Non-linear enhancement of laser generated ultrasonic Rayleigh waves by cracks

S. Dixon, B. Cann, D. Carroll, Y. Fan and R.S. Edwards

Department of Physics, University of Warwick, Coventry, CV4 7AL, UK

Abstract

Laser generated ultrasound has been widely used for detecting cracks, surface and sub-surface defects in many different materials. It provides a non-contact wideband excitation source which can be focused into different geometries. Previous workers have reported enhancement of the laser generated Rayleigh wave when a crack is illuminated by pulsed laser beam irradiation. We demonstrate that the enhancement observed is due to a combination of source truncation, the free boundary condition at the edge of the crack and interference effects. Generating a Rayleigh wave over a crack can lead to enhancement of the amplitude of the Rayleigh wave signal, a shift in the dominant frequency of the wideband Rayleigh wave and strong enhancement of the high frequency components of the Rayleigh wave.

---

1. Introduction

Laser generated ultrasound [1-4] is now used fairly extensively in research laboratories as it provides a non-contact, wideband and controllable generation source capable of simultaneously generating compression, shear and surface waves on a range of materials.

There have recently been several papers that report non-linear enhancement effects observed when a Rayleigh wave interacts with a surface crack or slot [5-10]. Some of this work focuses on the case where the detector is close to the crack when the Rayleigh wave arrives at the crack [7-10], and it has been shown [10] that the enhancement in this particular case is due in the main to constructive interference of the incident and reflected Rayleigh wave and a reflected mode converted compression wave. Recent publications have considered the effect on the generated Rayleigh wave when irradiating a surface crack with a pulsed laser beam [5,6] at low optical energy densities in the thermoelastic regime. Enhancement of the Rayleigh wave amplitude and a change in the frequency characteristics of the generated wave was reported, and the main feature measured was the position of the maximum peak in the magnitude FFT of the Rayleigh wave pulse. A clear shift in the peak to a higher frequency was observed and modeling [6] has shown that the shift is mainly due to the change in the boundary conditions for the ultrasonic generation source.

In this paper we show that for realistic rough surface cracks on metal samples, enhancement of both the amplitude of the wideband Rayleigh wave and enhancement of the high frequency components of the Rayleigh wave can be used to detect the presence of a surface breaking crack. Rayleigh waves are generated using a pulsed Nd:YAG laser with a Gaussian beam profile of approximate diameter 3mm with a 10ns pulse width at 1064nm and an energy of 40mJ per pulse. A Michelson interferometer, which is shown schematically in figure 1, with a bandwidth of 80MHz and sensitivity down to 10pm is used to measure the absolute surface displacement associated with the Rayleigh wave.

As in the work by Nagy [5], here there are three key points that we consider when discussing the effect of irradiating a slot or crack with the pulsed laser beam.

- Truncation of the source.
- Reflection of waves at the slot or crack.
- Changes in the boundary conditions due to the edge of the slot or crack.

1.1 Changes in the boundary conditions for the generation source due to the edge of the slot or crack.

This is the most difficult of the three effects to describe as the effect of changing the boundary conditions of the generation source cannot be intuitively understood. As the edge of the slot or crack is free to expand into the void created by the slot or crack the boundary conditions for the transient force that generates the ultrasonic waves are very different. We do not attempt to model this effect in this paper, and in any case this has already been done by previous workers [6] but by comparison of various experimental conditions, it can be shown that the change in the boundary condition plays a key role in the non-linear effects that we observe.

1.2 Truncating the source

The overall effect of source truncation is that it makes the spatial extent of the source smaller. When calculating the resultant Rayleigh wave generation by a laser one needs to convolve the temporal and spatial profiles of the generation source. The laser pulse itself is of short duration, typically less than 10ns, and so it tends to be the spatial extent of the source that dominates the frequency characteristics of the generated Rayleigh wave [3]. If one reduces the size of the beam by truncation then one would expect the generated Rayleigh wave to have relatively more of its energy at higher frequencies. Also, it is well known that different source profiles yield very different Rayleigh wave profiles [4]. This truncation effect has been demonstrated and measured by truncating the source by partially blocking the beam and generating on a clear region of the sample surface.

