An ultrasonic transmission technique is described which images the velocity variation within metal parts. The arrival time of the first ultrasonic pulse to traverse the object is detected and displayed as a gray scale on a cathode ray tube while the part is being scanned horizontally and vertically. The velocity variation imaged within several cast turbine parts will be shown. The system can detect voids as small as 0.020 inch. With a more complex computer program and knowing the dimensions of the part, tomographic reconstruction of the velocity variation within parts with curved surfaces should be possible.

Introduction

In casted or pressed metal parts, it is desirable to achieve theoretical density without voids or microporosity. Voids, if large enough, can be detected by standard NDT techniques but microporosity may go undetected especially when it extends over a discernible volume within the part. Ultrasonic velocity variations have been correlated with microporosity, but accurate velocity measurements have remained a laboratory procedure.

This paper describes an ultrasonic time of flight (TOF) system to accurately measure the velocity along a line through the part and displays the velocity variations as gray scale on a cathode ray tube. The accuracy of the velocity measurement is about 0.1% and our present display resolution capability is about 0.8 mm. If two orthogonal views are taken through the part, the location of the low velocity areas can be determined by scaling each view.

This TOF velocity profile imager was adapted for NDT from an ultrasonic breast scanner conceived by G. H. Glover.

System

A block diagram of the TOF velocity measuring system is shown in Fig. 1. The two 5 MHz transducers are mounted coaxially and spaced a fixed distance apart. Both transducer faces are restricted to form a small diameter pencil beam. Since the distance between transducers is fixed, the arrival time of the first ultrasonic pulse is a measure of the propagation velocity in the medium between the transducers. The arrival time is measured by making the width of a constant amplitude gate proportional to the TOF. A delay trigger from the repetition rate generator starts the gate and the threshold detector stops the gate. All later arriving ultrasonic pulses are ignored. The average value of this variable width gate is read on an analog meter and converted to a digital signal for tape recording and later transferred to the computer program file.

If a metal part is placed in the water tank between the two transducers, the average propagation velocity is increased, the arrival time is decreased and analog signal is reduced. Any velocity variation within the metal part will be recorded as a deviation from the composite water-metal average propagation velocity. The computer program simply expands any selected velocity window into 64 levels of gray and displays the results as intensity variations on a cathode ray tube.

The system can be calibrated by measuring the TOF with and without a sample of known thickness and velocity. The analog output is increased or decreased so that one count equals 2 nanoseconds. The signal-to-noise of our system is sufficient to reproduce the readings to within 5 nanoseconds. Since the TOF of a 1.1/4" thick steel part is 5 usec, a velocity resolution capability of 0.1% is feasible. The repetition rate of our system is chosen so that several ultrasonic pulses are detected at each scan position to enhance the signal-to-noise ratio.

The horizontal scan is done with a stepping motor which advances both transducers and a TOF reading is taken every .04" or 1 mm. After one horizontal line is scanned, the part is withdrawn 0.0385" from the water tank and the horizontal line scanned in reverse direction. Our beam diameter is larger than the individual vertical displacement so that we have some overlap on each horizontal scan. The computer program takes this scanning geometry and the TOF data and makes a velocity variation intensity picture with the correct orientation. The pixel size is 0.03" or 0.8 mm which gives a maximum picture size of 2.4" by 2.3" with our present computer program. Each picture contains 3660 TOF data points.

Results

Figure 2 is a composite ultrasonic gray scale velocity image of a HIP Rene 95 sample. The sample is 6" in diameter and 2 1/8" thick with parallel ground faces. The part was too large to scan and image in one picture so that it was scanned in four sections and put together as a composite picture. The irregular imaging of the edge is caused by acoustic refraction which makes the ultrasonic image larger than the true dimension of the part and backlash in the scanning lead screw. This sample was known to have low average density and our results show that there is a large low velocity area in the center of the sample and a low velocity striation in the
lower right hand section. The entire lower right hand section has low average velocity. The black area has 16.4% lower velocity than the white area which is enough to account for the low density of the sample. A similar sample which was pressed to theoretical density had no detectable velocity variations. Clearly this imaging technique can show the location of low velocity (density) areas inside HIP parts and perhaps lead to improved process control during the design phase of the part's manufacture.

