17th World Conference on Nondestructive Testing, 25-28 Oct 2008, Shanghai, China

Performance of UT Creeping Waves in Crack Sizing

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Abstract

Crack sizing is of fundamental importance for achieving safety and reliability in design and validation of mechanical structures, especially considering wide-spread and well-known fatigue design methodologies such as the “Damage Tolerant Approach”. From this point of view, the present paper analyses the so-called “Creeping Waves”, sub-surface longitudinal waves sometimes suggested in the literature as particularly useful in crack sizing.

To this aim, experimental results obtained from a dedicated sample block have been compared with suitable numerical simulations carried out by means of both CIVA$^{nde®}$ v. 9.1 and WAVE2000$^{®}$ Pro v.2.2. From the results, some advantages of the CW technique remain confirmed, but some strong limits of their application to crack sizing could also be defined.

Keywords: ultrasonic testing, creeping waves, crack sizing

1. Introduction

The present paper focuses, from an applicative point of view, onto the problem of crack sizing by means of non-destructive ultrasonic testing (“UT”)[1-3]. Such a problem is of fundamental importance for achieving safety and reliability in design and validation of mechanical structures, especially considering wide-spread and well-known fatigue design methodologies such as the “Damage Tolerant Approach”[4].

In particular, we will here analyse the wave propagation modes from probes inclined beneath the first critical angle, i.e. those probes that, for refracted angles close to 90°, generate the so-called “Creeping Waves” (“CW”)[5-7]. Since sometimes such waves are suggested in the literature as particularly useful in crack sizing, this topic has been here addressed in order to better understand their capabilities and performances in the case of surface breaking defects in both inner diameter (“ID”) and outer diameter (“OD”) configurations.

To this aim, experimental results obtained from a dedicated sample block have been compared with suitable numerical simulations. In particular, the evolution of modern calculation tools is continuously extending also the application fields of traditional and well consolidated NDT techniques such as UT. These new possibilities, nowadays essential to automatically control multiple probes (i.e. phased arrays) and to easily build complex scans (B-, C-, D-, L-, P- or S-) starting from multiple A-Scans, can be also useful in traditional applications giving:

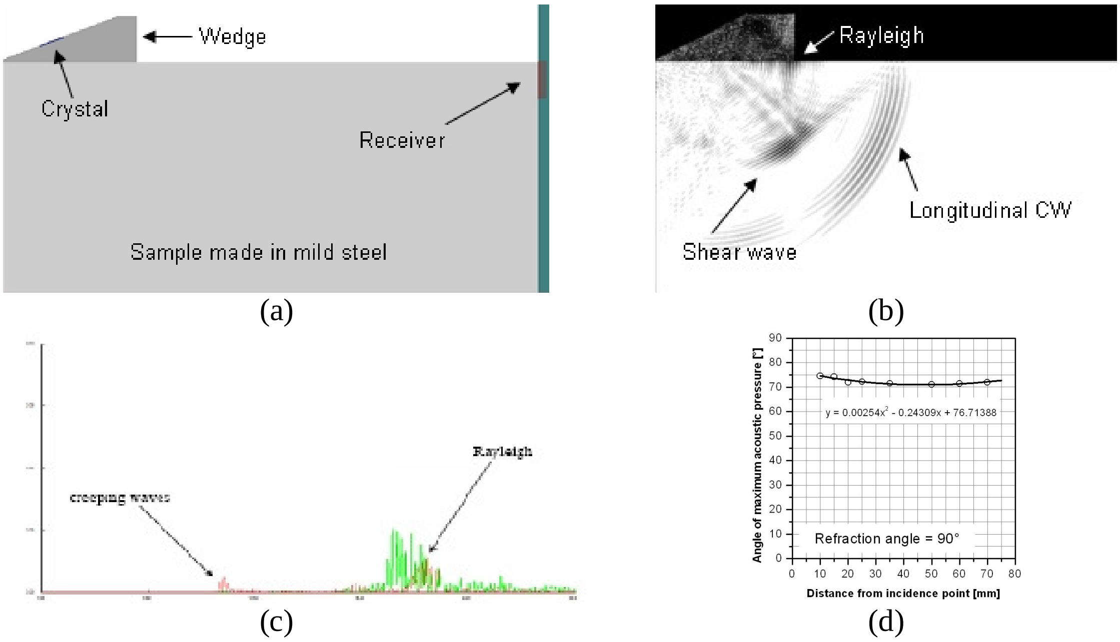
- the availability of flexible and dedicated software packages (such as EFIT[8], CIVA$^{nde®}$[9] and WAVE2000$^{®}$ Pro[10]) for the simulation of the phenomenon;
- the help in understanding and interpreting complex experimental outcomes.

