Determination of minimum flaw size detectable by ultrasonics in titanium alloy plates

N.K. Batra and H.H. Chaskelis

Titanium alloys, due to their light weight, high strength, and corrosion resistant properties, are employed in many structural applications. For design purposes it is important to determine the limit of sensitivity of ultrasonic crack detection techniques for these alloys. This paper demonstrates that it is possible to detect electronic discharge mill (EDM) slots as small as 0.025 mm deep in thick plates, using commercial ultrasonic instrumentation. The effect of grain size, frequency and orientation of the flaw upon the limit of detection is also discussed.

Keywords: ultrasonic testing, titanium alloys, planar cracks

Titanium alloys have a high strength/weight ratio and are corrosion resistant. The types of flaws that can degrade the performance of these alloys include surface-breaking or near-surface planar defects caused by fatigue. Detectability of flaws like flat-bottom holes in ingots of titanium alloys[1] and steel plates[2] have been discussed earlier. Recently Chern[3] *et al* detected electronic discharge mill (EDM) notches from the *accessible* surface using back-scattering of Rayleigh waves. This paper determines the minimum size of a planar defect that can be identified from the *inaccessible* side using commercial ultrasonic instrumentation. Knowledge of the minimum planar flaw detectable by non-destructive means is essential so that suitable safety margins can be used in design.

The sensitivity limit of ultrasonic crack detection is also important from a reliability point of view. The smallest defect that can be detected reliably using ultrasonic methods will depend upon several factors which affect the signal-to-noise ratio. Among these are ultrasonic equipment parameters such as source level, detection threshold, directivity index of the transducer, electronic noise *etc*; transmission losses through the couplant material and host material; ambient noise level due to grain size and surface conditions — all affect detectability. Parameters which directly affect the signal strength from a flaw are its shape, orientation, size and texture. Given these limiting influences it is desirable to establish some practical limit on the minimum size that can be detected. This information may subsequently be used to establish inspection reliability criteria.

Ultrasonic waves incident upon a boundary in a propagating media, under appropriate boundary conditions, follow the laws of reflection, refraction, interference, diffraction and scattering. The detectability of the flaw is affected by all these physical processes. For ultrasonic wavelengths greater than the defect dimensions ($\lambda > a_x$ and a_y, where a_x, a_y are the x, y dimensions of the planar defect), the scattering due to diffraction is dominant. As the size of the defect becomes much smaller than the wavelength, the shape of the defect becomes immaterial and it acts as an isotropic point source under an insonifying ultrasonic field. On the other hand, if any dimension of the defect normal to the direction of propagation is much greater than the wavelength, it can be treated as a reflector. The energy will be reflected back directly to the transducer for a limited range of angles. The geometrical laws of ray tracing are adequate to describe backscattering from the defect.

Experimental

The detectability of various flaw sizes was evaluated using a Ti-6211 plate approximately 25.4 cm long, 5.84 cm wide and 2.3 cm thick. The faces of the plate were machined flat and parallel within ± 0.025 mm. Twelve EDM notches ~0.25 mm wide, 2.50 mm long and from 0.025 mm to 2.59 mm deep, were spark-eroded into the specimen using an EDM machine. The notches were set along a straight line, approximately 33 mm from the long edge and parallel to it. The notches were spaced approximately 10 mm apart. The depth of these notches was checked using a needle-like electrode and a depth gauge. These types of flaws are a close simulation of planar, sharp cracks. Watertight tape was placed over the notches so that maximum incident ultrasonic energy is scattered back from the defect (keeping in mind that real cracks constitute interfaces of maximum acoustic impedance mismatch). The test piece was placed on a rotary table in a water tank of an Automation Industries US 450 series laboratory scanner, equipped with a commercial pulser-receiver, TEK-TRAN Immerscope 725.

Conventional pulse-echo techniques were used to detect these cracks. Since corner surface-breaking cracks are good reflectors of obliquely incident bulk waves, ultrasound of suitable frequency was injected into the specimen at a suitable angle of incidence. The angle of incidence was adjusted so that only vertically polarized

