New Generation of High Resolution Ultrasonic Imaging Technique for Material Characterization and NDT

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Abstract. The role of non-destructive material characterization and NDT is changing at a rapid rate, continuing to evolve alongside the dramatic development of novel techniques based on the principles of high-resolution imaging. The modern use of advanced optical, thermal, ultrasonic, laser-ultrasound, acoustic emission, vibration, electro-magnetic, and X-ray techniques, etc., as well as refined measurement and signal/data processing devices, allows for continuous generation of on-line information. As a result real-time process monitoring can be achieved, leading to the more effective and efficient control of numerous processes, greatly improving manufacturing as a whole. Indeed, concurrent quality inspection has become an attainable reality. With the advent of new materials for use in various structures, joints, and parts, however, innovative applications of modern NDT imaging techniques are necessary to monitor as many stages of manufacturing as possible. Simply put, intelligent advance manufacturing is impossible without actively integrating modern non-destructive evaluation into the production system.

Introduction

Acoustical imaging is a well-known and powerful tool for studying the microstructure and properties of materials. It has attracted the efforts of numerous research groups throughout the world. In actuality, high-resolution acoustic imaging is a relatively new technique that has only recently been employed to evaluate the microstructure of condensed matter. The suggestion to use of sound rather than light as a microscope was first put forth by a Russian scientist (Solokov, 1934) just before the Second World War. However, due to the limitations of existing technology, it was many years before high-resolution acoustic imaging was fully realized. The first acoustic microscopy prototype was fabricated in the United States (C. Quate, Stanford University) in 1974. Today the industrial application of acoustic microscopy continues to be a developing field of study [20].

The most popular quantitative technique in acoustic microscopy is the V(z) method [1, 2], in which the acoustic velocity and attenuation of leaky surface acoustic waves, as well as a reflectance function, is determined from the output signal V of the transducer. This information is acquired as a function of the specimen displacement, z. In addition to the V(z) method, several techniques employing separate transmitting and receiving transducers have been recently developed for both the analysis of acoustic parameters and quantitative material characterization. For example, an ultrasonic micro-spectrometer with spherical-planar-pair lenses allows for the measurement of the reflection coefficient [3, 4]. Here the angular spectrum of the reflected wave in such system is determined by the rotation of the lens system as a whole, relative to the specimen surface.

A two-transducer ultrasonic system is also used to obtain the resonant transmission coefficient [5], as well as for the determination of Lamb dispersion curves [6]. To gather the data necessary for reconstruction, two measurements were required: the voltage of the output transducer as a function of (1) the lateral displacement of the transducer on the specimen's surface and (2) the frequency of the probing electrical tone burst pulse. A two-dimensional recording of the wave (as scattered by the specimen) was proposed [7] for measuring elastic constants. In this method the transmitting transducer is focused at the surface of the specimen; the scan plane of the receiver is located far from the focus. Thus, the recorded spatial distribution represents the angular spectrum of the reflected or transmitted wave. The angular resolution of this method is determined by both the spatial resolution of the receiver and the distance between the scan plane and the focus. In previous articles we developed a new technique for measuring acoustical parameters called the A(z) method for the transmission mode [8, 9]. A new V(x) method was introduced later for the reflection mode [10, 11]. Both the A(z) and V(x) methods may include additional options, based on the air-coupling pair measurement technique for both the reflection and transmission modes.

1. High Harmonic Mode of the Acoustical Microscope

The signal of the second harmonic, generated by nonlinear reflection, is in most cases 30–50 dB weaker than the signal of fundamental frequency. Therefore, it is necessary to select the experimental parameters with care. To maximize the spatial resolution of the acoustic microscope, a single, short pulse of sound is usually generated. The wide-band spectrum of such a pulse, however, contains strong components at double frequency. In addition, the inherent bulk nonlinearity of the acoustical components of the microscope and object (and especially of the coupling liquid) produces uninteresting second harmonic waves, which accompany those of the fundamental frequency. These waves will therefore contribute to the image at second harmonic—identical information to that already found in the linear picture [12]. In [13-15], this was demonstrated experimentally for the resolution of weak-reflecting inclusions using a scanning microscope with a 25 MHz acoustical focusing lens. A selective filter-amplifier with a basic frequency of 50 MHz and a bandwidth of 4 MHz was incorporated into the receiving branch (see Fig 1).

