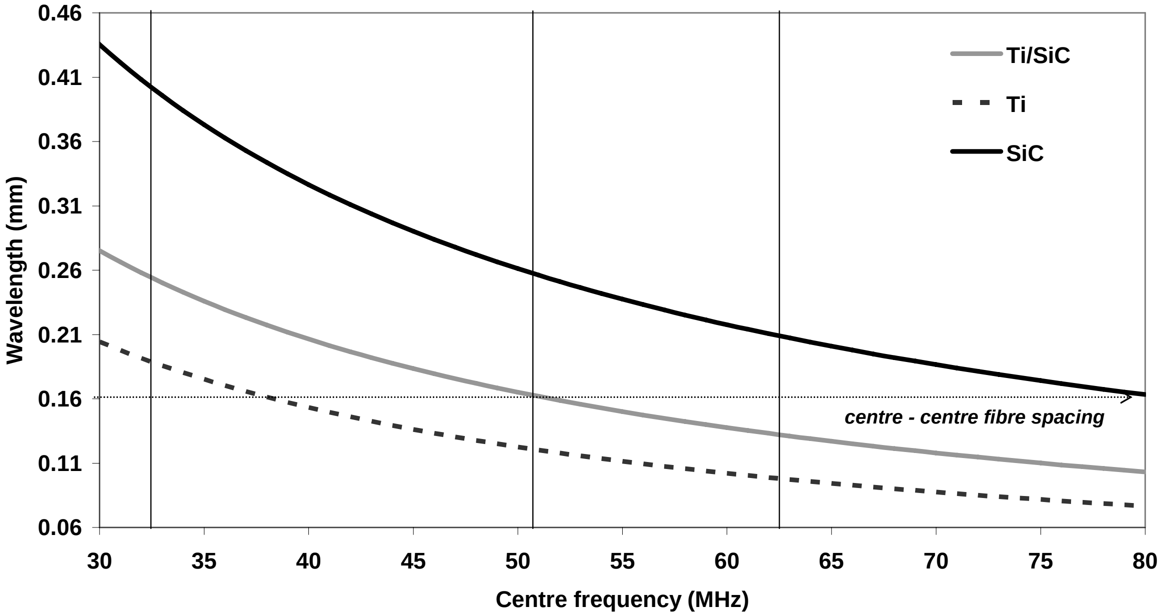


Figure 1. Wavelengths in the separate components and in 'mixed' Ti/SiC material as a function of frequency. Mean peak frequencies (represented by vertical lines) for nominally 35 MHz, 50 MHz and 80 MHz polymer probes are 33.3 MHz, 50.2 MHz and 62.5 MHz respectively [1]. Centre-centre fibre spacing is 0.16 mm.

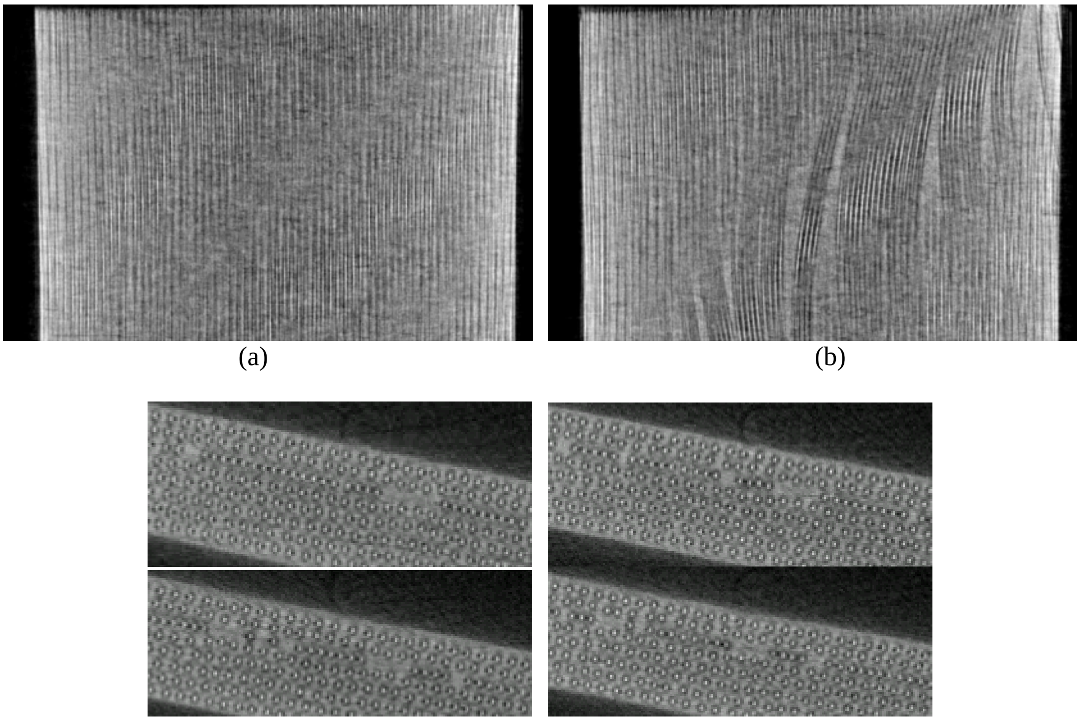
In this paper, high frequency ultrasonic inspection and frequency spectrum analysis of a defective, 8-ply TiMMC specimen will be discussed. An investigation into the frequency penetration in particular plies is considered and a micro-tomography (micro-CT) scan is compared with the ultrasonic images obtained. Analysis of the ultrasonic frequency spectra will eliminate any ambiguity that may exist with an amplitude study.