The present paper considered both CIVA$^{nde®}$ v. 9.1 and WAVE2000$^{®}$ Pro v.2.2. The former software calculates the solution of the elasto-dynamic equations by means of a finite difference procedure [10] able to completely compute the wave characteristics at every spatial point and at every time step, but with the disadvantage of a long computational time. For this reasons, it is very well suited for calculating the beam properties but not for defect response [11]. Contrarily, the latter software adopts an approximated analytical solution of the same equations [9] resulting to be faster in calculations, but less precise in the beam characterisation. It will be then used for defect response computations.

From the comparison between the experimental and numerical results some advantages of the CW technique remained confirmed, but some strong limits of their application to crack sizing could also be defined.

2. Beam numerical computation and analysis for an inclined crystal

Firstly, wave propagation from a mono-crystal low inclined probe (refracted longitudinal wave in the range $70° < \alpha_L < 80°$) has been simulated by means of WAVE2000 Pro in order to analyse the generation of the longitudinal CW, of the shear wave and of the surface wave. The crystal was 5 mm long (so to generate a plane wave front) and had a frequency equal to 5 MHz. The refracted angles were simulated modelling a plastic wedge made in plexiglas (V_L=2700 m/s and $_{VT}$=1000 m/s, see Fig. 1a). In particular, the considered angles of incidence were 20°, 25.5°, 26.2° and 30° corresponding to refractions of longitudinal waves in steel equal to ≈40°, 70°, 74° and 80°. The receiver (separated from the transmitter) was located on the right face of the sample so to get clear response from the different surface waves.



(a) (b)

(c) (d)

Figura 1 – Wave propagation from inclined mono-crystal: a) numerical model; b) beams for angle of refraction equal to 74°; c) response at the receiver; d) angle of maximum acoustic pressure as a function of the distance from the incidence point.

The best response from CW was achieved in correspondence of a refraction angle of longitudinal waves equal to 74°. Fig. 1b shows the different beams generated by the crystal in this particular case. Here, it is possible to observe, together with the shear wave, a complex composition of waves (usually indicated as CW) consisting of a wide longitudinal component acting on a large sub-surface zone and of the head wave. Furthermore, it was also possible to observe the presence of the slower Rayleigh wave (as it can be seen also from the A-Scan shown in Fig. 1c). As expected from the literature[5], the intensity of CW diminishes during its travelling through the sample so justifying the low amplitude at the receiver.

Further observations could be drawn. In particular, the analysis of the angle of the maximum acoustic pressure showed that: i) given a refraction angle of longitudinal waves suitable for CW (in the figure is 90°), the angle of the maximum acoustic pressure is significantly lower and depends on the distance from the entering point of the acoustic wave into the sample(Fig. 8d); ii) repeating this analysis and adopting different refraction angles of longitudinal waves between 70° and 90° the maximum acoustic pressure was always at about 74°.

3. Experiments

In order to check the performances of UT CW in sizing ID and OD cracks, a dedicated sample block has been designed and realised. A mild carbon steel characterised by a velocity of longitudinal waves V_L=5920 m/s and of shear waves V_T=3230 m/s was chosen. The prismatic geometry is shown in Fig. 2 where it is also possible to observe the shape of the four artificial defects introduced into the sample by milling.

