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

An Analysis of UT Echoes Coming from Fatigue Cracks and Artificial Defects on Railway Axles

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Abstract

Non Destructive Testing applied to railway axles is performed both in production and in maintenance. During production, NDT is carried out at different stages adopting different techniques, while during maintenance (in-service inspection) only ultrasonic testing is usually carried out.

The present paper is focused on some aspects of calibration related to the in-service inspection of railway axles by means of ultrasonic NDT. In particular, applied standards request to calibrate sensitivity on suitable reference blocks provided with notches. In order to investigate the performance of these notches in respect to real cracks, the echoes coming from fatigue cracks generated onto hollow axles made in A4T steel by means of a dedicated test bench have been compared with those detected from suitable reference blocks. The results suggest some clues for designing effective sample blocks for railway axles.

Keywords: ultrasonic testing, railway axles, fatigue cracks, notches, sample blocks

1. Introduction

Railway axles are designed to have an infinite lifetime[1]. Even if this is accepted as adequate, the fact remains that occasional failures have been and are observed in service[2]. Such failures always occur as fatigue crack propagations whose nucleation can be due to different causes[3]. In the case of railway axles, the presence of wide-spread corrosion or the possible damage due to the ballast impacts may constitute such causes.

This kind of failures is usually tackled by employing the “Damage Tolerance” methodology, whose philosophy consists[4-6] in determining the most opportune inspection interval given the “Probability of Detection” (POD) of the adopted Non-Destructive Testing (NDT) technique or, alternatively, in defining the needed NDT specifications given a programmed inspection interval.

Concerning NDT applied to railway axles, it is performed both in production, where it is necessary to certify to the buyer the initial axle condition, and in maintenance, in order to guarantee adequate reliability and safety during service. During production, NDT is carried out at different stages adopting different techniques (usually, the last one is ultrasonic testing[7] “UT”), while during maintenance (in-service inspection) only ultrasonic testing is usually carried out.

The present paper is focused on some aspects of calibration related to the in-service inspection of railway axles by means of ultrasonic NDT. In particular, applied standards request to calibrate sensitivity on suitable reference blocks provided with notches, and is obviously important to state if these reflectors can “describe” the echoes arising from real defects such as fatigue cracks. In order to investigate this aspect, the echoes coming from fatigue cracks generated onto hollow axles made in A4T steel by means of a dedicated test bench have been compared with those detected from suitable reference blocks provided with notches or side drilled holes (SDH) produced from a twin axle. This analysis has also been extended considering semi-circular concave and convex defects obtained by EDM. The results suggest some clues for designing effective sample blocks for railway axles.

2. UT response of fatigue cracks in hollow railway axles

Fatigue cracks were generated on full-scale hollow railway axles in the frame of the WIDEM European Project[8] with the aim to derive crack propagation curves under both constant and variable amplitude loading for all the typical steels[9] used in axles production. Some interesting results of this research are summarised in[10-13]. During fatigue tests, extensive UT inspections were also carried out in order to characterise and record the response echoes coming from a fatigue crack increasing its dimensions due to the applied cyclic loads.

2.1. Fatigue crack growth tests on full-scale axles

The considered material is an A4T medium strength steel typically used in the production of European railway axles[9]. Fatigue tests were carried out by means of the dedicated bench shown in Fig. 1a available at the labs of the Dept. of Mechanical Engineering of Politecnico di Milano. In particular, the bench can be assimilated to a three point bending equipment where the axle is statically loaded and then subjected to rotating bending conditions by an electrical engine.