2. Background

2.1 Microtomography (Micro-CT)

Microtomography is a non-invasive high resolution technique for inspecting the interior of the structure of materials. The micro-CT of the TiMMC specimen was carried out using a SkyScan 1172 desk-top x-ray micro-scanner. The technique is comparable to the CAT scanners used in medical diagnosis, but the small focal spot size of the source (20 kV to 100 kV) allows imaging of samples at a much higher resolution of 4 µm, rather than 1 mm characteristic of medical systems. But, the disadvantages of this technique include cutting the specimen to fit the scanner (in this case to a maximum size of 15 mm diameter, and maximum height 30 mm) and achieving the necessary alignment of the specimen during the scan. The specimen was rotated by a specified amount until x-ray images were captured from 200-3600 views through 180º of rotation. Back projection was used to convert the captured images into a 3D view of the specimen. This 3D view is composed of millions of cubes in which the level of x-ray absorbed can be represented by the transparency or density of each cube. Feldkamp cone-beam algorithm for circular and spiral acquisition was implemented to complete the microtomographical reconstruction [4, 5, 6].

Fig. 2(a, b) show micro-CT cross sections of the sample, in the plane of the plies, for (a) a ply with regular fibre arrangement and (b) a defective ply. Fig. 2(c) shows sections across the fibres. Note in Fig. 2(c) that there are the same number of fibres in each ply, however in the third ply from the top surface, the fibres are compressed together at different positions creating fibre-dense regions and titanium-rich (Ti-rich) regions.



(a) (b)

(c)

Figure 2. Microtomograph of TiMMC specimen (a) top-down view of a ply consisting of a regular fibre arrangement (b) top-down view of ply 3 containing Ti-rich and compressed fibre regions and (c) end view of 8 plies (taken at incremented distances along the sample) showing the non-uniform spaced fibres in ply 3.

2.2 Phononic Crystals

Phononic crystals have been studied for some time and are now being investigated because of their similarity to photonic crystals and their potential for producing acoustic super-resolution imaging. The elastic constants periodically change in a phononic structure. This can produce phononic band gaps occurring where the propagation of acoustic waves (with certain frequency ranges) passing through a periodic structure is forbidden [7, 8].

In this study, we have a TiMMC sample that is similar to 2D crystal containing a defective layer. In addition to any phononic crystal effects, it is likely that a Ti-rich region may allow a higher transmission deeper into the structure producing enhanced responses from all plies below that region.

3. Experimental Technique

Initial tests showed that, of the nominally 35, 50 and 80 MHz focused probes used (all focused at 12.5 mm in water), the 80 MHz probe provided ultrasonic data with the best resolved plies. Thus ultrasonic immersion scanning of the defective TiMMC sample was implemented using the 80 MHz high frequency focused polymer probe in pulse-echo configuration (Fig. 3). The scanned area of the sample was 40 x 3 mm^2, scanned with a step size of 50 µm. Additional characterisation of the probe has been documented elsewhere [1].

