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Finite element investigation on the wave-particle interactions in ultrasonic inspection of SiCp/Al composites

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Abstract
While particulate-reinforced metal matrix composites are composed of two phase materials with dramatically different physical and mechanical properties, sound wave-particle interactions play an important role in their ultrasonic inspection tests. In the present work, we investigate the sound wave-particle interactions in silicon carbide (SiC) particle-reinforced aluminum (Al) matrix composites under the pulse-echo mode ultrasonic inspection by means of finite element simulations. Be consistent with experimentally observed real microstructures, the simulated SiC particles have polygon shapes and are randomly dispersed in the Al matrix. In particular, the sound wave-particle interactions are revealed, and their correlations with the A-scan signals are investigated. Furthermore, the effects of extrinsic pulse frequency and intrinsic SiC particle size on the ultrasonic inspection of the composites are addressed. Simulation results indicate that the interference of sound waves with heterogeneous SiC particles leads to more pronounced deflection, scattering and conversion of sound waves than the pure Al matrix, which in turn result in higher attenuation of sound waves in SiCp/Al composites. It is also found that the sound wave-particle interactions have a strong dependence on both pulse frequency and particle size.

1. Introduction
Particulate-reinforced metal matrix composites (PRMMCs) are important engineering materials due to their unique mechanical and physical properties. For instance, silicon carbide (SiC) particle-reinforced aluminum (Al) matrix (SiCp/Al) composites are advanced light-weight materials, in which light aluminum alloys are reinforced by dispersed hard SiC particles. SiCp/Al composites have been widely used in fields of aerospace, automotive, optical instruments and electronic engineering, due to their high strength, high wear resistance, high stiffness and high weight savings [1–5]. While flaws such as voids and particle agglomeration are inevitably generated in the powder metallurgy processes and following mechanical shaping processes, pre-existing surface and internal flaws have a strong impact on the performance of SiCp/Al-based components. Thus, how to precisely and effectively characterize the geometrical characteristics of existed flaws is crucial for enhancing the safety and reliability of SiCp/Al composites-based advanced components and parts.

Ultrasonic inspection (UI) is one of the most commonly used non-destructive testing techniques for characterizing geometrical features of internal microstructures and measuring dimensions of a variety of materials [6]. In the UI processes of flaw detection, ultrasonic pulsed sound waves with high frequencies ranging from 0.1 to 10 MHz are transmitted through tested materials, and part of the waves are reflected back from the
flaw surface or bottom boundary. Consequently, the location, size and orientation of pre-existing flaws can be acquired by analyzing obtained signal strength-time curves and performing related advanced image post-processing. It is known that the estimation of Probability of Detection (PoD), which is widely used as a metric of quantifying the reliability of the UI method, primarily relies on experimental UI trials of reference specimens with known artificial flaws [7, 8]. However, those experimental processes can be fairly time-consuming, given the statistical approaches used and the difficulties in the fabrication of tested specimen. To optimize the UI equipment parameters and decrease the costs for experimental work, much attention has also been paid on developing predictive and quantitative numerical models for UI [9–12]. The feasibility of applying UI in detecting internal and surface flaws in single phase materials has been well demonstrated by tremendous finite element (FE) simulations and experimental investigations [13–16].

However, there is rather limited work focusing on the UI of composite materials that contain no less than two phases with distinctly different mechanical and physical properties. In particular for SiCp/Al composites, SiC particle and Al matrix possess significant differences in their acoustic impedances due to different densities and sound velocities in the two materials, which in turn lead to significant reflection of sound waves from the interfaces between Al matrix and SiC particles. Furthermore, the characteristics of random distribution and random shape of SiC particles result into multiple oblique angles of incident wave beams with respect to the Al matrix–SiC particle interfaces, which in turn lead to pronounced refraction and scattering of sound waves. Consequently, the propagation of sound waves in SiCp/Al composites is significantly different from that in their pure matrices. Specifically, while the sound beam has irrotational characteristics in the pure Al matrix, the interaction of sound waves with SiC particles leads to pronounced vorticity [17]. And the attenuation of sound waves in SiCp/Al composites is more pronounced than that in the Al matrix, due to increased reflection, refraction and scattering accompanied by the presence of dispersed SiC particles. Thus, examining the sound wave-particle interactions, as well as their correlations with the acquired ultrasonic signals, are essentially required to improve the fundamental understanding of the UI of PRMMCs.