1.3 Reflection of waves at the slot or crack

A truncated source will produce a complicated directivity pattern, but will still radiate the Rayleigh wave in different directions. Where the pulsed laser beam irradiates the edge of a slot or crack the edge will reflect and scatter the incident Rayleigh wave energy. Thus one could expect enhancement from a consideration of the interference between the Rayleigh waves directly radiated away from the slot or crack and those reflected from the slot or crack. The level and form of enhancement that one observes when the detection point is close to a slot or crack would not be expected in this case as the near field measurement close to the defect is strongly influenced by the mode converted compression wave, which attenuates rapidly at the surface away from the edge of the slot or crack [10]. When the Rayleigh wave is incident upon the slot a certain portion of the energy is reflected back in the opposite direction, whilst some is mode converted and some passes directly under the slot [10]. As the Rayleigh wave is wideband it contains a range of ultrasonic frequency components whose displacements fall off exponentially with depth, such that most of the energy associated with a particular wavelength is confined within a depth roughly equal to one wavelength. Thus one would expect the waves reflected from the machined slot to contain relatively more of the higher frequency components as lower frequency components traveling deeper within the sample surface are able to pass under the slot more readily than higher frequency components.

2. Experimental set-up

A pulsed Nd:YAG[1] laser with an approximately Gaussian beam energy distribution is used to thermoelastically generate ultrasonic waves in the aluminium samples studied. The rise-time of the 3mm diameter laser beam pulse is 10ns, at an energy of 40mJ per pulse at a wavelength of 1064nm. A modified Michelson interferometer is used to detect the ultrasonic waves at the sample surface [3]. The particular interferometer used has a high spatial resolution (focused to a point of <0.2 mm diameter) and a bandwidth of 80MHz. Aluminium samples are used for the experiments, containing a range of machined slots with slot widths of approximately 0.7 mm in addition to a section of billet sample containing a real crack.

2.1 Laser generation on the sample and machined slot edge

The pulsed laser beam is of sufficiently low energy density such that the source is thermoelastic and it generates both surface and bulk waves in the sample simultaneously which radiate out in all directions with a complicated directivity function [2]. The purpose in this measurement is to demonstrate that there is a strong enhancement of the detected high frequency components of the detected Rayleigh wave when the pulsed laser beam irradiates the slot or bar edge.

To simulate a crack of infinite depth, the generation laser beam is scanned towards the edge of a thick aluminium bar as shown in figure 2a. The detection laser beam is fixed 35 mm from the end edge of the bar whilst the generation laser beam is scanned from 10 mm away from the end of the bar to completely off the end of the bar. When the generation laser approaches the end of the bar the source is truncated by

---

the material itself and the boundary conditions are significantly different to those when the source is entirely on the surface of the sample, well away from an edge.

Machined slots are often used to simulate surface cracks in ultrasonic measurements and whilst they do not always ideally represent a realistic crack they are still a valuable and a standard calibration tool. A machined slot of width 0.7 mm and depth 0.9 mm in an aluminium bar sample of width and depth 65 mm with a length of 200mm is used for the first ultrasonic experiment. The Michelson interferometer and the sample are fixed in position such that the detection point lies along the centre line of the sample surface, 60mm from the edge of the slot. The pulsed laser beam starts at a position between the detection point and the slot and is moved towards the slot away from the detection point along the centre line of the sample surface. The detected ultrasonic wave form is recorded as the pulsed laser beam approaches the slot as shown in figure 2a for an infinite depth slot.