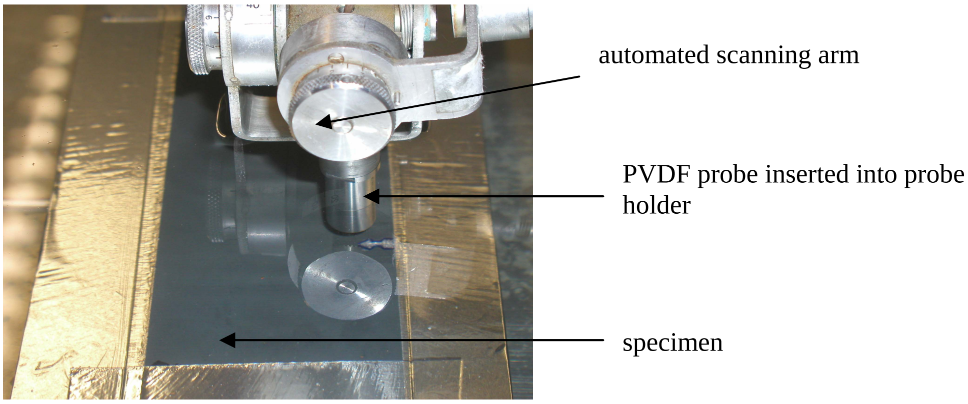


Figure 3. Ultrasonic immersion scanning set-up

4. Experimental Results

To analyse the signal from each of the plies, a time ‘gate’ was placed over the two-cycle reflection from each 160 μm ply. The C-scan images shown in Fig. 4 (labelled with co-ordinates of the scanned specimen area) in mm were obtained from the top surface to the back wall of the TiMMC specimen by plotting the amplitude of the time-gated reflections. Distance amplitude correction (DAC) has been incorporated into the C-scan images.

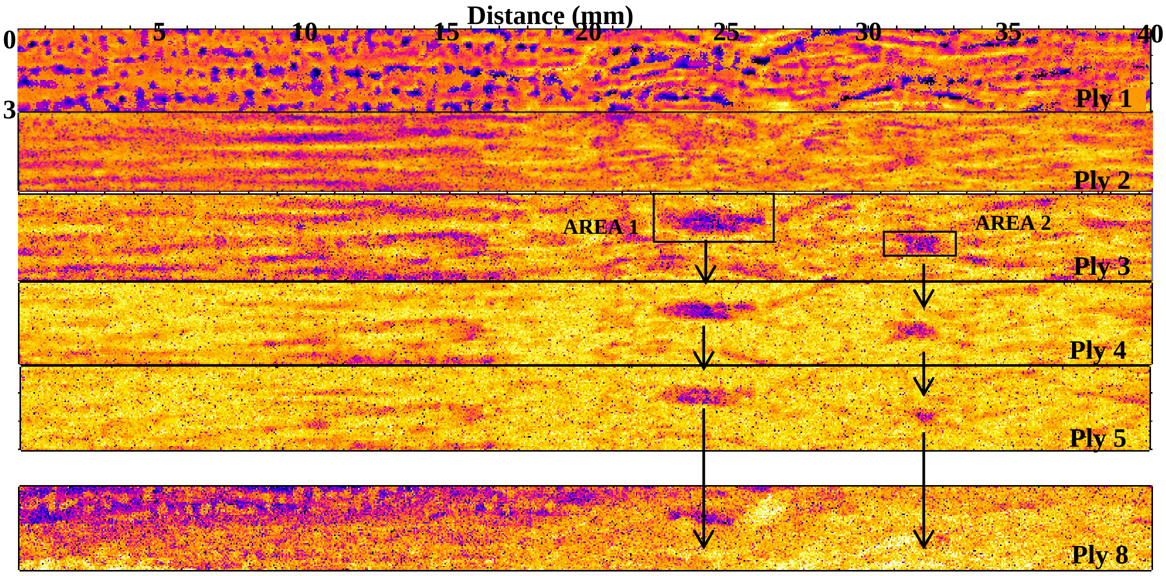
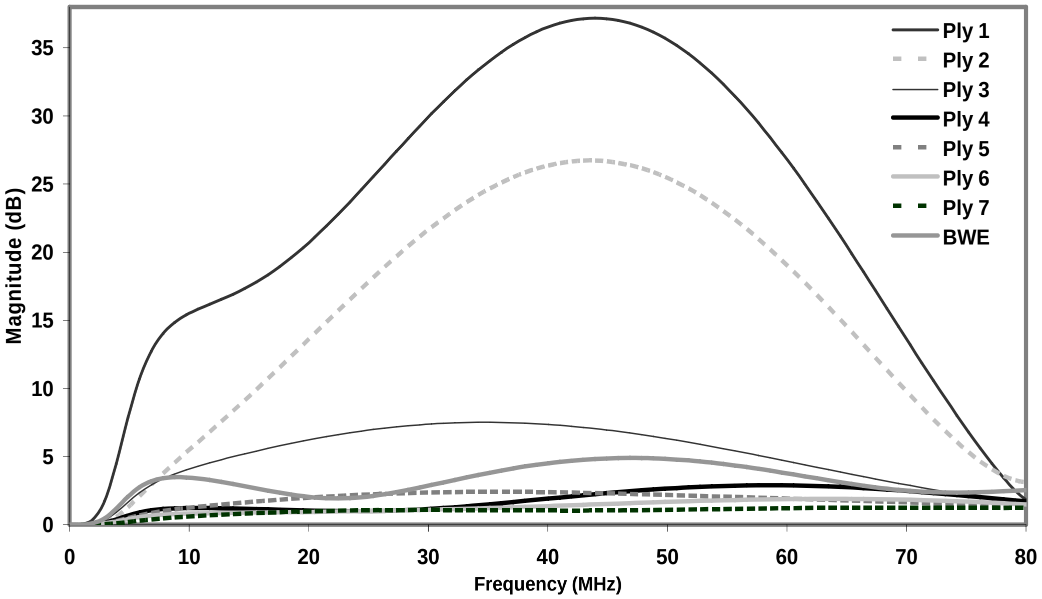


