# NON-CONTACT ULTRASOUND MATERIALS TESTING FOR PROCESS AND QUALITY CONTROL AND FOR ENERGY, COST, TIME, AND ENVIRONMENT SAVINGS

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## INTRODUCTION

Non-Contact Ultrasound (NCU) is highly desirable for testing and analyzing early stage materials formation (green ceramics, powder metals, elastomers, composite pre-pregs, etc.), and for contact and liquid-sensitive materials (porous materials, food, pharmaceutical and hygroscopic materials,) or where contact with the test media is simply a nuisance. Materials such as these cannot be reliably tested by conventional ultrasound, which utilizes liquid coupling of the transducer to the test material. The true impact of NCU is in cost-effective materials production, time, energy, and environment savings; quality and process control; and reliable and safe uses of materials.

However, there are realities that defy NCU, which are: extremely high absorption of ultrasound by air or other gases, phenomenally high acoustic impedance (Z) mismatch between air and the test media, and inefficient ultrasound transduction from a piezoelectric material into the rarified media like air or other gases, Fig. 1. The first two are natural phenomena about which nothing can be done. Thus we are left to

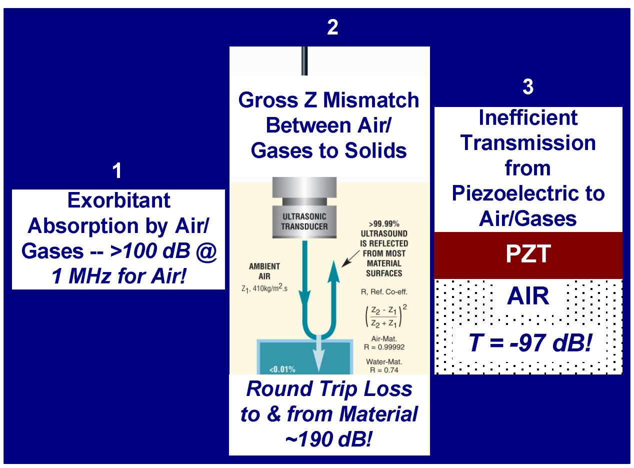


Fig. 1. Realities that defy non-contact ultrasound. Numbers 1 and 2 are natural phenomena about which nothing can be done. Therefore, one is left with piezoelectric material #3, about which something must be done to increase the transduction efficiency in air/gas media.

do "something" to the piezoelectric material! To this effect a handful of researchers have been busy developing transducer designs that are based upon acoustic impedance, Z matching to air by utilizing a variety of polymers as the final matching layer on the piezoelectric material, Fox et al. (1), Bhardwaj (2), Yano et al. (3), Haller and Khouri-Yacub (4). These transducers exhibit reasonable efficiency, but only for limited NCU applications, and that too at relatively low frequencies such as, <500 kHz. Further, in order to investigate attenuative materials such as concrete, very thick multi-layered composites and sandwich structures, rocks, wood, lumber, etc., polymer Z matched transducers have to be excited with abnormally high powers, thus risking transducer failure besides causing other problems.

In 1997 Bhardwaj after decades of attempts finally succeeded in producing a transducer that is characterized by phenomenally high transduction in air (5) from 50 kHz to more than 5 MHz frequencies. This transducer is Z-matched with compressed fiber material the acoustic impedance of which is extremely close (arguably the closest) to that of air, which is primarily responsible for extraordinary transduction in air and other gases. Simply known as NCU transducers, their efficiency relative to polymer Z matched transducers is order of magnitude more. Further, in ambient air the sensitivity of the NCU transducers is 14 to 30 dB lesser (depending on the frequency) than their equivalent contact and immersion counterparts, when tested with appropriate solids or with water.

Considering the magnitude of NCU applications made possible by these transducers, a new field of significance in materials and bio-medical diagnostics has now become a reality. Details of NCU transducers, acoustic measurements, and applications have been provided by Bhardwaj in the Encyclopedia of Smart Materials (6). In this paper our focus is on providing the reader with introduction to NCU transducers, systems, and applications for a wide range of materials testing by utilizing the well known ultrasonic techniques.