2.2 Truncation of the source

A face of the aluminium bar that does not contain any slots is used to investigate the effect of truncating the pulsed laser beam using a metal beam stop positioned roughly half way across the beam, as shown in figure 2b, so that the laser beam irradiates the surface of the sample. Thus the shape and size of the beam is nominally identical to that which was created by the slot or the edge of the sample.

2.3 Laser generation on a billet sample containing a real crack

A section of aluminium billet that had been found to contain a crack during manufacture is used to demonstrate that the effects described in this paper are not restricted to edges that are straight and well defined. A photograph of the crack on the billet is shown in figure 3, together with a measurement of the depth of the crack made using a calibrated ACPD crack depth gauge. Again, the detection laser beam spot was held stationary and the generation laser beam was scanned towards the shallow and deeper regions of the crack.

3. Experimental results

Because the samples used are relatively thick, the ultrasonic waveform tends to be dominated by the Rayleigh wave signal, at least for earlier arrival times. The laser beam source generates a Rayleigh wave that radiates out from the impact point as a circular wavefront. The first signal that the detector receives is actually a relatively low out-of-plane amplitude surface skimming compression (P) wave, which is followed by the Rayleigh wave (R) as shown in figure 4. Dependent on relative position the next arrival may be a reflection of the Rayleigh wave from the side face of the sample or a Rayleigh wave that has been reflected from the slot.

The data is processed by firstly identifying the Rayleigh wave signal and windowing it. This Rayleigh wave waveform is then padded with null or zero points and a magnitude FFT is applied to the data. In order to more clearly show the effect of the pulsed generation laser beam approaching the slot the magnitude FFT amplitude is digitized into a colour scale where blue and red indicate the larger and smaller amplitudes of the signal. These traces are then stacked side by side to form a type of B-scan in which one can see how the amplitude of a particular frequency component changes as the pulsed laser beam approaches an edge.

A B-scan of the FFT data for the laser beam approaching the edge of a sample is shown in figure 5. The position of the maximum has been overlaid on this plot as a black dotted line. Note that as the beam is truncated by the edge of the sample there is a clear increase in the position of the peak in frequency space.

Magnitude FFTs for three different locations of the sample beam are shown in figure 6. Note again that the peak frequency clearly increases as the beam is truncated by the sample edge and can also show an increase in the amplitude of the peak. More importantly one should also note that the higher frequencies beyond 2 MHz show a high level of enhancement. The peak intensity and position are plotted in figure 7, where the left hand axis corresponds to the position of the peak in frequency and the peak amplitude has been normalized to the maximum value measured and has arbitrary units.

A B-scan of the FFT data for the laser beam located in the middle of the sample and being increasingly truncated by blocking more of the beam to create the same shape of beam as obtained when the sample edge truncates the beam is shown in figure 8. Note that this time there is no significant change in the peak frequency as the beam is truncated. As expected there is some relative increase in the level of the high frequency components as the beam will have a physically narrower extent on the sample surface. This arises because the frequency characteristics of the Rayleigh wave are due to a convolution of the spatial and temporal profile of the generation source. Magnitude FFTs for three different locations of the sample beam are shown in figure 9, and the relatively small difference between these FFTs demonstrates that a very different effect must be responsible for the enhancements seen in figures 6 & 7.

A B-scan of the FFT data for the laser beam approaching a machined slot of width 0.7 mm and depth 0.9 mm (+/-5%) is shown in figure 10. Note that as the beam is truncated by the edge of the simulated crack, there is again a clear increase in the position of the peak in frequency space. The low frequency feature that appears around 200 kHz when the laser beam is apparently centred on the very edge of the simulated crack or slot, was found to be due to ultrasonic generation at the bottom of the slot. This was verified by placing an absorbing material in the slot and observing that the low frequency feature in the B-scan disappeared. B-scans of the FFT data for the laser beam approaching two different regions of a real crack (figure 3) are shown in figures 11 and 12. The reflection and boundary conditions for this real, rough and non-planar crack are very different to those for a machined slot or sample edge. Nevertheless, as the beam is truncated by the edge of the crack there is again a clear increase in the position of the peak in frequency space.