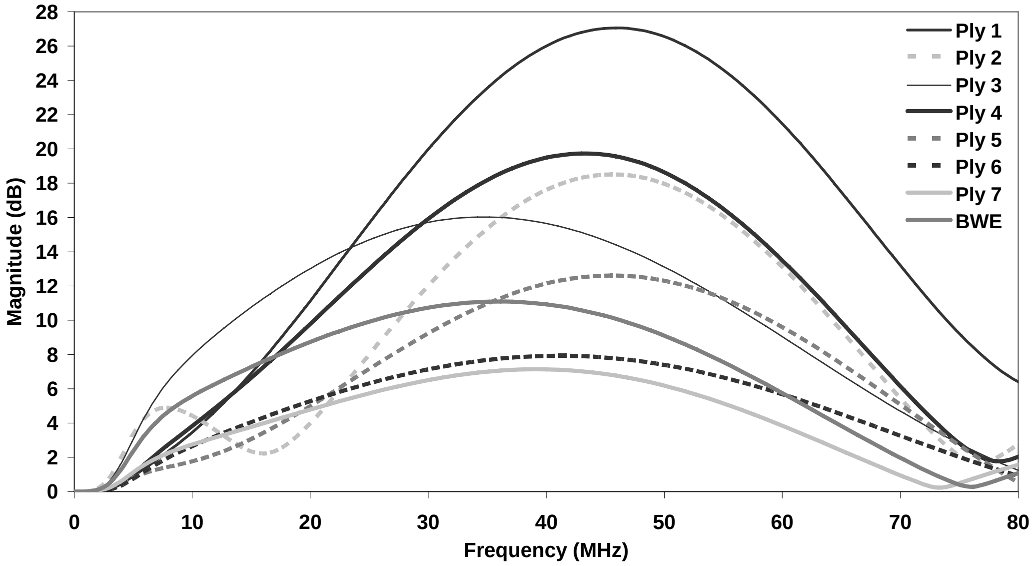
Figure 4. 80 MHz C-scans taken from different ply reflections. Co-ordinates in mm. The darker regions represent a stronger signal on these images. Yellow corresponds approximately to the noise threshold.

Frequency spectrum analysis was carried out on the full waveform capture (FWC) data. For this analysis no DAC was used. Time-gates were placed over the reflections from each ply and the time-gated portion of each waveform was Fourier transformed to give the frequency spectrum. In each case the average spectrum over an area size of 0.1 mm^2 was used to eliminate any single point anomalies. The frequency spectrum for each ply is sensitive to the position selected on the C-scan images in Fig. 4. Therefore, the frequency spectrum has been analysed at following regions of interest in Fig. 4; co-ordinate (5, 1) where the structure is considered regular and co-ordinates (24, 1) and (31.5, 2) where the Ti-rich areas exist in ply 3. The evolution through plies at particular regions, and then the frequency spectra from the defective areas will be discussed.