## 1. NCU TRANSDUCERS

It should be pointed out that early NCU transducers that are based upon conventional solid and polymer matrix piezoelectric materials allowed relatively easy production from 1 MHz to 5 MHz frequencies. Dissatisfied with the performance and Signal to Noise Ratio (SNR) of NCU transducers between 50 kHz to 500 kHz based on conventional piezoelectric materials, forced us to think even more unconventionally.

In 2002 this resulted in the development of a new piezoelectric composite. Known as Gas Matrix Piezoelectric (GMP) composite (7), it is characterized by extremely unusual features. For example, the thickness coupling constant of this material is nearly equal to longitudinal coupling constant. GMP is also characterized by zero acoustic cross-talk, very large displacement in the coupling direction, -ve Poisson's ratio, very low mechanical Q, low dielectric constant, low density, and many other useful properties. Further, the manufacturability of GMP allows the production of extremely large transducers, hitherto considered arduous or impossible. GMP is particularly suitable between <50 kHz to >500 kHz. This material has not only enhanced the performance of NCU transducers, but has also elevated those contact and immersion applications that require low ultrasound frequencies to new heights.

NCU transducers have been successfully produced from <50 kHz to >5 MHz and in the dimensional range from < 1 mm to >250 mm in planar, point and cylindrical focused configurations. For high throughput applications besides the large transmitters, multi-element arrays have also be produced and deployed in the industry. Table 1.1 provides the salient features of NCU transducers and Fig. 2 shows a number of these devices varying in frequency and dimensions.

**Table 1.1 Salient characteristics and features of NCU transducers**

| Characteristics/ Features | Description |
|---|---|
| Frequency range | <50 KHz to >5 MHz |
| Dimensional range | <1 mm to >250 mm (extremely large dimensions also possible) |
| Shape | Circular, square, or rectangular |
| Field geometry | Planar, point and cylindrical focused |
| Sensitivity | Extremely high in ambient air – typically 14 to 30 dB below conventional contact and immersion transducers |
| Bandwidth | Typically between 30 to 50% at bandwidth center frequency |
| Housing | Two part aluminum protected with plastic cover |
| Coaxial connector | Standard BNC or on demand other |
| Mechanical construction | Robust, factor suitable |
| Environment limitations | Temperature: -20 to 60ºC. RH: Up to 80%, higher with special provisions |

Fig. 2. NCU transducers.

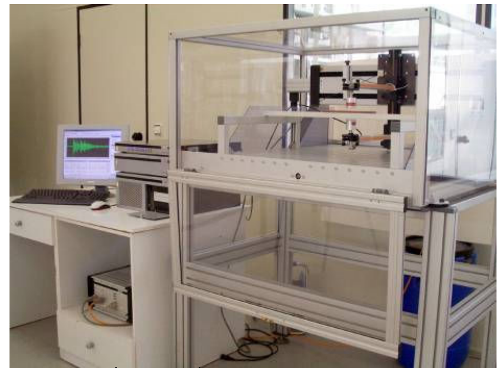

Fig. 3. $2^{nd}$ Wave[1] M510 NCU system.

## 2. NCU SYSTEM AND SIGNAL PROCESSING

NCU transducers can be used with conventional pulsers and receivers (designed for contact and immersion ultrasonic testing), but only for limited applications. However, for wide range of materials and testing objectives it is necessary that suitable transducer excitation and receiver amplification be used. One such system is Ultran's $2^{nd}$ Wave[1] M510 which is composed of computer controlled burst pulser, single and multi-channel receiver amplifier, and high speed signal processing, Fig. 3. This system is sufficient to generate NCU images of materials in various formats and measurements, which can also be post-processed to convert acoustic data into characteristics and features relevant to the test material.

## 3. NCU TECHNIQUES AND APPLICATIONS

Techniques such as through transmission, T-R pitch-catch, and single transducer pulse-echo that are well known in conventional ultrasound can also be applied to NCU. In this section we provide brief introduction to these techniques and exhibit NCU analysis of a wide range of materials. Details of materials analyzed are given in the figure captions.

**3.1 Direct or Through Transmission NCU:** This technique, which requires access to both sides of the test material, Fig. 4, is the easiest to use in NCU mode. By utilizing suitable transducers in this section we show imaging and analysis of a number of materials, including prepregs, composite laminates, sandwich composites; green and fired ceramics, refractories, rubber, plastics and foams, concrete, wood, food, and other materials. Details of materials, observations, and transducers are given in the figure captions.