Recently, UI has been theoretically and experimentally utilized to characterize the distribution characteristics of SiC particles in PRMMCs. Deng et al explicitly investigated the phenomenon of particle clustering in SiCp/Al composites using a two-dimensional FE method [18]. Podymovra et al applied the broadband laser-ultrasonic spectroscopy to quantitatively evaluate the effects of reinforcement fraction and porosity content on the phase velocity of longitudinal acoustic waves in SiCp/Al composites [19]. Liu et al evaluated the inhomogeneity of SiC particles in SiCp/Al composites using the Collinear nonlinear ultrasonic method [20]. Although previous theoretical and experiment work provides valuable insights into the UI of PRMMCs, the investigation of the UI of SiCp/Al composites is far from being completed. Firstly, most of the previous work of the UI on PRMMCs was focusing on roughly establishing the uniformity of particles by evaluating the distribution of ultrasound wave speed, while lacking microscopic details of sound wave-particle interactions. Specifically, the sound wave is subjected to multiple mutual scattering by SiC particles in the composites, which may result into non-linear signal characteristics. Secondly, previous FE simulations of the UI of PRMMCs mainly treated particles as circularities. However, the real microstructures of PRMMCs observed in experiments show that the particles have arbitrary polygonal shapes, and are randomly distributed in the matrix. Since the orientation of sound beam with polygon particles are dramatically different from that with circular particles, the scattering of sound waves by particles and resulting attenuation may be also different in the FE simulations of the UI of SiCp/Al composites with different representations of SiC particles.

Therefore, in the present work FE modeling and simulations of the UI of SiCp/Al composites under the pulse-echo mode are carried out. Simulated SiC particles with polygon shapes are randomly distributed in the Al matrix, which are consistent with experimentally observed real microstructures. The sound wave-particle interactions, as well as their correlations with A-scan echo signals, are revealed. Furthermore, the influences of intrinsic SiC particle size and extrinsic pulse frequency on the sound wave-particle interactions and pulse-echo signals are addressed.

2. Simulation methods

Figure 1 shows the FE model of the UI of SiCp/Al composites. The SiCp/Al specimen has a dimension of 1.5 mm in length and 3.2 mm in height. The specimen consists of polygon-shaped SiC particles, which are randomly distributed in the Al matrix. SiC particles have a specific equivalent mean size with a constant volume fraction of 25 vol%. The SiCp/Al composites normally have an average particle size ranging from a few to hundreds of micrometers. To address the influence of particle size on the UI, five particle sizes, as 20, 40, 60, 80 and 100 μm, are considered. The specimen is equally meshed by the CPS4R elements with an element size of 5 μm. Both the left and right sides of the specimen are fixed. And the infinite element methods are imposed on the left and right sides of the specimen to prevent horizontal reflection of sound waves. The interfacial bonding
between SiC particles and Al matrix is represented by binding constraints. Table 1 lists the physical properties of the Al matrix and SiC particles used in the FE simulations of the UI of SiCp/Al composites.

Table 1. Physical parameters of Al matrix and SiC particles utilized in the FE model of the UI of SiCp/Al composites [21].

| Material properties          | Al6063 | SiC  |
|------------------------------|--------|------|
| Thermal conductivity (W/(mm·K)) | 193    | 81   |
| Density (Kg m⁻³)             | 2.7e3  | 3.13e3 |
| Elastic modulus (GPa)        | 68.9   | 420  |
| Poisson’s ratio              | 0.33   | 0.14 |
| Specific heat capacity 1/(Kg·K) | 900   | 427  |
| Thermal expansion coefficient (K⁻¹) | 2.18e-5 | 4.9e-6 |

FE simulations of the UI of SiCp/Al composites are carried out under the pulse-echo mode. As indicated by the red line shown in figure 1, the ultrasonic wave emitted from the transducer is modeled by applying appropriate transient excitation pulses from the transmitter placed on the centered upper surface of the specimen. The transmitter has a length of 0.2 mm, which is composed of 33 special nodes. The function of the applied transient excitation pulse is expressed by equation (1):

\[
Y(t) = \begin{cases} 
\cos(2\pi ft) \left[ 1 - \cos \left( \frac{2\pi f}{N} t \right) \right] & 0 \leq t \leq \frac{N}{f} \\
0 & \text{else} 
\end{cases}
\]  

where \( f \) is the excitation pulse frequency and \( N \) is the number of waves in the excitation pulse waveform. Figure 2 plots the variation of pulse amplitude with time within 0.3 μs. And five points of peak and valley of amplitudes
are marked. To investigate the influence of pulse frequency on the UI of SiCp/Al composites, eleven frequencies as 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15 MHz are considered.