4. Discussion & Conclusion

The results we present here are consistent with those taken by previous workers [5,6], where the position of the maximum magnitude frequency was measured. However, it would seem that a more reliable and significant feature to measure would be the relative magnitude of the high frequency components of the laser generated Rayleigh wave beyond the peak in the magnitude FFT when using this scanned laser beam approach. Changes in the position of the maxima are typically in the region of up to a factor of two, but changes in the relative and absolute magnitude of the higher frequency portion of the Rayleigh wave have increased by factors of over two orders of magnitude. A detection system sensitive to these higher frequency enhancements can be used to provide a clear indication of the presence of a crack. There is undoubtedly some enhancement of the Rayleigh wave in the far field that is due to interference between the wave that travels directly to the detector and one that has reflected from an edge. However, one would expect a very deep slot to have a constant reflection coefficient for all frequencies, and the level of enhancement for any particular frequency component would clearly need to be significantly less than a factor of two. Further work will include extending these measurements to plate like samples, where it is anticipated that a similar high frequency enhancement will be observed for Lamb wave type modes.

5. References

1. White
2. Hutchins
3. C. B.Scruby and L. E. Drain, *Laser Ultrasonics: Techniques and applications*, Adam Hilger, Bristol (1990), 76
4. Davies

[5] Yan Z and Nagy PB 2003 *Review of QNDE* vol 22 p 204
[6] Kromine AK, Fomitchov PA, Krishnaswamy S and Achenbach JD, *Mat. Eval.* vol 58 (2) p 173
[7] Boonsang S and Dewhurst RJ 2003 *Appl. Phys. Lett.* vol 82, 19 p 3348
[8] Boonsang S and Dewhurst RJ 2005 *Ultrasonics*
[9] Edwards RS, Dixon S and Jian X, 2004 *J. Phys. D: Applied Physics* vol 37 pp 2291-2297
[10] Edwards RS , Jian X, Fan Y and Dixon S, Applied Phys Lett, 2005

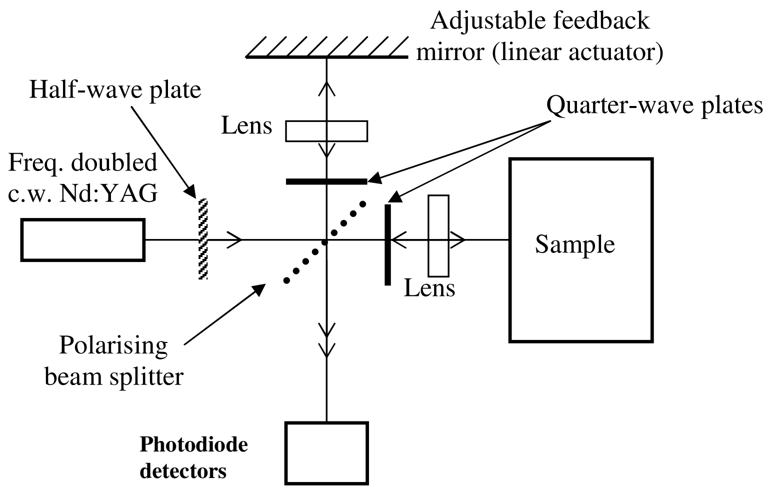
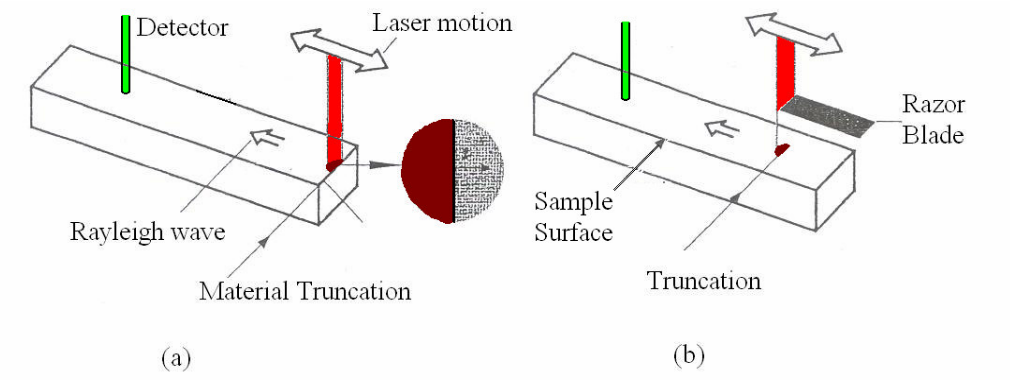