This imaging technique also has good spatial resolution as shown by Fig. 3 for a cast stainless steel turbine blade section. Fig. 3a is a full size front surface photograph of the turbine blade section. The area shown is the same as that imaged in Fig. 3b being 1.5" wide by 2.3" high. Note the two 0.02" diameter holes spaced about 1.1" apart on the center line of the sample. The ultrasonic gray scale velocity image is shown in Fig. 3b. The acoustic edge refraction has been marked to indicate the true dimensions of the sample. Black is low velocity and the black/white ratio in this case is 4%. The one pixel high and two pixel wide black strips spaced 1.1" apart on the center line are the images of the two 0.02" diameter holes. The hole image is horizontally elongated due to diffraction from the small diameter hole projected on the back face which is 0.67" behind the holes and also due to the horizontal scan speed which is too fast for the A/D converter used in this system. The larger black low velocity areas are internal defects. Figure 3c is the side view ultrasonic image of the same sample. Using Fig. 3b and 3c the position of the defect areas can be located. Thus, the lower black areas of Fig. 3b are mostly located near the back of the part, the middle black areas of Fig. 3b extend through the entire depth, while the upper black areas of Fig. 3b are very near the front surface.

Figure 4 is a different set of TOF data showing an expanded front view of the defects in the cast turbine blade section. This data was taken without scanning over the edges of the front surface, thus, enhancing the internal structure. The top hole is imaged in the center of the view. Note the tensile structure emanating from the large low velocity areas. The defects imaged by ultrasonic TOF in this cast turbine blade section have not been identified. They do not show up with standard x-ray examination. The sample is now being sectioned for detailed metallurgical examination and some microporosity has been discovered but the examination is not complete.

Tomographic Imaging

The ultrasonic TOF imaging discussed above required samples with parallel faces. To image the internal structure of samples with complex surfaces, tomographic imaging must be used.

By using ray-tracing techniques, the time-of-flight method can be extended to include corrections for refraction in metals. This can be important in two ways. Firstly, correcting for refraction at the water-metal interfaces can be used to account for curved surfaces for imaging of odd-shaped specimens. Secondly, images can be enhanced by correcting for refraction of sound at boundaries of different acoustic velocity within the specimen.

In order to accomplish ray-tracing in odd-shaped metallic specimens, it is necessary either to have prior knowledge of the shape of the part (usually known) or to use a hardware scanning device which can follow surface contours (such as a state-of-the-art eddy current probe). Then the angles of the specimen boundaries can be determined. Finally, a small microprocessor and a simple algorithm can account for the odd shape of the specimen by reconstructing the path of the sound wave, and the velocity profile can be displayed with suitable gray scale. (See Fig. 5.)

Production of accurate time-of-flight profiles is the first step towards a full tomographic reconstruction. Tomography requires that many profiles or "projections" of the ultrasonic velocity be measured at different viewing angles. Then the ensemble of data is used by a minicomputer to reconstruct the image. The acoustic absorption can also be reconstructed using this technique without any major additions to the scanning hardware.

It is considerably more difficult to reconstruct quantitative images from ultrasound data measured in the reflective mode. However, this mode is desirable, because it has the advantage of one-port viewing. Only one transducer may be necessary, and it is possible to image specimens with obstructions that prevent imaging in the transmissive mode (e.g., very large samples). The quantity to be imaged is generally either the acoustic impedance or the attenuation. For smaller specimens, reflective and transmissive techniques may be combined to provide more complete information about the material.

In the reflective mode, it is necessary to collect and analyze complete echo traces. Then these traces are converted into projections of the acoustic impedance or attenuation for input to the tomographic reconstruction programs. Another advantage of such an approach is that it provides the opportunity to obtain quantitative images of specimens where specular reflections are important. This can be accomplished in some specimens by using a deconvolutional procedure and a mapping algorithm.

Conclusion

A transmissive ultrasonic TOF quantitative velocity measuring system has been shown to image the internal structure of parallel face metal samples with good velocity and spacial resolution. The internal defects are probably density variations (microporosity) but their positive identification is not complete. Using a more complex computer program and the known dimensions of the sample, it should be possible to correct for variation in sample thickness and the effects of edge refraction to image the internal structure of samples with complex surfaces. Tomographic reconstruction techniques must be used possibly with a contour following mechanism and wide angle receiving transducers or arrays. Tomographic reconstruction techniques open the possibility of imaging the sample using the measured values of velocity, impedance or attenuation in both the transmissive or reflective mode.
References


Figure 1. Block diagram of TOF velocity measuring system.

Figure 2. Composite ultrasonic gray scale velocity image of HIP Rene 95 sample. Black/white velocity ratio is 16.4%.

Figure 3. Cast turbine blade section. (a) Front surface photograph. Note the two 0.02" dia. holes on the center line. (b) Ultrasonic gray scale velocity image. Black is low velocity, white high velocity, B/W ratio 4%. The 0.02" dia. holes are clearly imaged. (c) Side view velocity image of same part.

Figure 4. Expanded front view of defects in cast turbine blade section. The top hole is imaged in the center of the view. Note the testicle structure emanating from the large low velocity areas.

Figure 5. Block diagram of apparatus used for producing quantitative tomographic imaging in specimens of arbitrary shape.