3. Results and discussion

3.1. UI: pure Al matrix versus SiCp/Al composites

2D FE simulation of the UI of SiCp/Al composites under a frequency of 10 MHz is performed to obtain the first impression of sound wave propagation in the composites. The SiCp/Al composites have a mean particle size of 100 μm. For comparison purposes, 2D FE simulation of the UI of the pure aluminum matrix under the same frequency of 10 MHz is also carried out. The longitudinal wave is used for achieving wave propagation in the vertical direction of the specimen, and the displacement of the special nodes for applying transient excitation pulses is monitored. Figures 3(a) and (b) plots the A-scan signal obtained in UI of pure Al matrix and SiCp/Al composites, respectively. Meanwhile, figures 3(c) and (d) also presents the configuration of wave propagation in pure Al matrix and SiCp/Al composites at the highest amplitude of the echo, respectively. The color bars in figures 3(c) and (d) indicate the Von Mises stresses of the specimen.

It is seen from figure 3(a) that in the UI of pure Al matrix, the special nodes receive the echo reflected from the back wall of the specimen at the time of 1.376 μs. Figure 3(b) indicates that although the A-scan signal for SiCp/Al composites shows similar features to that for pure Al matrix, the degree of echo signal attenuation for SiCp/Al composites is higher than that of pure Al matrix. The ripples shown in figures 3(c) and (d) indicate the propagations of ultrasound waves in the two specimens. It is seen from figure 3(c) that when the reflected wave reaches the incident point, the stress wave is concentrated on the top of the specimen, causing a large displacement of the surface. Furthermore, the ultrasound wave propagation has a mirror symmetry along the vertical line, on which the exciting special nodes reside. In contrast, figure 3(d) shows that there is no symmetry of ultrasound wave propagation observed in the UI of SiCp/Al composites. Furthermore, the stress distribution of SiCp/Al composites is more dispersed than that of pure Al matrix, which is mainly caused by the strong reflection and scattering of stress waves around randomly distributed SiC particles in the composites.

Figure 4 presents sequential snapshots of wave propagation in the isotropic pure aluminum at different time locations. The stress wave propagates downward in an ellipse-like shape, and the waveform tends to become parallel to the surface after it is far away from the excitation special nodes. Figure 5 presents sequential snapshots of wave propagation in the heterogeneous SiCp/Al composites at different times. The waveform morphology of the stress wave can be better maintained during the initial downward transferring process in the pure Al matrix. However, the stress wave starts to become messy when it is transferred upward after being rebounded by the lower surface. This can be attributed to that the stress wave has been greatly attenuated when it is propagating downward. It can also be found that the higher stress regions are all displaced inside SiC particles, and the remaining stress regions mainly exist in the Al matrix. It is seen from figures 4 and 5 that the propagating wavefront in SiCp/Al composites suffers more severe scattering and conversion than that in pure Al matrix. There is no discontinuity to interfere with the propagation of ultrasonic waves in the pure Al matrix, so it can always
maintain a good waveform. In contrast, the waveform in SiCp/Al composites gradually diverges during the propagation process due to the interference of the sound beam with SiC particles.

Figure 6 presents enlarged views of sound wave-particle interactions in SiCp/Al composites at different time locations. Figure 6(a) clearly shows that the propagation velocity of the stress wave in SiC particles is larger than that in the Al matrix, because the higher sound velocity of SiC than that of the Al matrix. Under the same strain condition, the material with larger elastic modulus obviously has higher stresses. Therefore, it can be observed from figures 6(b) to (f) that stress peak regions are formed around SiC particles directly below the excitation source, which is the position of sound waves getting incidence with particle-matrix interfaces. Since the Al matrix and SiC particles have different acoustic impedances, there are significant reflections of sound waves at the interfaces between the Al matrix and SiC particles.
3.2. Effect of pulse frequency

FE simulations of the UI of SiCp/Al composites with a mean particle size of 100 μm under different pulse frequencies are performed. In addition, FE simulations of the UI of pure Al matrix under the same pulse frequencies are also conducted for comparison purposes. Figure 7 plots variations of echo amplitude with frequency for the two materials. It can be seen from figure 7 that the amplitude of echo signal for pure Al matrix is almost proportional to the excitation frequency, which increases monotonously with increasing frequency ranging from 5 to 14 MHz. Therefore, the attenuation of sound wave in pure Al matrix is more pronounced under a smaller pulse frequency. But the amplitude of the echo signal decreases at the highest frequency of 15 MHz. The attenuation of sound wave in SiCp/Al composites is significantly different from that in pure Al matrix. Specifically, the amplitude of the echo signal for SiCp/Al composites also increases with increasing frequency ranging from 5 to 11 MHz. However, with a further increase in the frequency, the amplitude of the echo signal decreases monotonously, indicating increased attenuation of the sound wave.