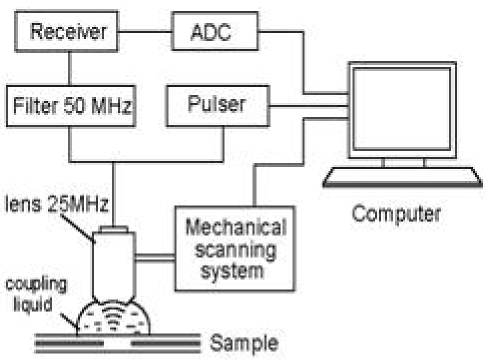


Fig 1. Schematic diagram of the scanning acoustical microscope as used for second harmonic imaging.

The sound wave was excited by applying a single pulse to the lens transducer with amplitude 120 V and duration 16 nS. Without taking any specific action to enhance the second harmonic, its level in the received signal stood at approximately 25 dB (measured during reflection from the surface of a steel plate in beam focus). By decreasing the receiver bandwidth, the tone burst of the second harmonic had a significantly longer duration compared to that without frequency selection. This led to the deterioration of spatial resolution for depths up to 0.5–0.7 mm.

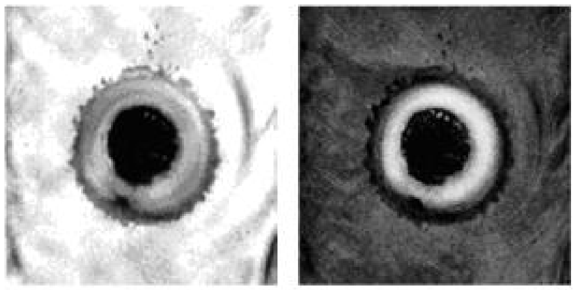


Fig 2. C-scans of spot weld, obtained on fundamental frequency (left) and on second harmonic (right). Size of scanned region is 12×12 mm.

The C-scan image was generated by the mechanical raster scanning of an area up to 40 × 40 mm along the surface with steps of 0.01–0.05 mm thickness. Fig 2 presents the scans of a specimen consisting of two galvanized steel sheets with a thickness of 2 mm, joined together by a resistance spot weld. To exclude any aberration due to non-planar surface conditions, the indentation from the weld electrode was removed by milling. The dark spot in the center of the pictures is the weld nugget. Sound can freely pass through this area; only some reflecting in-homogeneities are visible as light points.

The bright area outside the weld corresponds to the free internal surface of the upper sheet—an area with nearly 100% sound reflection. Between these regions lies a gray ring that corresponds to a zone with poor acoustical contact. It is known that within this zone melted zinc accumulates during the welding process (the so named “corona effect”), creating numerous connected stalactite-stalagmite type structures, [14]. Such a micro rough connective layer is expected to be a very good source of contact acoustical nonlinearity. Since the thickness of this layer and its microstructures are much less than that of a wavelength, they contribute in an integral way. Indeed, the second harmonic picture shows this region as a bright white ring. The amplitude of the second harmonic in this region is at least ten times larger than that of the other regions.

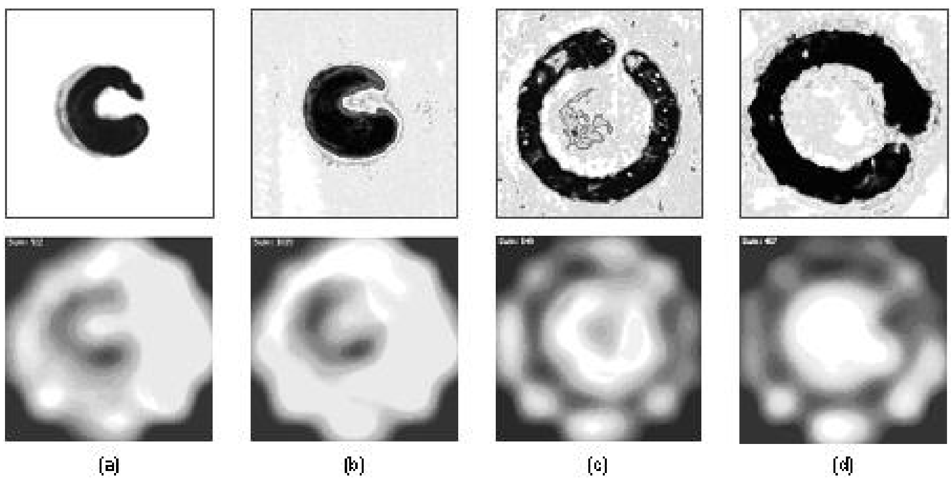


Fig 3 - Acoustic imaging inspection of laser spot welds with a desktop scanning acoustic microscope and corresponding images obtained with the 52-element array: (a), (b) 0.75 mm thick steel plate approximately 3.0 mm. weld; (c), (d) 1.0 mm thick steel plate around 7.0 mm weld. Detectable imperfections: Insufficient length, Seam interruption, Lack of fusion, Pin hole existence.