The frequency spectra of reflections for the regular region at position (5,1) in the specimen are shown in Fig. 5(a). For ply 1 and ply 2, the magnitude of the frequency spectrum decreases with ply number (this attenuation is due to either visco-elastic damping or scattering/reflection from layers). Beyond ply 2, a phononic crystal effect is likely to occur due to the formation of the structure. Here, from ply 3, a band gap at around 20 MHz is apparent. The frequency spectra analysed for the propagation through the centre position of the Ti-rich areas, chosen from the dark regions highlighted in Fig. 4, are illustrated in Fig 5(b,c). These indicate that additional amplitude is transmitted into the lower plies beyond the Ti-rich region. The back wall echo (BWE) signal is of larger size than the ply 7 signal because it is caused by the interface of the Ti to the water. This measurement also confirms that the C-scan images correspond to the reflection from the interface beyond the numbered ply layer.



(a)



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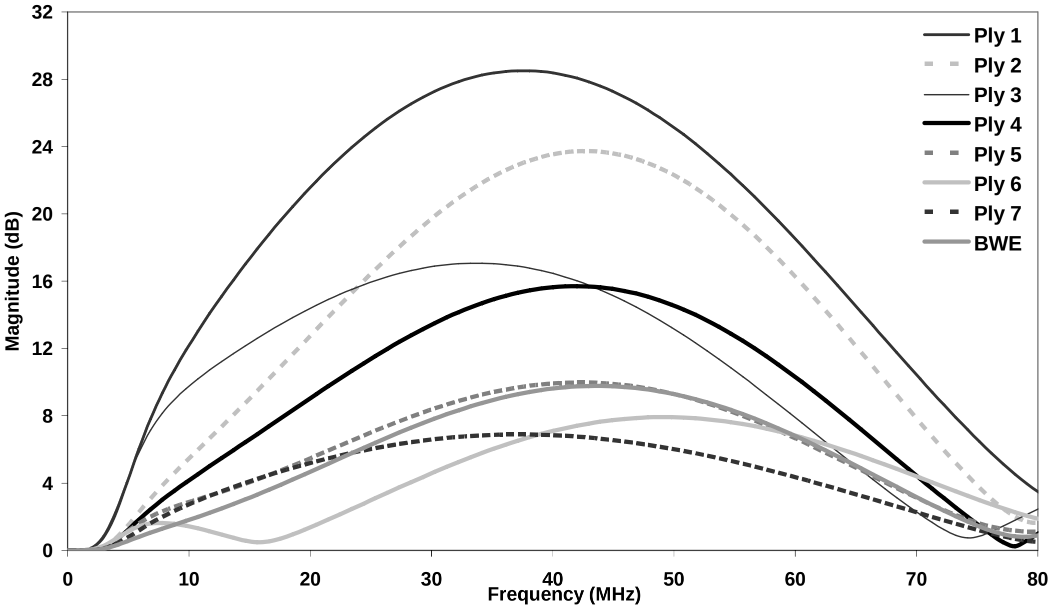


(c)

Figure 5. Frequency spectrum analysis for (a) regular region (5,1), (b) and (c) irregular regions (24,1) and (31.5,2) of TiMMC specimen. The frequency spectra have no DAC correction used for attenuation.

Fig. 6 shows the evolution of the peak amplitude from ply 1 to ply 8 (back wall). For the ‘regular’ region, there is a decay in amplitude with ply number. However, where the Ti-rich areas are located in ply 3 there is a larger amplitude reflection from the deeper layers, indicating a greater transmission of ultrasound into the plies beyond layer 3. Fig 6 shows the signal from 'regular' areas has disappeared below the noise threshold by ply 4. Hence, in Fig 4, beyond ply 4 darker areas can be seen where something increases the reflection from the particular ply above the noise threshold.