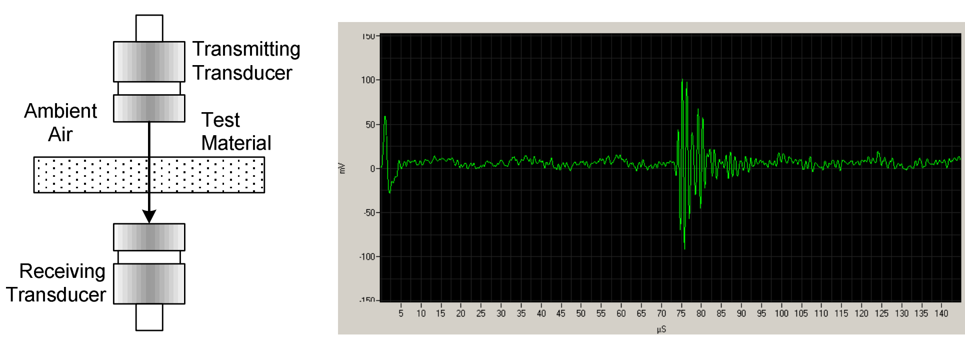


Fig. 4. Non-Contact ultrasound direct transmission technique showing an example of ultrasound transmission signal through a material. In this case from 8 mm CFRP composite with 1 MHz transducers.

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[1] $2^{nd}$ Wave is an Ultran Trademark under which systems are marketed.

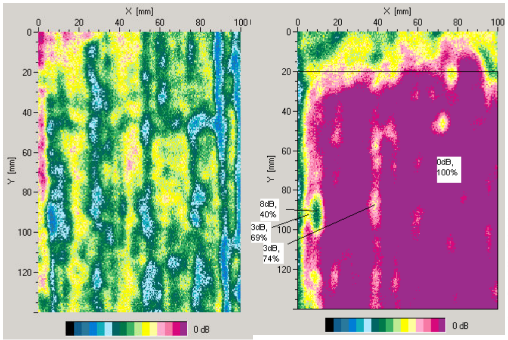


Fig. 5. UNCURED (LEFT) AND CURED (RIGHT) CFRP stacks transmission NCU images. Darker regions in the uncured material image are indicative of poor adhesion. During the curing process several such areas are bonded, while some are not such as the ones indicated by the lighter areas in the cured material. Transducers: 500 kHz 12.5 mm active diameter. By permission of HEXCEL Composites, UK.

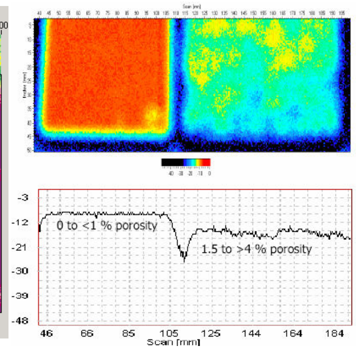


Fig. 6. 10 mm VARYING POROSITY CFRP COMPOSITES NCU imaging and analysis, left 0 to 0.1% porosity and right 1.5 to >4% porosity. Porosity variation across both samples is also shown by cross-sectional profile, bottom, where y-axis scale is in dB. Transducers: 500 kHz 12.5 mm active diameter.

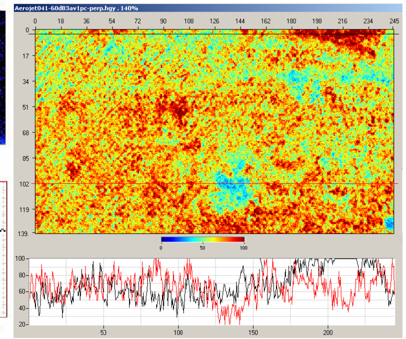

Fig. 7. GRAPHITIZED WOVEN CFRP NCU transmission image exhibiting gross porosity and apparent defects. Transducers: Focused 500 kHz 12.5x12.5 mm active area.