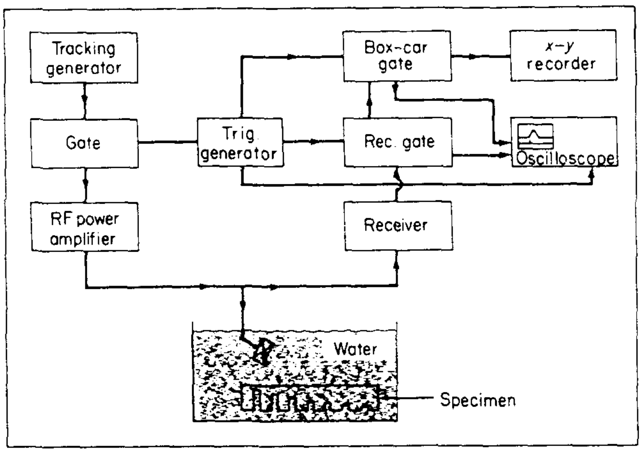

Fig. 1 Schematic of RF toneburst system

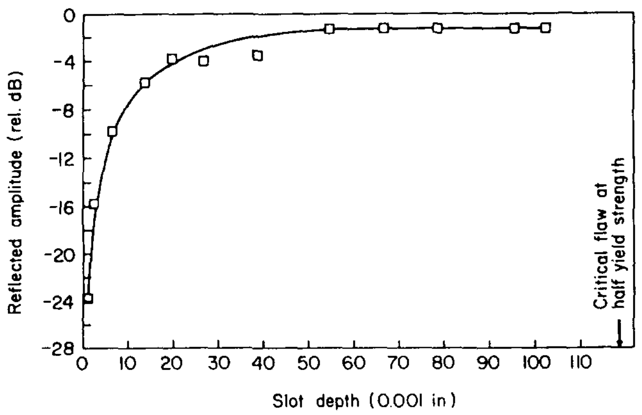

Fig. 2 Reflected amplitude for various EDM slot depths using a commercial pulser-receiver. Ti-6211 (as received); plate thickness = 22.9 mm, angle of incidence = 18°; 5 MHz focussed transducer; Tek-Tran Immerscope 725 (0.001 in = 0.025 mm)

shear waves propagated into the specimen. The position of the transducer was adjusted such that the reflected ultrasonic echo signals were maximized. The received echoes were amplified and displayed. Flaws were considered detected when an echo exceeding the noise level of the system could be observed. Signal processing can improve the signal-to-noise ratio. The strength of the signal can be taken as an indication of the severity of the crack. However, as discussed earlier, many factors influence the amplitude of the echo. With this in mind, the amplitude of the backscattered ultrasound from the EDM slots of varying depth was recorded.

To study the frequency dependence of the ultrasound backscattered from these planar flaws, a laboratory version of the RF toneburst system (Figure 1) was used to transmit and receive ultrasound of suitable frequency. Since the signal is repetitive, the signal-to-noise ratio can be improved further by using a box-car integrator. This averages the echoes over a large number of repetition periods, integrating out electrical noise (self noise). The echo can be recorded on an x–y recorder. To image these planar cracks we used a conventional MetroTek ultrasonic imaging system.

Results

Figure 2 shows the relative amplitude of the ultrasound backscattered from the various EDM notches. As the slot depth increases, the backscattered signal increases, reaching a plateau when the size of the slot becomes much larger (infinite scatterer) than the focal spot. We chose a transducer with a rather small focal spot to determine the minimum flaw size. Note that the relative amplitude of the signal from the 0.001 in (0.025 mm) slot is almost 22 dB lower than the maximum signal from the infinite slot. These results are similar to those obtained by Marianeschi and Tili[2] on flat-bottom holes in steel.

Frequency dependence of the backscattered ultrasound from EDM slots of various depths is presented in Figure 3.