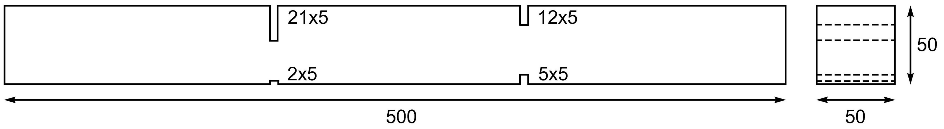


Figure 2 – Sample block for Creeping Waves characterisation.

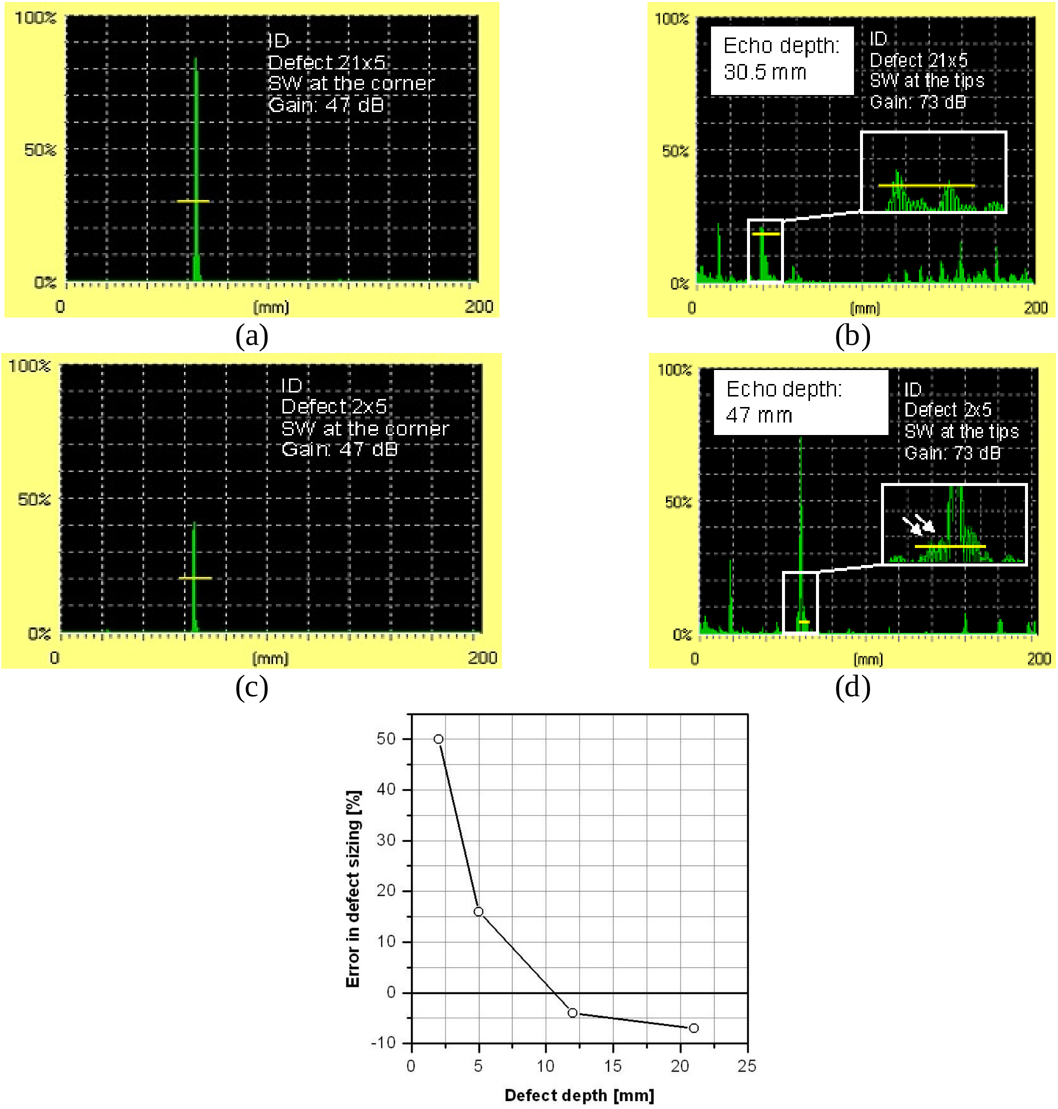
The adopted equipment consisted in a Gilardoni RDG500 UT unit together with a Gilardoni CW double crystal CRW4 probe characterised by a total crystal dimension equal to 8x9 mm and a frequency equal to 4 MHz. The double crystal configuration was chosen in order to annihilate the dead zone due to the transmission. The nominal behaviour of this probe used on steel consists in a shear wave (carrying the most of the ultrasonic energy) and a weaker CW. The calibration of velocities and refracted angles has been carried out onto the V1 specimen and afterwards confirmed onto sample block using one of the extreme corners.