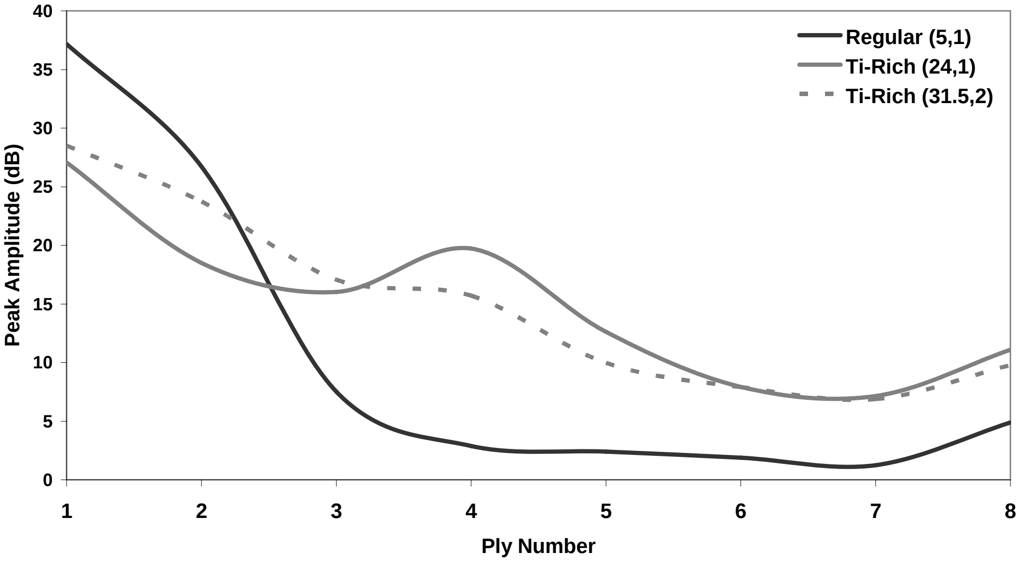


Figure 6. Frequency spectrum analysis of the peak amplitude as a function of ply number at regular region (5,1) and Ti-rich regions (24,1) and (31.5,2)

To understand what phenomenon may be occurring within the TiMMC structure, further frequency spectrum analysis was undertaken for co-ordinates located within the ‘regular’ and ‘defective’ regions of the specimen. These were from (0,1) to (10,3) and from (22,1) to (32,3) respectively. From Fig. 7 it is evident that the full frequency spectrum propagates through ply 2 with little variation in magnitude and the ultrasound has yet to experience any phononic crystal signatures such as band gap behaviour.

The frequency spectrum analysis for ply 3 is demonstrated by Fig. 8. From the regular region, see Fig. 8(a), a band gap for reflections is apparent at 20 MHz. However, the defective region shown in Fig. 8(b) contains a number of interesting frequency effects. The centre regions of the Ti-rich regions, both depicted by a dashed line style, allow the full frequency spectrum to be reflected at this ply interface. But, for the areas adjacent to the Ti-rich regions where the SiC fibres are likely to be tightly packed together (as shown by the micro-CT in Fig. 2), different frequency effects are evident. Band gaps are seen in reflection, which indicate that certain frequencies are not reflected and therefore must be either scattered out of the beam or transmitted further into the structure.

Next, the frequency spectrum was analysed for ply 4. Fig. 9(a) shows a clear band gap in reflection at approximately 20 MHz for the regular region. Analysis of the areas located below the centre of the Ti-rich regions of ply 3, shown by the dashed lines in Fig 9(b), once again provides evidence that the full frequency spectrum with the greatest magnitude exists in these regions compared to the surrounding fibre dense regions.