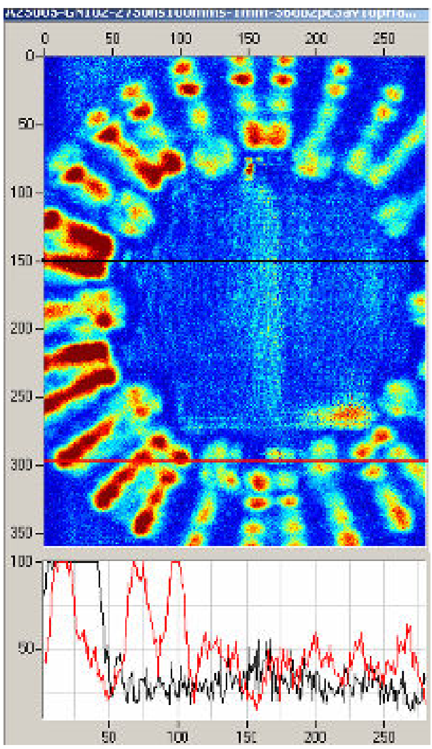

Fig. 8. 2D CARBON-CARBON DISC BRAKE NCU transmission imaging showing regions of very high and very low ultrasound transmission, presumably indicative of varying material density. Transducers: Focused 200 kHz 25 mm active diameter.

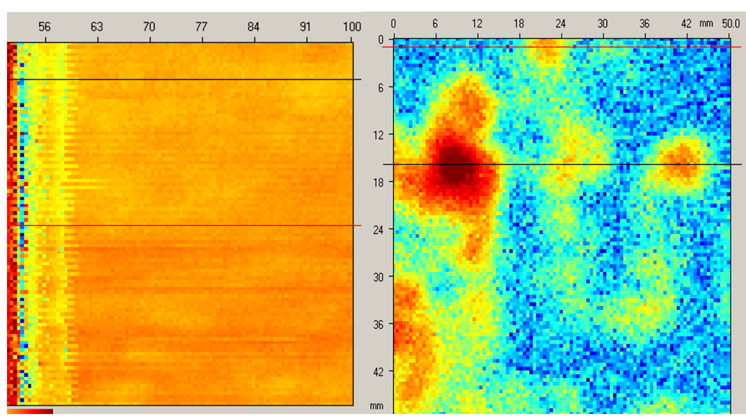

Fig. 9. TIRE RUBBER MIXES NCU imaging. Left: Homogeneous mix. Right: Heterogeneous mix. Transducers: 500 kHz 12.5 mm active diameter.

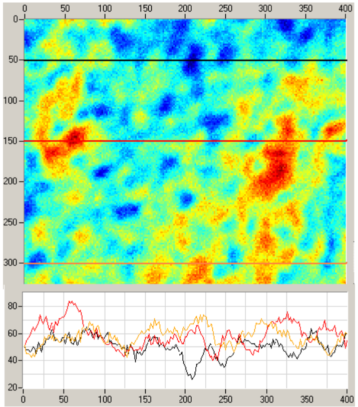

Fig. 10. 100 mm POLYURETHANE FOAM NCU imaging, presumably showing porosity/density variations. Transducers: 200 kHz 25 mm active diameter.

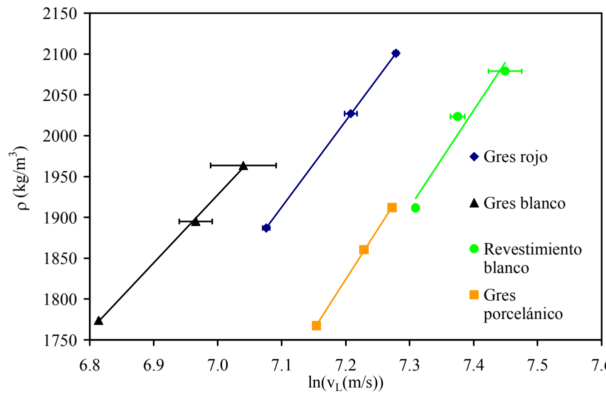


Fig. 11. GREEN CERAMIC FLOOR TILES NCU velocity-density relationships for a variety of compositions. Transducers: 500 kHz 19 mm active diameter.