Figure 8 presents configurations of sound wave propagation in SiCp/Al composites under different pulse frequencies. It is seen from figure 8 that with the increase of pulse frequency, propagating wave-front undergoes increased attenuation and distortion. This can be attributed to that with the increase of frequency, the wavelength decreases to get close to SiC particle size, which results into an increased degree of ultrasound scattering. Furthermore, the waveform conversion shown in figure 8(d) for the frequency of 15 MHz is more obvious than that for the pulse frequency of 5 MHz shown in figure 8(a), due to the twice longitudinal wave speed as the transverse wave speed. The longitudinal wave reaches the bottom boundary of the specimen earlier than the transverse wave, as indicated by figure 8.
3.3. Effect of particle size
FE simulations of the UI of SiCp/Al composites with different particle sizes are performed. While the particle volume fraction is fixed as 25%, five mean particle sizes of 20, 40, 60, 80 and 100 μm are considered. For each particle size, the utilized excitation frequency is the same as 10 MHz. Figure 9 plots the variation of attenuation degree of the echo signal in SiCp/Al composites with SiC particle size. It is seen from figure 9 that the amplitude of echo signal decreases with increasing particle size, corresponding to increased attenuation degree of the sound wave. The wavelength of ultrasound wave is approximately 600 μm for the pulse frequency of 10 MHz. When the particle size is closer to the wavelength of ultrasound wave, there is a more severe scattering of sound wave caused by the particle-matrix interface.

Figure 10 presents configurations of wave propagation in SiCp/Al composites at the echo peaks for different particle sizes. It is seen from figure 10 that for larger particle size, the degree of ultrasound wave distortion is more severe. In addition, the smaller the particle size, the larger the peak value of the stress. Therefore, it indicates that particle size is directly proportional to the attenuation of the sound wave. Since the sound waveform conversion occurs, it can be identified that the entire reflected wave contains both reflected longitudinal wave and transverse wave. It is possible to distinguish the two kinds of reflected waves by the time of wave propagation, since the twice velocity of the reflected longitudinal wave as the reflected transverse wave.

Figure 10(d) demonstrates that while the reflected longitudinal wave is about to reach the incident point, the reflected transverse wave has a certain distance from the incident point. And the larger the particle size, the higher the degree of wave conversion. However, figure 10 also shows that the time points of the echo signal peaks are consistent for all the particle sizes, which indicates that the wave velocity is independent on particle size.

Figure 11 further presents enlarged views of sound wave-particle interactions in SiCp/Al composites with different particle sizes. It can be seen from figure 11 that the distortion of wave-front increases progressively with the increase of particle size ranging from 20 to 80 μm. Furthermore, with the increase of particle size, the derivation of transmission direction of stress from the sound wave direction also increases, which may be caused
Figure 9. Variation of echo amplitude with particle size in the UI of SiCp/Al composites under a frequency of 10 MHz.

Figure 10. Configurations of wave propagation in SiCp/Al composites with different particle sizes: (a) 20 μm; (b) 40 μm; (c) 60 μm and (d) 80 μm.

Figure 11. Enlarged views of sound wave-particle interactions in the UI of SiCp/Al with different particle sizes. (a) 20 μm; (b) 40 μm; (c) 60 μm and (d) 80 μm.
by increased reflecting and scattering effects of large size particle to the sound wave. It is also found from figure 11 that the smaller the particle size, the more obvious the stress concentration of particles beneath the excitation source. And the degree of wave-front skewing and distortion is more pronounced for larger particle size due to the inherent particle scattering, which is not improved by average procedures.

4. Summary

In summary, we perform 2D FE modeling and simulation of the UI of heterogeneous SiCp/Al composites under the pulse-echo mode, with an emphasis on the sound wave-particle interactions and their correlations with echo signals. The simulated 25 vol% SiC particles with polygon shapes are randomly distributed in the Al matrix, which is consistent with the experimentally observed real microstructures. The presence of SiC particles leads to distortion of ultrasonic wave-front propagating, accompanied by pronounced deflection, refraction and scattering of sound waves from the SiC particle-Al matrix interfaces. Consequently, the attenuation of sound beam in heterogeneous SiCp/Al composites is higher than that in a homogeneous pure Al matrix. It is found that sound wave-particle interactions have a strong dependence on both pulse frequency and particle size. Specifically, the attenuation of the ultrasonic wave-front propagating in SiCp/Al composites is higher for a larger excitation frequency or a larger particle size.

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