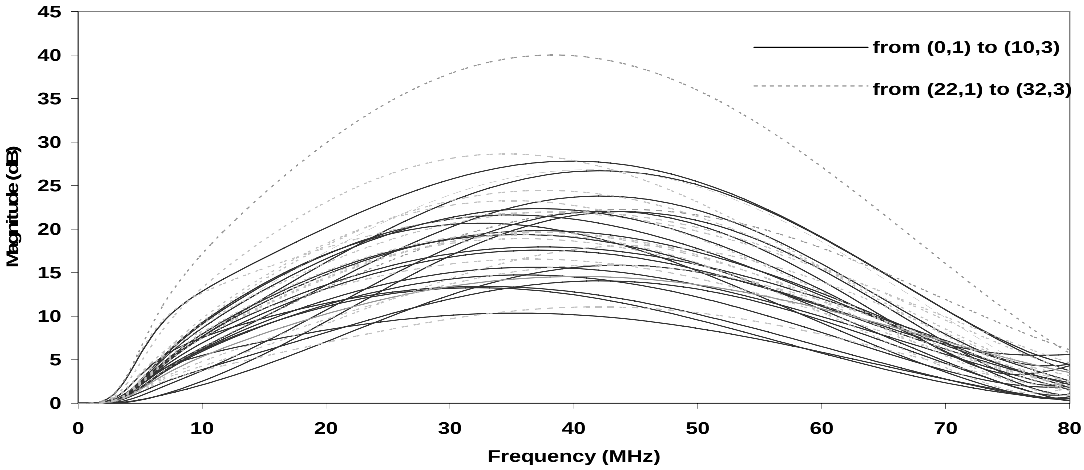
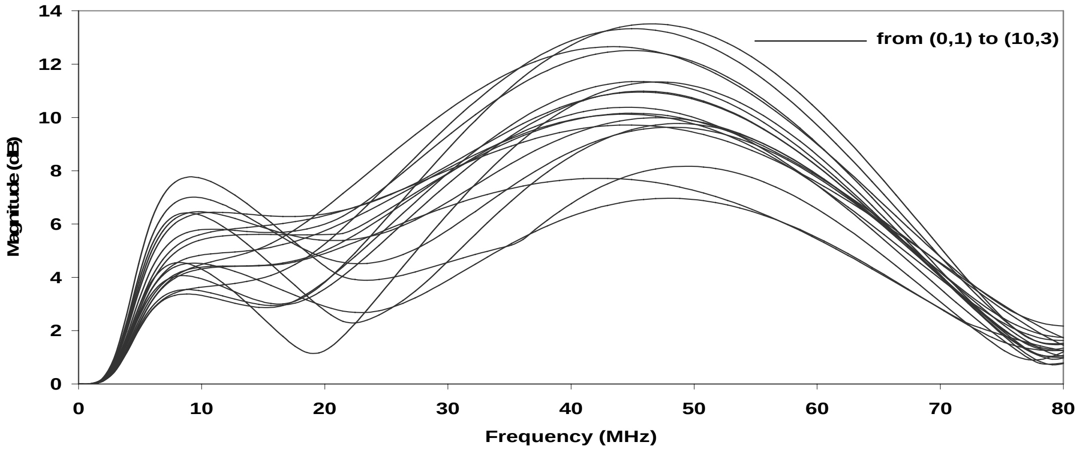
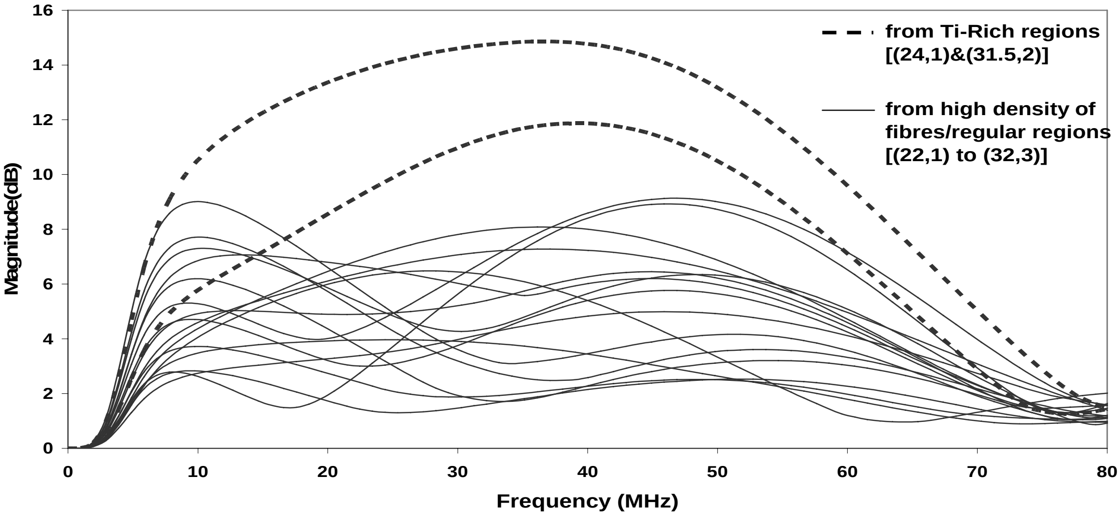


Figure 7. Frequency spectrum analysis of ply 2



(a)



(b)

Figure 8. Ply 3 frequency spectrum analyses for region that appears (a) to have uniform fibre spacing and (b) non-uniform fibre spacing