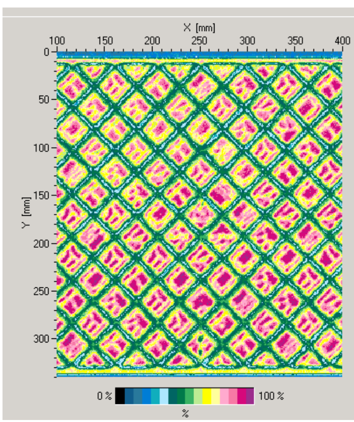


Fig. 12. GREEN CERAMIC FLOOR TILE high resolution NCU image. Transducers: Focused 500 kHz 19 mm active diameter.

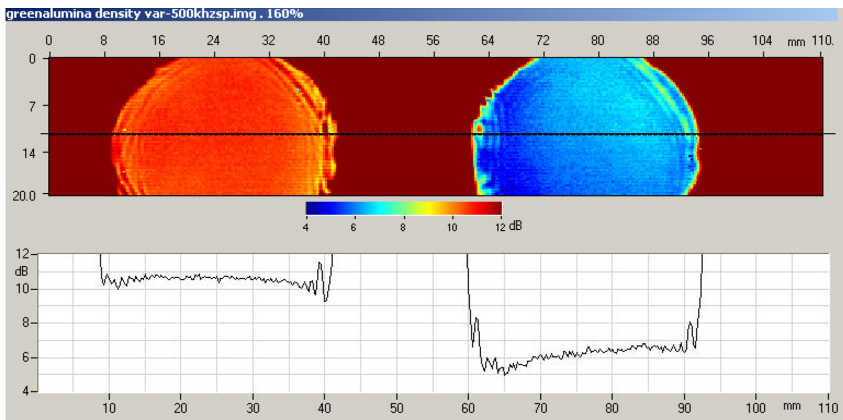


Fig. 13. GREEN ALUMINA VARYING IN DENSITY NCU image analysis. Left: Pressed at 9,000 psi, right: pressed at 15,000 psi. Note as the density increases (higher pressing pressure), in NCU mode ultrasound transmission decreases. Transducers: 500 kHz 12.5 mm active diameter.

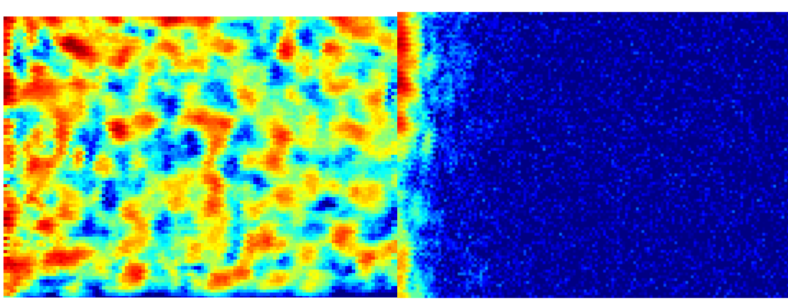

Fig. 14. FIRED SILICA REFRACTORY NCU imaging. Left: Defect-free. Right: Cracked. Transducers: 500 kHz 12.5 mm active diameter.

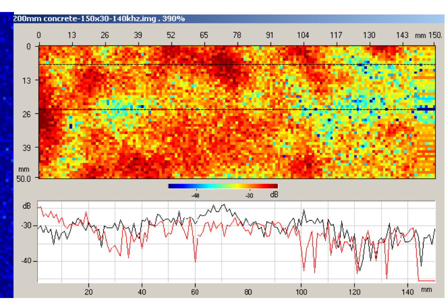

Fig. 15. 200 mm CONCRETE NCU imaging showing internal defects. Transducers: Mixed 140 kHz.

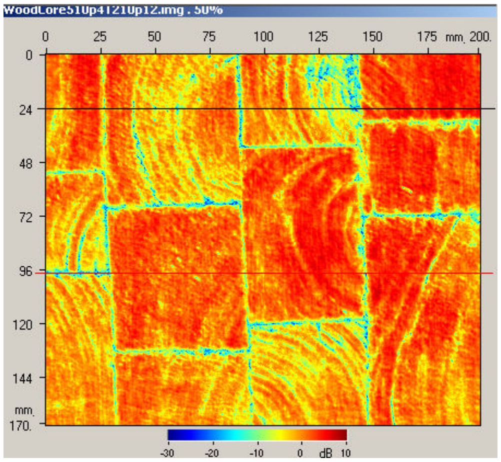


Fig. 16. POROUS WOOD CORE NCU high resolution imaging. Transducers: Mixed 1 MHz.