Adjustable feedback
mirror (linear actuator)
Half-wave plate
Lens
Quarter-wave plates
Freq. doubled
c.w. Nd:YAG
Sample
Lens
Polarising
beam splitter
Photodiode
detectors

FIGURE 1



Detector
Laser motion
Rayleigh wave
Material Truncation
(a)
Razor
Blade
Sample
Surface
Truncation
(b)

FIGURE 2

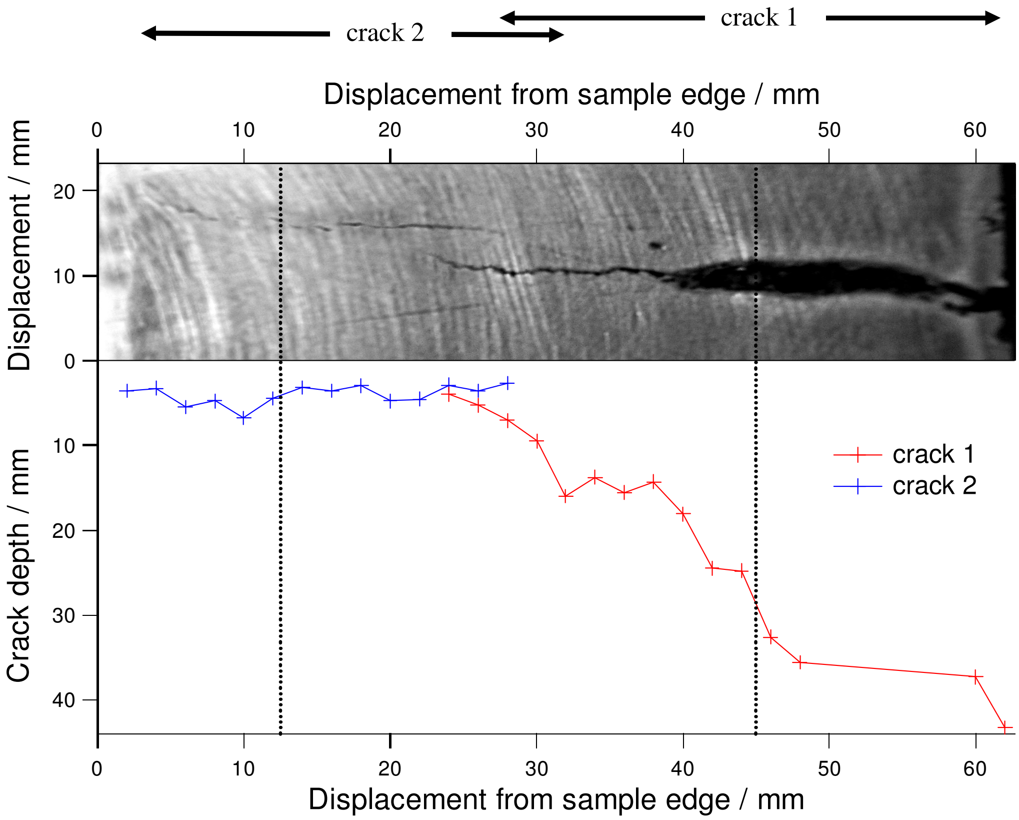


FIGURE 3

The top photograph shows the dimensions of the cracks at locations 1 and 2 along the machined surface of the aluminium billet sample. The depths of these cracks as measured by ACPD are shown directly underneath the photograph of the surface. The dashed lines mark the displacement from the sample's edge where the two sets of ultrasonic readings were taken.