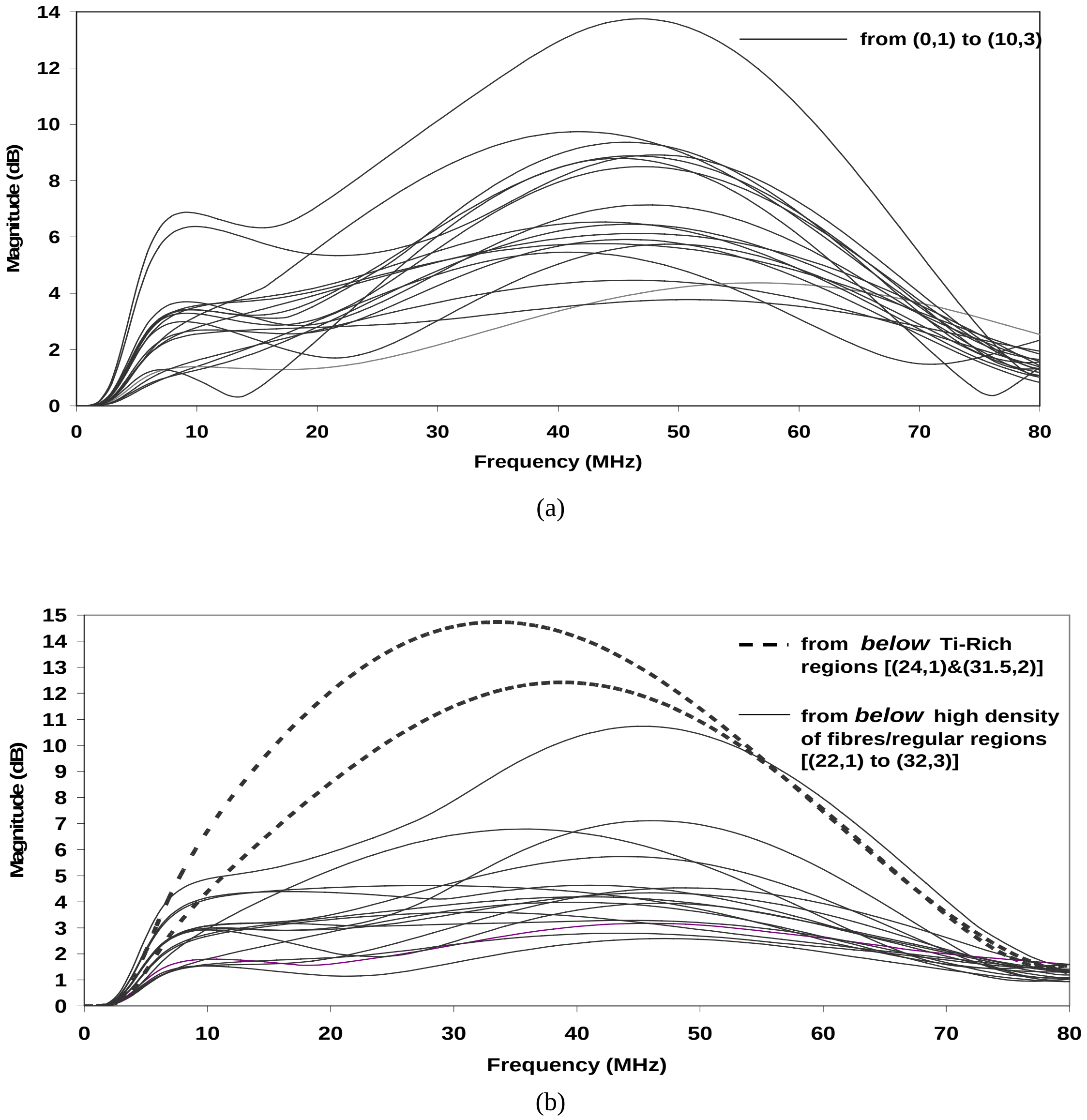


Figure 9. Ply 4 frequency spectrum analyses for (a) region that appears to have uniform fibre spacing and (b) area below Ti-rich regions located on ply 3

5. Conclusions

We have used ultrasonic immersion scanning with a polymer probe with centre frequency of 62.5MHz. The images obtained from a micro-CT scan of the TiMMC specimen have verified the results from high frequency ultrasonic imaging. In particular, the defective regions present on the ultrasonic C-scan images are confirmed by those computed from the micro-CT scan. Ultrasonic frequency spectrum analysis has demonstrated that a regular periodic region of a TiMMC specimen has some similarly to a phononic crystal, in that certain frequencies are preferentially reflected or transmitted. In the defective region of a multi-layer TiMMC sample (such as the Ti-rich regions investigated), different frequency effects are observed. We have seen an increase in the magnitude of ultrasound propagating beyond the defective region compared to regions with a regular fibre arrangement.

An analogy to the behaviour of phononic crystals has provided exciting evidence that a defective layer within the TiMMC sample is capable of transmitting sound waves of greater magnitude (compared to the ‘regular’ peak magnitude with depth relationship) through to the back wall of the structure. Potentially, these frequency effects could be implemented as an alternative technique for identifying defective components which have been produced by Hot Isostatic Processing.

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