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Effect of alumina composition and surface integrity in alumina/epoxy composites on the ultrasonic attenuation properties

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ABSTRACT

We report a method of fabricating backing blocks for ultrasonic imaging transducers, using alumina/epoxy composites. Backing blocks contain scatterers such as alumina particles interspersed in the epoxy matrix for the effective scattering and attenuation of ultrasound. Here, the surface integrity can be an issue, where the composite material may be damaged during machining because of differences in strength, hardness and brittleness of the hard alumina particles and the soft epoxy matrix. Poor surface integrity results in the formation of air cavities between the backing block and the piezoelectric element upon assembly, hence the increased reflection off the backing block and the eventual degradation in image quality. Furthermore, with an issue of poor surface integrity due to machining, it is difficult to increase alumina as scatterers more than a specific mass fraction ratio. In this study, we increased the portion of alumina within epoxy matrix by obtaining an enhanced surface integrity using a net shape fabrication method, and verified that this method could allow us to achieve higher ultrasonic attenuation. Backing blocks were net-shaped with various mass fractions of alumina to characterize the formability and the mechanical properties, including hardness, surface roughness and the internal micro-structure, which were compared with those of machined backing blocks. The ultrasonic attenuation property of the backing blocks was also measured.

1. Introduction

Ultrasound imaging technology is used in many applications including medical diagnosis and non-destructive testing. Ultrasound imaging systems are typically equipped with a probe to examine the target object by generating ultrasound. As shown in Fig. 1, the ultrasound probe consists of four functional parts: a piezoelectric element for signal generation, an acoustic lens, a matching layer for ultrasound focusing, and a backing block for signal attenuation.

When an ultrasonic probe is designed, if front matching layer is very well designed by use of ideal material and thickness, then wideband performance is obtained even without using backing absorber. Since it is actually difficult to design ideal front matching layer, then backing absorber is necessary to be attached [1]. When the ultrasound signal is generated from the piezoelectric element, the function of the backing block is to prevent reflections from the backside by absorbing the ultrasound signal [2]. Another function of backing absorber is mounting transducer to housing structure, which is often metal with very low absorption. Then, if attenuation in absorber is not high enough, vibration is transmitted to housing and housing resonances modify frequency response and spurious peaks make problem. If the attenuation is too low, very thick backing absorber has to be used [3].

There have been several reports of approaches to increase the attenuation of the ultrasonic signal by the backing block, via modifying the acoustic impedance and attenuation [4–9]. Grewe et al. fabricated backing blocks using tungsten, alumina (Al_2O_3), and lead zirconium titanate (PZT) as a filler on various polymer matrices, and studied the ultrasonic attenuation property of the resulting composite materials [7]. El-Tantawy et al. analyzed the ultrasonic attenuation characteristics of backing blocks fabricated from polymer composites containing nano-scale hydroxyapatite and carbon black [8]. Nguyen et al. reported an improvement in the physical properties of epoxy composites via the formation of heterogeneous materials formed of two different polymers [9].

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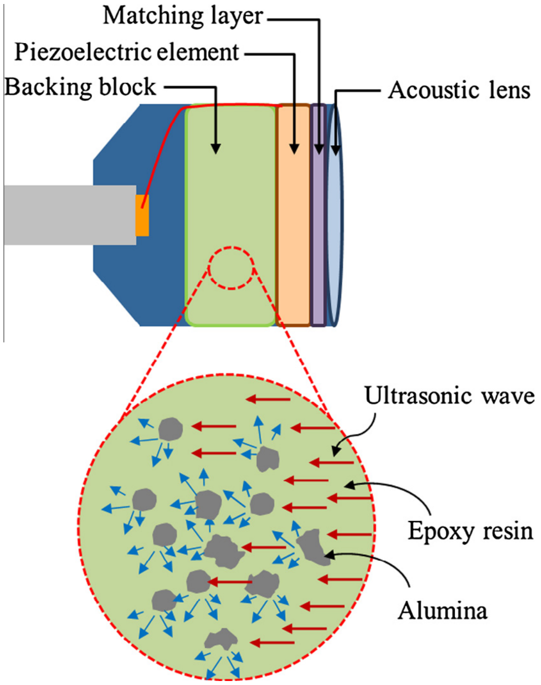

Fig. 1. A schematic diagram showing the ultrasound probe and the mechanism of ultrasonic attenuation within the backing block.

However, for fabricating backing blocks using a conventional machining, surface integrity can be an issue because of differences in strength, hardness and brittleness of the hard Al_2O_3 particles and the soft epoxy matrix. Fig. 2 shows schematic diagrams describing the effects of the surface integrity of the backing block on the reflection of the ultrasound signal. The finishing and polishing procedures used may result in topographical changes to the surface, including fractures, or tearing of the Al_2O_3 scatterers from the matrix. With Al_2O_3 powder-filled epoxy composites, which are commonly used as backing blocks, the differences in strength, hardness and brittleness between the Al_2O_3 scatterers and the epoxy resin matrix suggest the possibility of the Al_2O_3 particles being fractured or torn out of the epoxy matrix during machining [10–12]. This results in a large surface roughness, as shown in Fig. 3(a), which leads to a large reflected ultrasound signal.