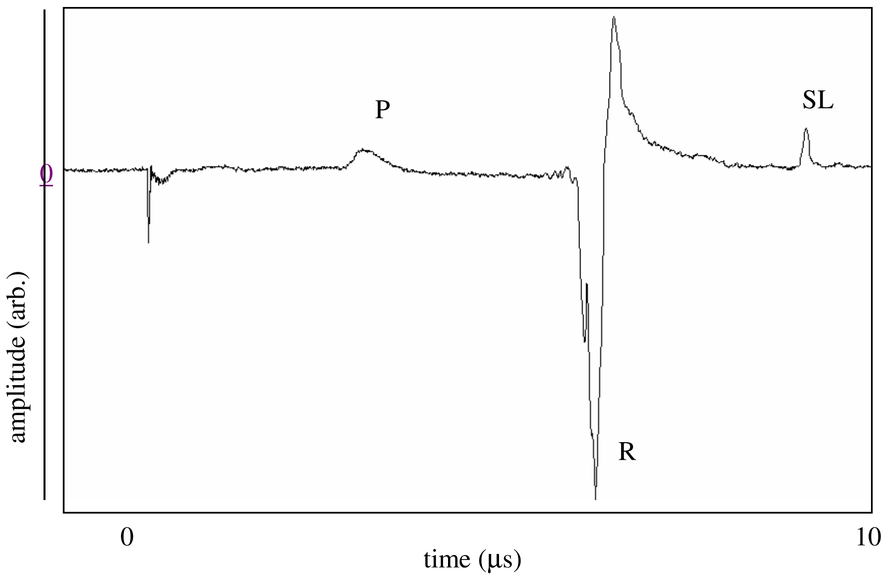


FIGURE 4

The signal received from crack-free sample showing the general profile of the wave form. From this, four distinct features can be observed and are labelled (T) trigger at t = 0s, (P) surface skimming longitudinal wave, (R) Rayleigh wave and (SL) a longitudinal bulk wave that has mode converted and reflected back up to the surface as a shear wave or vice-versa from the bottom face of the sample.

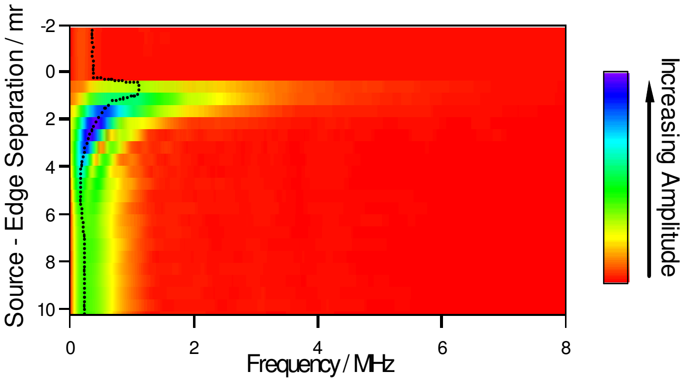


FIGURE 5

Fourier transform image B-scan plot for the Rayleigh waves detected by the interferometer for the generation pulsed laser beam approaching the edge of an aluminium sample. The dotted line shows the position in frequency space of the peak amplitude in the magnitude FFT. Note that the frequency of the maximum increases and the absolute magnitude of the peak also increases and then rapidly falls off as the generating laser beam approaches the edge of the sample.