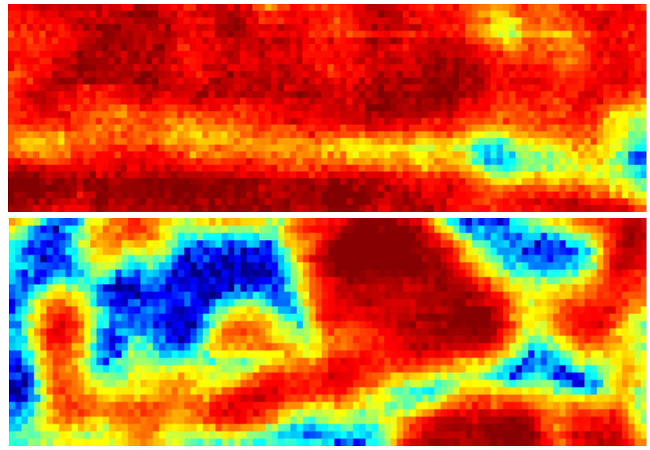

Fig. 17. CHEDDAR CHEESE NCU imaging. Top: Reduced fat. Bottom: Extra sharp. It appears as the fat content in cheese increases so does the ultrasound attentuation. Transducers: 1 MHz 12.5 mm active area diameter.

**3.2 T-R Pitch-Catch Same Side Reflection NCU:** By suitably angulating transmitting and receiving transducers on the same side of the test material where access is only from one side, besides launching the surface waves, it is also possible to launch bulk waves in materials, Fig. 18. By doing so either the far side reflection or reflections from within the material can be investigated to decipher the internal features or condition of the material. An example of this is shown in Fig. 19. Here we see the artificially embedded defects in a 4 mm thick panel of CFRP composite.

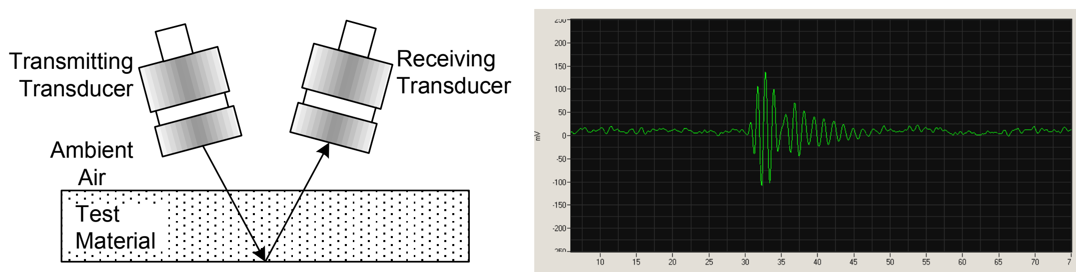


Fig. 18. Non-contact ultrasound T-R pitch-catch reflection technique showing far side (bottom surface) reflection from a material. In this case the bottom surface of 12.5 mm thick aluminum with 1 MHz transducers.