3.1 Experimental results for ID configuration

The A-Scan diagrams obtained from the ID analyses onto the deepest and the less deep defects (21 and 2 mm) are reported in Fig. 3. Particularly, the comparison between the echoes coming the shear wave (refracted at 37°) incident at the corner and at the tips of the considered defects is shown.

Considering the A-Scans acquired for all the defect dimensions and the direct application of the shear wave, it can be concluded, as expected, that the individuation of the corner is handy and unequivocal and that the amplitude of the echoes diminishes progressively with decreasing defect depth.

The direct application of the shear wave to the tips typically showed two echoes, due to the width of the defects (5 mm). Furthermore, considering the case of the deepest defect, these echoes resulted to be clearly separated from the one of the corner, while diminishing the defect depth all the three echoes tended to get closer and closer. It was however possible to estimate the depths of all the defects by means of the time of flight of the wave corresponding to tip closest to the probe and the application of the typical trigonometric calculations automatically carried out by the UT unit. The error trend in defect sizing is shown in Fig. 3e and it can be concluded that it increases decreasing the defect depth.



(a) (b)

(c) (d)

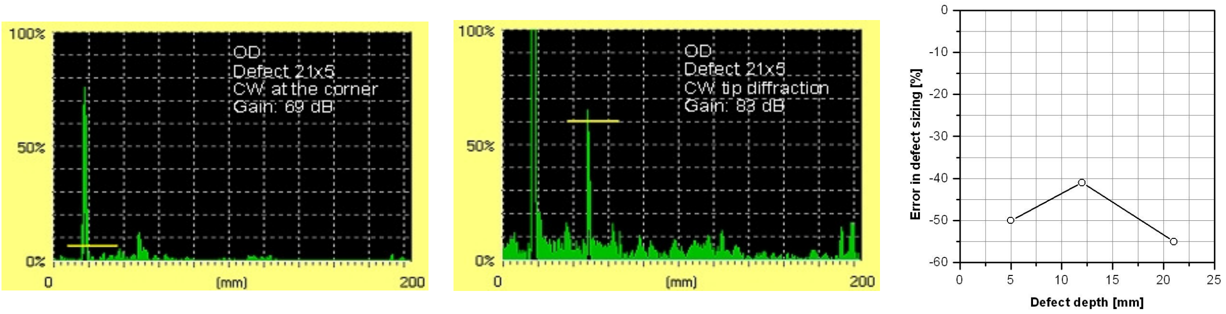
(e)

Figure 3 – Echoes coming from the shear wave incident at the corners and the tips of the 21x5 and 2x5 mm defects.

Applying the CW (refracted at 74°) to the corner of the deepest defect (21 mm) in ID configuration, no useful results could be obtained. This was due to the huge beam opening observed: the amplitude of the response echo remained constant for more than 50 mm of probe displacement neglecting the possibility to reliably and univocally individuate the tip echoes useful for sizing. Similar observations were obtained considering also the other defects. This fact is here ascribed to the unusual height of the sample block (50 mm) in respect to those used in the literature[5-7] for CW description and certainly represents a limit in the application of this kind of waves.

3.2 Experimental results for OD configuration

In the case of OD configuration, only direct longitudinal waves are able to provide a useful information. Fig. 4 shows the A-Scan obtained from the deepest defect (21 mm). In particular, it is possible to observe that, together with the corner echo (Fig. 4a), a tip diffraction echo, useful for defect sizing, is present (Fig. 4b). Considering all the defect depths, it was always possible to observe the corner echo, while for the less deep defect (2 mm) no tip diffraction could be observed. The estimates of the defect depths could then be carried out on the basis of the time of flight and the usual trigonometric calculations automatically carried out by the UT unit. The error trend is shown in Fig. 4c and it can be concluded that it is very high for all the defect depths.