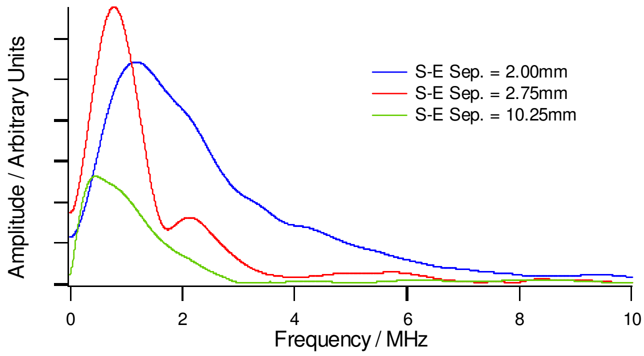


FIGURE 6

Magnitude FFTs for the Rayleigh waves detected by the interferometer as the source approached the edge of the aluminium sample at three distinct distances of the centre of the beam to the edge of the sample. These magnitude FFTs are normalised so that their relative amplitude to each other remains correct. Thus one can clearly see an increase in the absolute magnitude of the frequency content of the detected Rayleigh wave and a relative increase in the high frequency components of the Rayleigh wave signal which is most evident on the trace at a beam distance of 2mm from the edge.

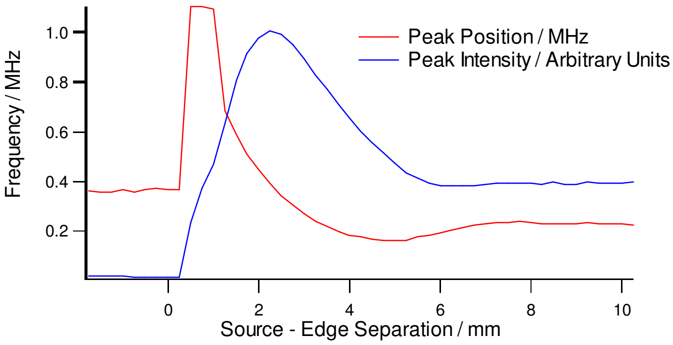


FIGURE 7

The above plot shows how the position in frequency space of the maxiumum peak and the normalised amplitude of this peak in the FFT change with generation laser beam - edge separation.

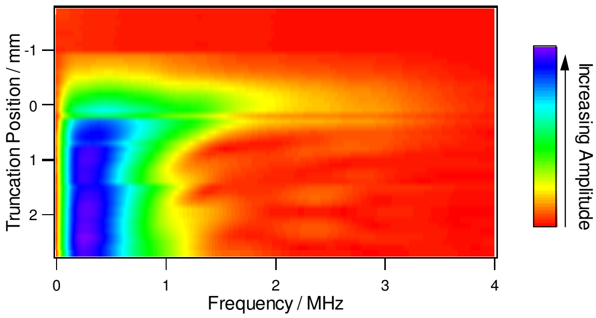


FIGURE 8

Fourier transform image B-scan plot for the Rayleigh waves detected by the interferometer upon truncation of the source as shown in figure 2b. Note that at a truncation position of 0.2mm there is one erroneous point which was due to interferometer instability.

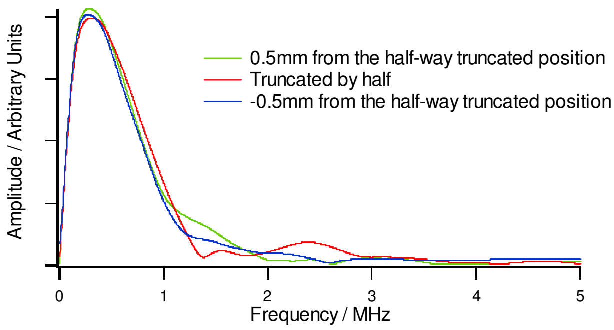


FIGURE 9

Magnitude FFTs for the Rayleigh waves detected by the interferometer upon truncation of the source by ± 0.5mm, and along the midpoint of the beam.. These magnitude FFTs are normalised so that their relative amplitude to each other remains correct. There is no apparent change in the absolute magnitude of the frequency content of the detected Rayleigh wave and no significant change in the frequency content of the Rayleigh wave signal, although one might expect a slight enhancement in the higher frequency components at smaller beam widths.