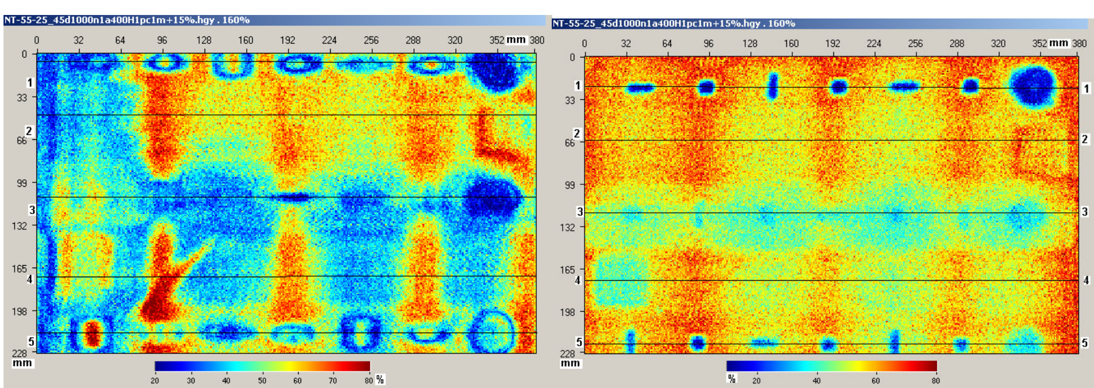


Fig. 19. Same side NCU image of a CFRP panel with embedded defects (left). As a comparison the right hand image shows similar image, but acquired by direct transmission mode. Transducers: 500 kHz 12.5 mm active diameter.

**3.3 Single transducer Pulse-Echo NCU:** Under ambient conditions it is very easy to obtain high quality signals corresponding to the reflection from the material surface, Fig. 20. By monitoring the amplitude and time of flight of surface reflections, materials can be characterized for surface roughness, texture, etc. Figures 21 and 22 provide examples to this effect for surface imaging of familiar and industrial materials.

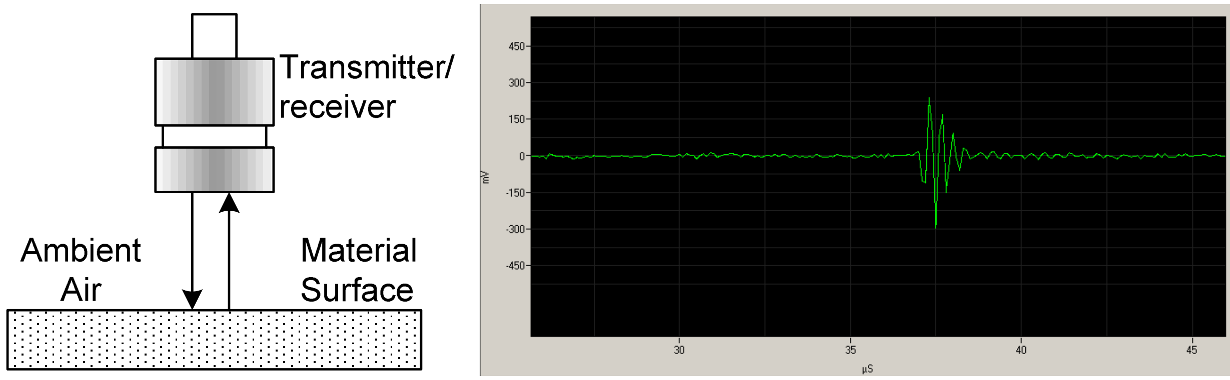


Fig. 20. Non-contact ultrasound single transducer, pulse-echo technique showing surface reflection signal from a material. In this case the surface of dense alumina with 3 MHz transducer.

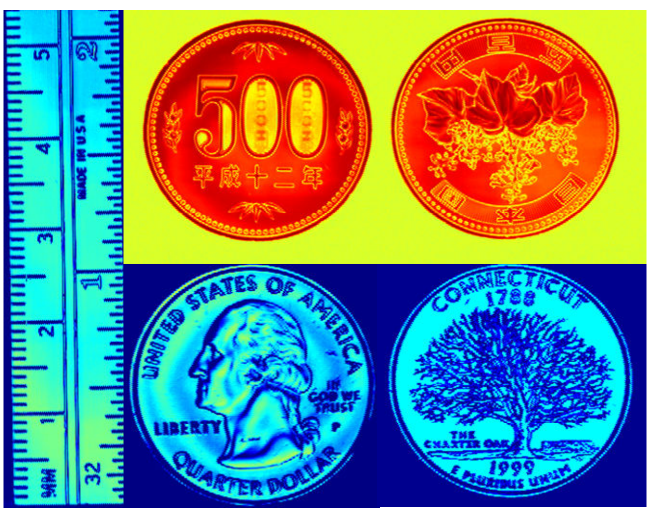


Fig. 21. Non-contact ultrasound surface images of familiar objects generated by 3 MHz sharply focused transducer.