2. 2D Matrix Transducer

2D Matrix array transducers offer several enhanced capabilities in imaging and beam formation when compared to single transducer scanning systems. 2D-Matrix array transducer technology allows for fast data acquisition and imaging even when using motionless transducers. Advanced technologies such as micro machining and IC manufacturing can produce matrices of thousands of elements less than 0.1 mm in size, in turn creating an acoustic analogue to the CCD camera [16]. The proper dimension of the elements in an array is of great importance; in order to achieve efficient beam forming, each must be approximately half a wavelength in size [17].

For matrices that do not use phased principles to build the acoustic beam, however, elements of this minute size are disadvantageous. Due to power dissipation restrictions, matrix transducers having such high densities can only operate in the pick-up mode. Moreover, acoustic wavelengths at megahertz frequencies are at least 103 times larger than that of light. Finally, imaging capability of a system is generally dependent on the penetration depth of the transducer. This penetration depth drops with the decreasing size of the element due to the beam divergence and the increasing electrical mismatch associated with 50 Ohm transmitters and receivers. Thus, there seems to be no reason to go down to the micron range resolution [16, 17].

3. High Resolution Ultrasonic Inspection Methods for Joints

Traditional methods of joint monitoring involve a combination of visual inspection, pry testing, and destructive tests. For example, in the analysis of resistance spot welds a hammer and chisel is often used. The only truly effective non-destructive evaluation technique has been the ultrasonic pulsed-echo technique, based on the evaluation of ultrasonic echo patterns in a specimen [18]. Current ultrasound methods are to determine both the micromechanical parameters and the microstructure of bulk materials and various joints.

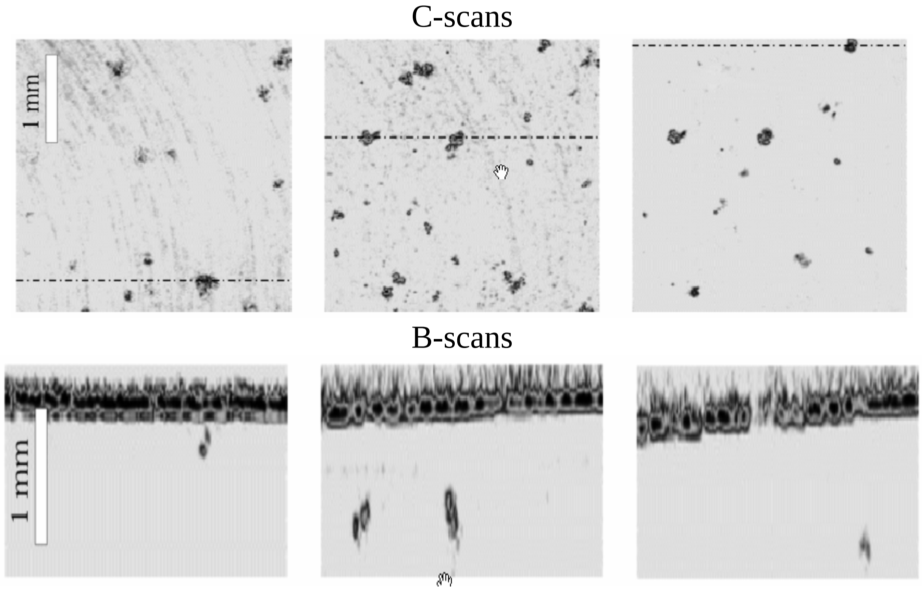
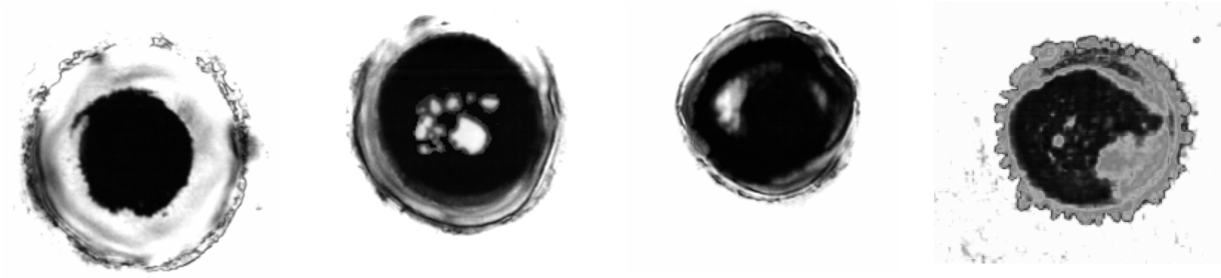


Fig 4. Acoustic images of various porosities in an aluminum casting.