Moreover, it is known that a backing block can obtain higher attenuation properties via scattering effect as the mass fraction of the Al_2O_3 scatterer increases. For machining process, however, obtaining high level of ultrasonic attenuation is limited since the attenuation eventually levels out due to the degradation in surface integrity. Additionally, when the amount of Al_2O_3 reaches certain levels, the portion of epoxy to Al_2O_3 becomes relatively low, which result in low formability.

Here we propose a net shape fabrication method to produce backing blocks ensuring surface integrity and formability as well as high ultrasonic attenuation, simultaneously, and verified the effect of surface integrity and Al_2O_3 composition on ultrasonic attenuation. Net shape fabrication is a molding method in which the workpiece is formed in a single process via molding at high pressure with a uniform temperature. This method can produce backing blocks by heating the epoxy matrix to the glass transition temperature and then pressing it, and allows us to achieve a flat surface with excellent surface integrity, provided that the mold has a smooth surface. The shape of Al_2O_3 mixed within the epoxy matrix is not modified because of its intrinsic properties of high strength and high hardness [13]. However, a flowability of epoxy matrix increases at a high temperature, which leads to a translation of Al_2O_3 near the mold and epoxy matrix interface when it is pressed and protruded oxide particles move into the composite. As a consequence, the surface of the backing block exhibits good surface integrity following the surface roughness of the mold (see Fig. 3(b)). Via the use of net shape fabrication, we may expect an improved attenuation performance by increasing the mass fraction of scatterer with maintaining a high surface integrity. Another advantage of net shaping is achieving high throughput via replacing a series of a bulk material preparation, post-baking, cutting and grinding processes with a single compression molding process, as shown in Fig. 4.

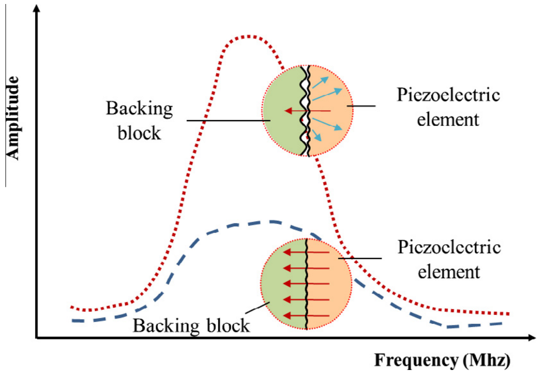

Fig. 2. Frequency spectra obtained with a backing block with a poor surface integrity and a backing block with good surface integrity.

We describe a compression-molding system for net shape fabrication, which is used to produce backing blocks for ultrasonic attenuation. To investigate the effect of the surface integrity and Al_2O_3 composition, the mechanical and acoustic properties were characterized with different mass fractions of Al_2O_3 scatterers, and the backing blocks fabricated using the net shape approach were compared with those formed using conventional machining.

2. Material and methods

A compression molding system was constructed to fabricate backing blocks via a net shape process. It consisted of upper and lower rams, a mold, a guide cylinder, and a temperature and pressure control unit, as shown in Fig. 5(a). The control system allowed us to vary the temperature and pressure during the process.

A blending process was used to form epoxy composites consisting of epoxy resin (diglycidyl ether of bisphenol A; DGEBA), hardener (triethylene tetramine; TETA), plasticizer, and Al_2O_3. When the thermosetting epoxy resin is mixed with the hardener, the polymer crystal structure changes in an exothermic reaction, and the composite hardens [14–16]. Table 1 lists the physical properties of composite materials. The plasticizer promotes bonding of the Al_2O_3 and epoxy resin by loosening polymer molecules and increasing the free volume [15].

The first step in the fabrication of the backing block was to heat the solid DGEBA to 70 °C to obtain a liquid state. 79.35 phr of plasticizer and 10.48 phr of hardener (triethylene tetramine; TETA) were added to the liquid DGEBA, and mixed thoroughly. Al_2O_3 was then added to the mixture and dispersed by further mixing. The resulting composite was then polymerized via an epoxy cross-linking polymerization reaction [15]. Net shape fabrication was achieved using the compression molding system. To produce accurate molded forms with desired level of surface integrity, governing process parameters such as mold temperature and compression pressure were controlled as shown in Fig. 5(b) [17]. Here, the mold was maintained at a uniform temperature of $T_2 = 110$ °C after placing the compound into the mold. The temperature was then increased to $T_3 = 130$ °C, and maintained for $t_7 - t_6 = 12$ min. Test samples were produced by varying the initial