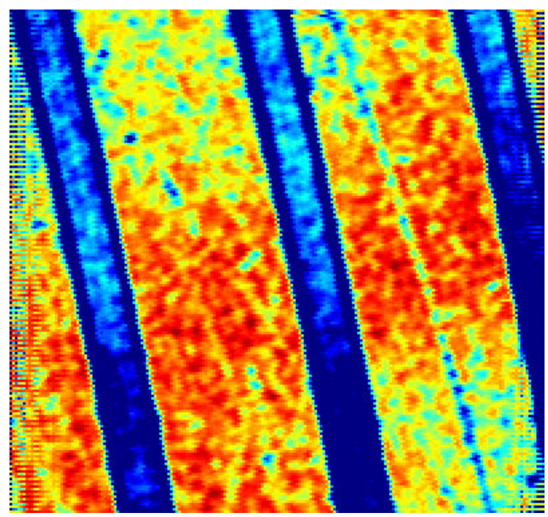

Fig. 22. Surface imaging of semiconductor polishing pad showing surface roughness.

While highly desired, pulse-echo NCU technique to obtain the far side materials reflection under ambient conditions is at best extremely arduous, if not impossible at the time of this writing. However, if the test is conducted under high air/gas pressure, then it is relatively easy to observe far side reflections in pulse-echo NCU mode. Fig. 23 shows an example of multiple thickness reflections from 10 mm steel at 50 bar air pressure by using a special broadband 3 MHz transducer.

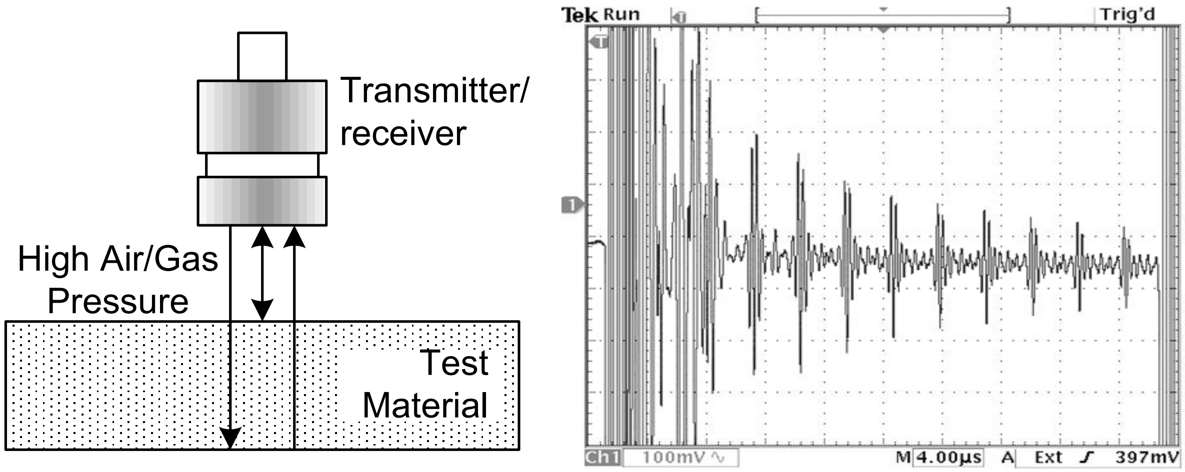


Fig. 23. Non-contact ultrasound single transducer, pulse-echo at high gas pressure. In this case far side (bottom surface) reflections from a 10 mm steel plate at 50 bar air pressure by using a broadband 3 MHz NCU transducer.

## 4. CONCLUSIONS

In this paper we have provided an introduction to an extraordinarily high air/gas transduction piezoelectric transducer and an ultrasonic excitation and amplification system for non-contact ultrasound imaging and analysis of wide range of materials. Examples of materials testing by NCU with well known ultrasonic techniques have also been given. In our laboratory work continues to enhance NCU by considering the geometrical acoustics in air and ultrasound interaction with materials. This work exhibits the unique nature of NCU with respect to very high resolution and detectability of discontinuities in materials, besides other applications of significance. The ultimate value of NCU is in cost-effective materials production, energy, time, and environment savings. We firmly believe NCU will greatly benefit the materials industry as well as in R&D of materials related to process and quality control for reliable and safe uses of materials.

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