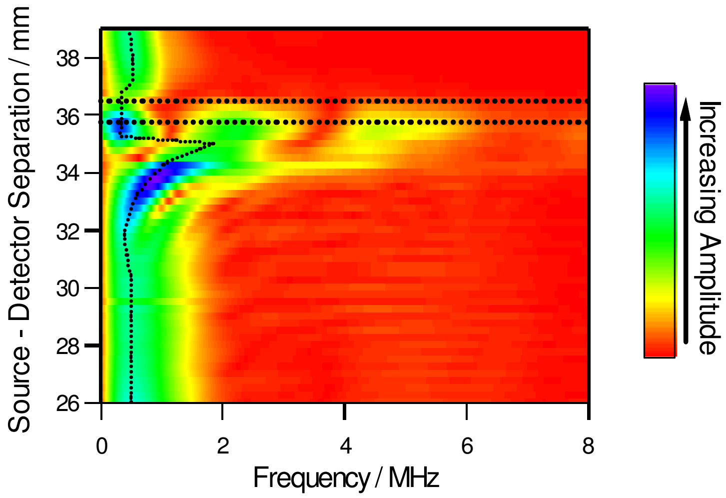


FIGURE 10

Fourier transform image B-scan plot for the Rayleigh waves detected by the interferometer for the generation pulsed laser beam approaching a simulated crack in an aluminium sample. The dotted line that runs in a vertical sense shows the position in frequency space of the peak amplitude in the magnitude FFT. The horizontal lines shown at around 36mm indicate the position of the edges of the machined slot.

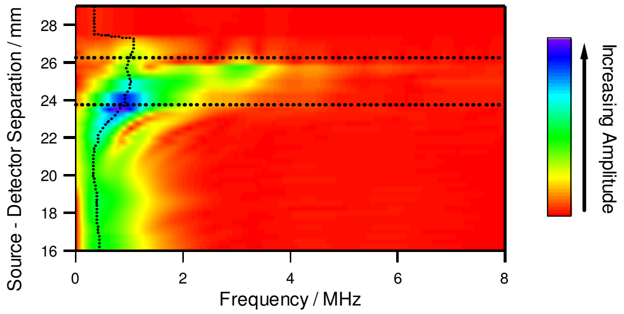


FIGURE 11

Fourier transform image B-scan plot for the Rayleigh waves detected by the interferometer for the generation pulsed laser beam approaching a real crack in an aluminium billet at location 1 as indicated in figure 3. The dotted line that runs in a vertical sense shows the position in frequency space of the peak amplitude in the magnitude FFT. The horizontal lines shown at around 24mm-26mm indicate the position of the edges of the crack.

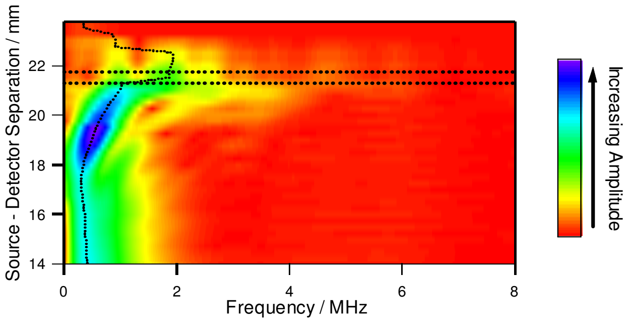


FIGURE 12

Fourier transform image B-scan plot for the Rayleigh waves detected by the interferometer for the generation pulsed laser beam approaching a real crack in an aluminium billet at location 2 as indicated in figure 3. The dotted line that runs in a vertical sense shows the position in frequency space of the peak amplitude in the magnitude FFT. The horizontal lines shown at around 22mm indicate the position of the edges of the crack.