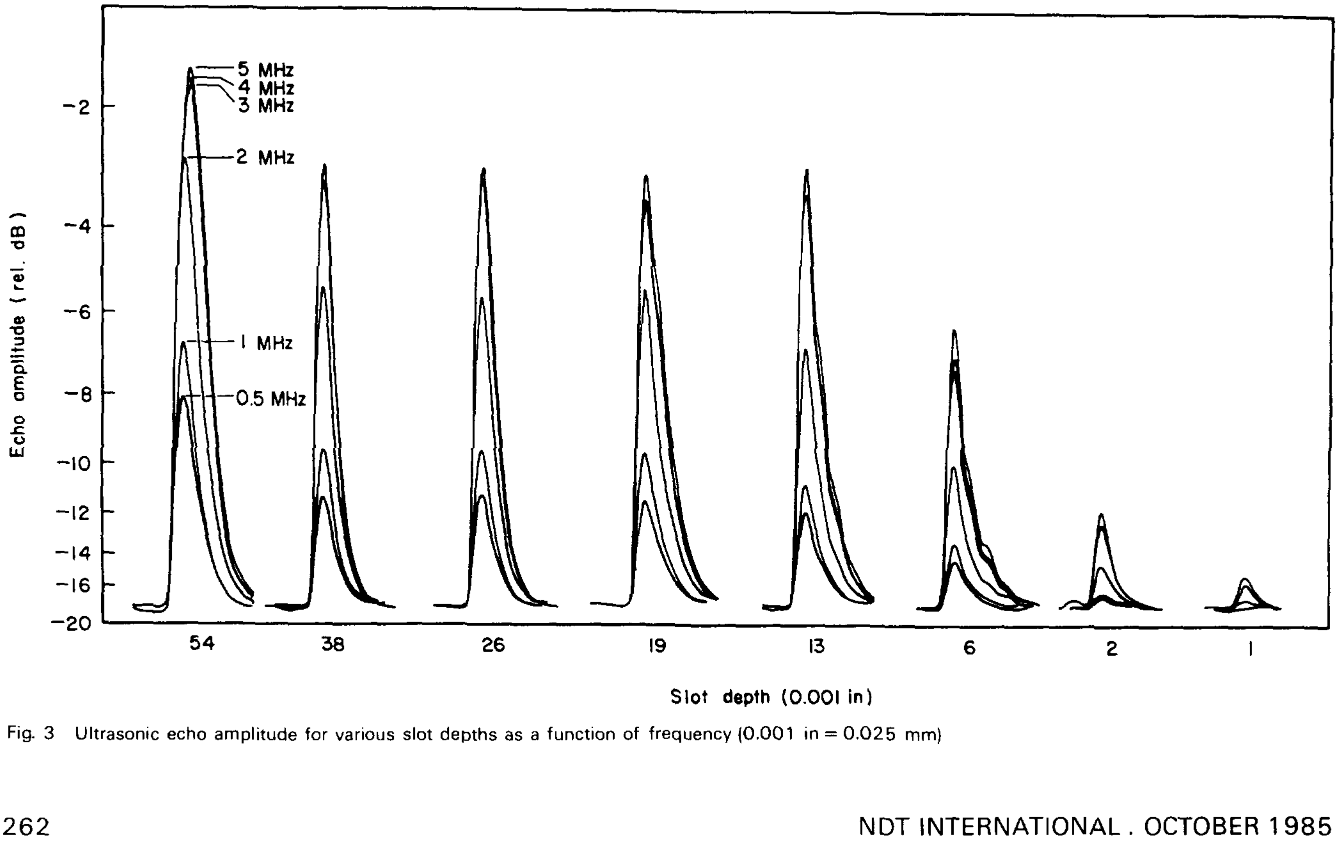

Fig. 3 Ultrasonic echo amplitude for various slot depths as a function of frequency (0.001 in = 0.025 mm)

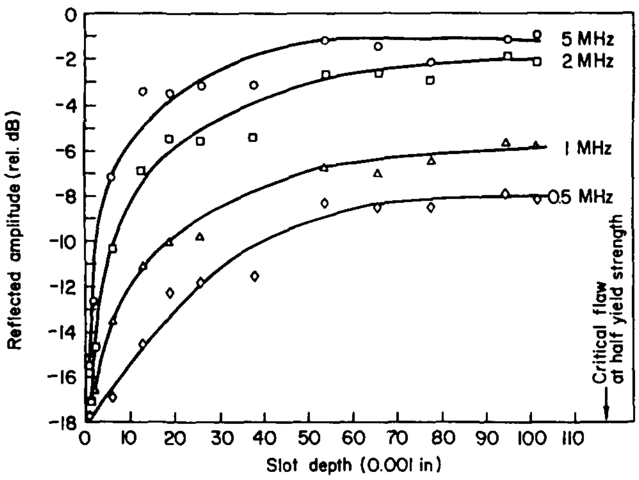

Fig. 4 Plot of reflected amplitude against slot depth at different ultrasonic frequencies. Ti-6211; angle of incidence = 16°; tone burst and box-car (0.001 in = 0.025 mm)

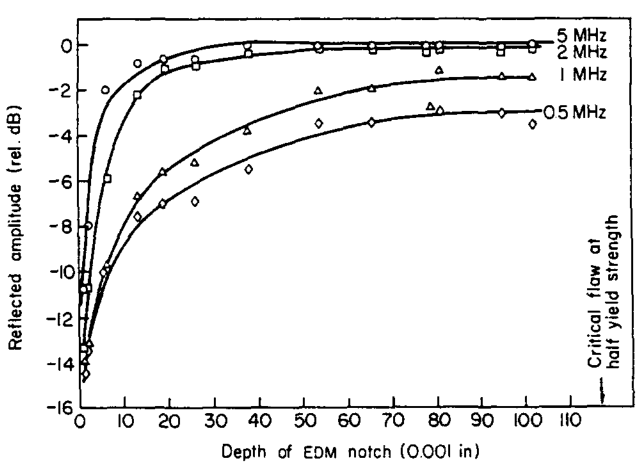

Fig. 5 Reflected amplitude at different frequencies for various water-filled EDM slots. Ti-6211; angle of incidence = 16°; tone burst and box-car; water-filled notches (0.001 in = 0.025 mm)