Measure of weld diameter.   Detection of inclusions.   Corona effect.   Stick weld.

Fig 5. C-scan Images of the interface area (depth penetration 1 mm) from the spot welding**.**

One of the hottest NDT problems of today involves the high-resolution inspection of welding joints. Indeed, the problems associated with the evaluation of the multi-layered joints formed by spot (or diffusion) welding are currently under intense scrutiny. Acoustic imaging systems using short probe pulses have been shown to provide an effective way to visualize small-scale failures of various defects at different depths. Further, acoustic spot weld imaging techniques make it possible to inspect the internal structure of joints in spite of the curved outer surfaces of welding spots.

To illustrate the potential that high-resolution acoustic imaging holds, we used a wide-field short-pulse acoustic microscope (see Fig.1). The method described above was utilized in the evaluation of the sub-surface microstructure of cast iron and aluminum castings (see Fig. 4), spot-welding and laser welding joints, etc. (see Fig. 3 and Fig 5). The combination of the C- and B-scan images in one picture can reveal the 3D representation of the defect distribution inside the welding zone, which can be also very useful from a technological point of view.

In spite of the fact that the top surface of specimen was distributed by welding, high quality acoustic images of the nugget zone were obtained (see Fig 5) [18-20]. The C- and B-scan images contain well-shaped defects of joints and confirm the power of the method for NDT and QC of spot-weld joints. Today we use SAM techniques as a routine certification procedure within the automotive industry (see Fig. 6).

The current results of this study show that high-resolution acoustic imaging techniques can be successfully applied to spot welding analysis. Certainly, one may detect internal defects of any kind by this effective inspection method. For this reason, it is easily adapted for us in the quality control of manufacturing welds.

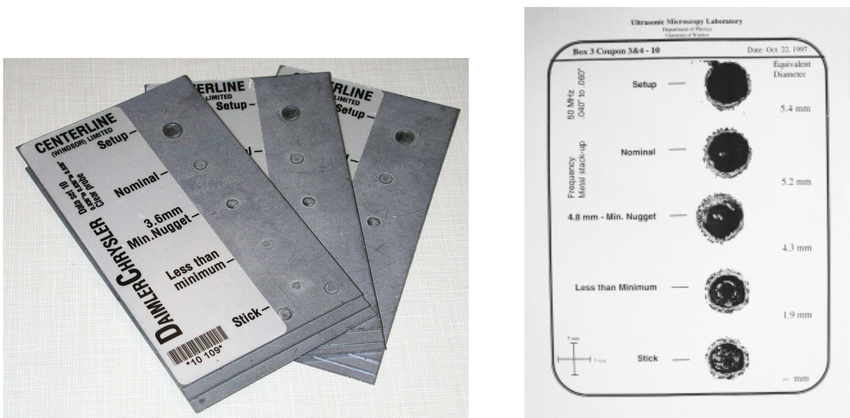


Fig 6. Certification of weld coupons

Acoustic imaging methods that are based on acoustic visualization and characterization are also extremely promising for the quality evaluation of laser welds and rivet joints (see Fig 3). This technique can provide the total bulk reconstruction of the joint zone, including the topography of the top and bottom faces, the structure of the interface between the sheets, and any expulsions, voids, pores, cracks or other defects in the welding zone.

4. Conclusion

During the last few decades, the acoustic microscope has become a common instrument for investigating the internal structure of materials and for industrial non-destructive evaluation. At the same time, quantitative acoustic imaging research has found its place in material imaging and various fields of biomedical imaging. Further improvements in quantitative methods may be realized using complimentary types of ultrasonic-media interactions and, accordingly, provide additional specific information about the object. The realization of these methods will constitute a considerable and exciting expansion in the applicability of the acoustic microscope.

Indeed, quantitative acoustical imaging techniques greatly enhance material characterization capabilities, making possible the effective imaging of various micro-inhomogeneities. This is crucial for the integrity of high-damage risk materials and products used in NDE aviation technology, automotive and nuclear power industries, and microelectronics as well. Such techniques have the potential to provide a reliable, rapid and cost effective method to visualize high contrast, small scale failures and defects at different depths within inspected objects.

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