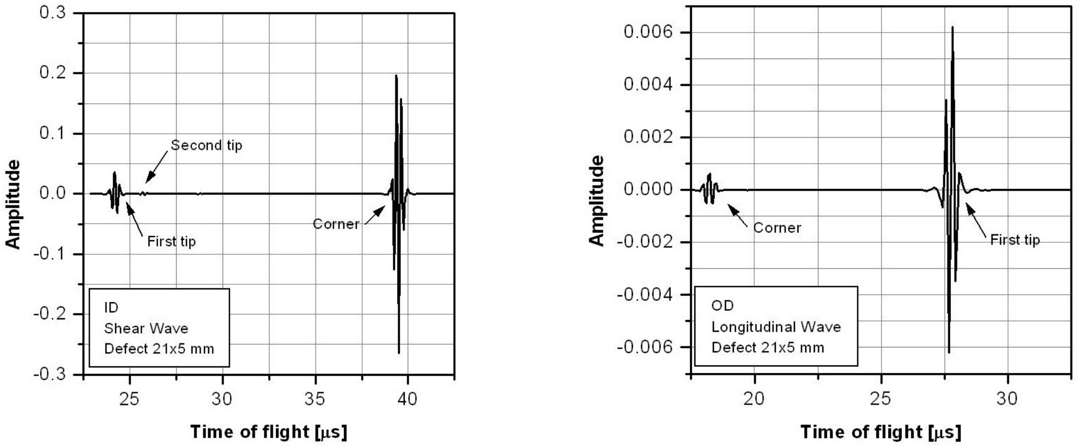
(a) (b) (c)

Figure 4 – Analysis of the OD configuration.

4. Numerical simulations

Preliminary numerical analyses were carried out by means of CIVA$^{\text{nde®}}$ v. 9.1 for the 21x5 mm defect. The numerical models were built to be coincident with the physical one in terms of all the interesting parameters (geometry, materials, acoustic properties, probe, etc.). The interaction of sound waves with corners was analyses adopting Kirchoff's theory[9], while tip diffractions were calculated by the Generalised Theory of Diffraction[9]. Fig. 5 shows the most relevant results obtained considering only the two experimental test configurations giving useful echoes for sizing: shear waves in ID and longitudinal waves in OD.

The comparison between experimental and numerical results showed a good similarity in terms of both amplitudes (significantly lower for longitudinal waves in OD) and time of flight (it was possible to observed the same echoes in nearly the same positions in the A-Scans). It was then possible to estimate the depth of the defect by means of such time of flight and the application of the typical trigonometric calculations. Considering the case of OD, a defect depth equal to 20.22 mm was determined (error equal to -3.8%), while in the case of ID the estimate was equal to 20.84 mm (error equal to -0.7%). It is worth noting that this very interesting results should be generalised considering also the other defect dimensions.



(a) (b)

Figure 5 – Numerical simulations of ID and OD configurations for 21x5 mm defect.

5. Concluding remarks

The conclusions of the present research work can be so summarised:

- the possibility to operate with the assistance of numerical simulations in presence of complex beams, such as those originated by CW probes, yields advantages in the interpretation of A-Scans. In particular, for the thicknesses considered in this work, the role of some wave components (reflected CW and head waves sometimes proposed in the literature for a reliable sizing) could be re-analyses and re-evaluated as not so much relevant;
- the direct shear and longitudinal waves of the CW beam are the most important. In particular, it was evidenced the possibility to estimate defect depths in ID configuration, with good accuracy till depths equal to 0.1 of the thickness, by the direct shear component. Contrarily, using the direct longitudinal component in OD configuration, the depths resulted to be underestimated of about 50%;
- the preliminary defect response numerical simulations seem to be a promising tool for inspecting and sizing defects.

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