As the frequency decreases, the overall amplitude of the backscattered signal decreases. This decrease in amplitude is partly due to the bandwidth roll-off of the transducer and partly due to the scattering mechanism. The EDM slot can be regarded as an ultrasonic radiator under the incident insonifying ultrasound. The beam profile of this radiator can be regarded as similar to that of an unfocussed transducer. The characteristic of such a radiator depends upon the shape, size and orientation of the slot. The amplitude of the backscattered signal varies with the depth of the slot. If the slot depth $a \gtrsim \lambda$, full reflection occurs and the amplitude does not decrease as the frequency is decreased. One can explain this result geometrically. As the frequency decreases, the size of the focal spot increases. As the size of the focal spot becomes more than the slot size, only a portion of the incident ultrasound intercepts the flaw and further decrease in frequency results in decreased backscattered amplitude. Figure 4 shows the plot of reflected amplitude against slot depth. The reflected amplitude becomes constant for much larger slot depth values at 0.5 MHz than it does at 5 MHz.

There are occasions when the cracks may be accessible to ultrasound only from the opposite surface. They may be filled with water and may not give maximum scattered amplitude. Figure 5 demonstrates detectability of the slots for such a case.

Figure 6 presents ultrasonic images of the EDM slots. These images indicate clearly the variation in the depth of the notches. The smallest flaw imaged is 0.152 mm. As the gain was increased (consequently noise increased also), we were able to extend the detectability down to a 0.050 mm deep slot.

Tests were also performed on specimens of Ti-alloy with a wide variation in their microstructure. The titanium alloy consisted of α–β microstructure. The volume fraction of these phases was varied by heat treatment. In the specimen used for detection of minimum flaw size, the volume fraction of α-phase varied from 69% to 90%, though the grain size was nearly constant (~200 μm), because the heat treatment was performed in the two-

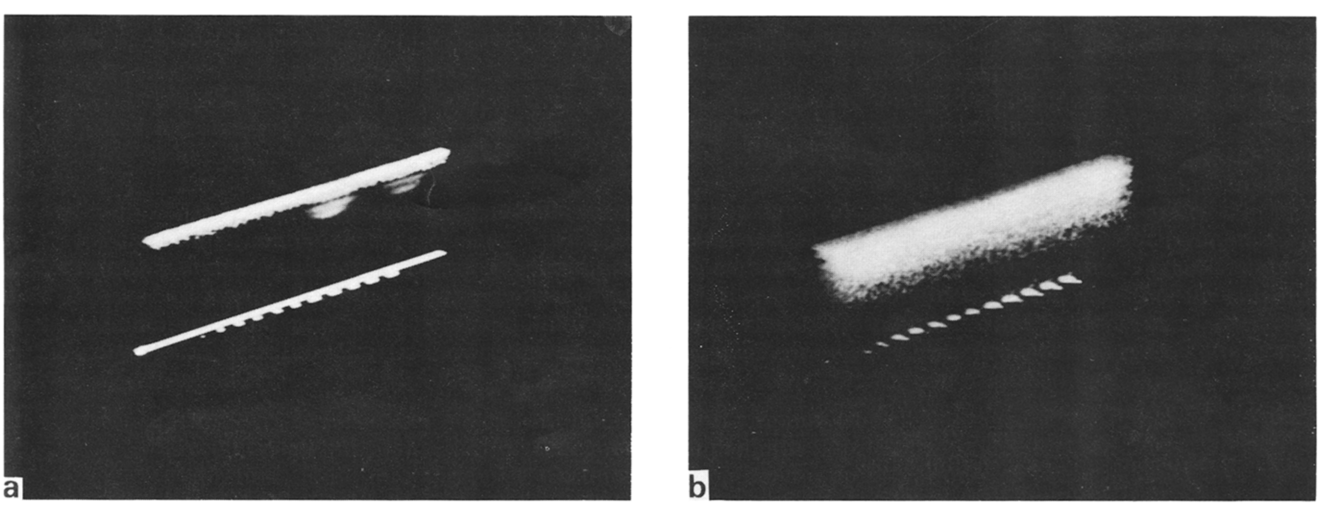

Fig. 6 Ultrasonic images of EDM slots of various depths: a — 0.152 to 2.591 mm; b — 0.051 to 2.591 mm

phase region. Thus, in all cases tested the background noise due to microstructural scattering did not mask the reflection from the 0.025 mm deep slot.

Conclusion

In this paper we have demonstrated that it is possible to detect EDM slots as small as 0.025 mm in titanium alloy plate approximately 25 mm thick. Based on half yield strength calculations, the practical detectable limit represents less than 1% of a critical flaw. Of course, the geometry of the test piece, surface conditions and metallurgical characteristics reduce the signal-to-noise ratio, and in the field the minimum detectable flaw size may be greater than reported here. The wavelength of the ultrasound used has been shown not to be a limiting factor on the sensitivity of the examination.

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