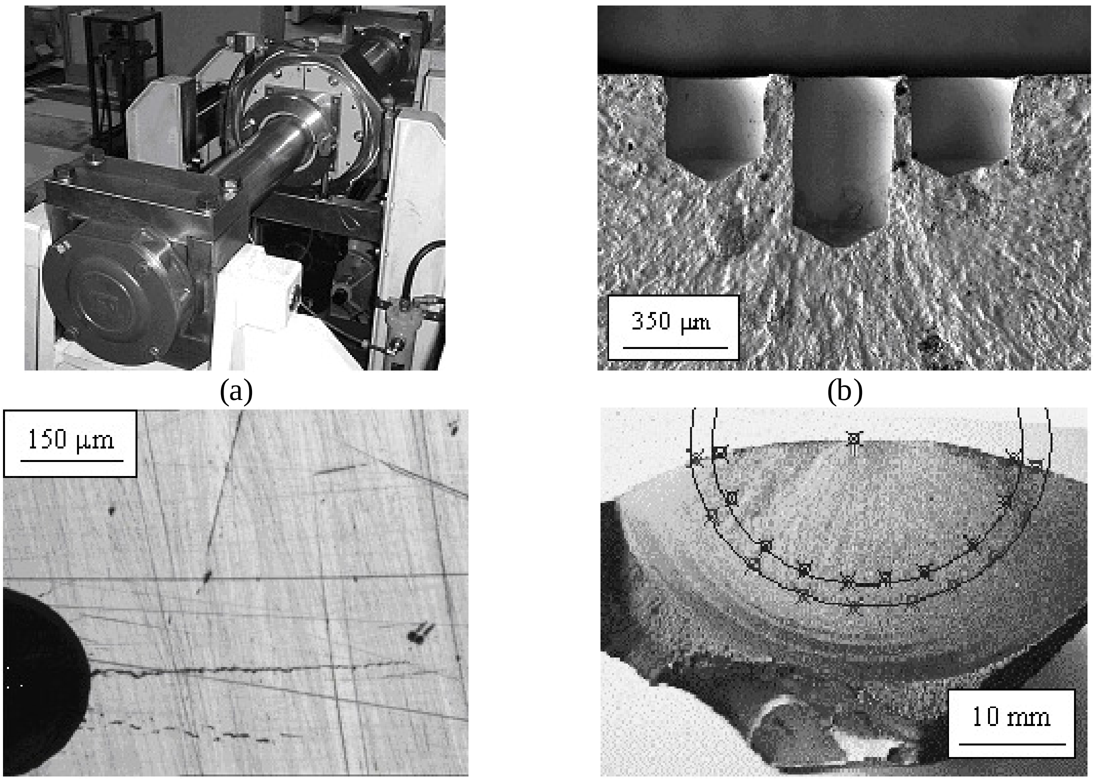


Figure 1 – Details of full-scale experiments on railway axles: a) the test rig; b) micro-holes on a full-scale specimen; c) an example of the axle surface during a propagation test; d) analysis of the crack shape evolution.

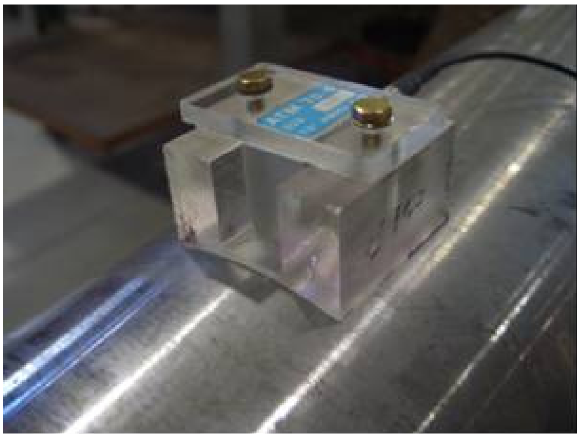
A transverse fatigue crack was nucleated on the body of the two tested axles by introducing a set of artificial holes obtained by micro-drilling (Fig. 1b). The measurement of surface length of the crack was monitored by means of a camera and an image analyser (Fig. 1c). The shape and depth of the crack was then derived by means of the following expression[14]:

$$a = r\left(1+\tan\vartheta-\sec\vartheta\right) \qquad (1)$$

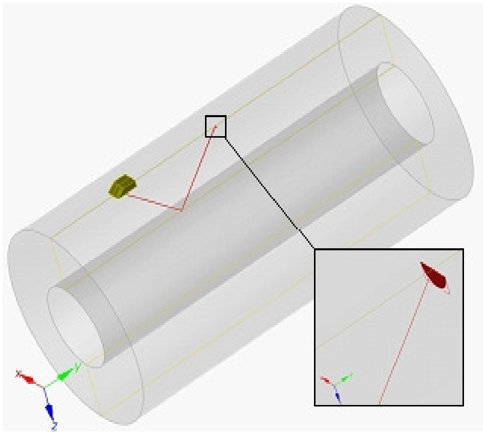
where *a* is the crack depth, *r* is the radius of the body and θ=c/r is the ratio between the surface length *c* and the radius. Finally (Fig. 1d), the evolution of crack shape was checked and validated *a posteriori* by analysing fracture surfaces.

2.2. UT measurements of developing fatigue cracks

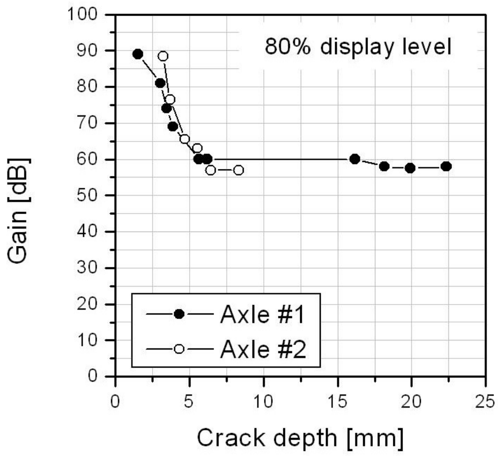
The equipment used for UT measurements of developing fatigue cracks consisted in a Gilardoni RDG500 UT unit and an ATM45/4 probe characterised by a 8x9 mm crystal, 4 MHz and a 45° refracted wave. Coupling between the probe and the axles made in steel (longitudinal wave speed V_L=5920 m/s and shear wave speed V_T=3230 m/s) was guaranteed by grease and a special designed wedge made in plexiglas (V_L=2700 m/s and V_T=1100 m/s) and characterised by a convex contact surface (Fig. 2a). A schematic of the "2nd leg" inspection carried out at different crack depths is shown in Fig. 2b.



(a)



(b)



(c)

Figure 2 – UT measurements of a developing fatigue crack: a) wedge in plexiglas; b) schematic of the "2nd leg" inspection; c) resulting dB-depth curves.

Fig. 2c shows the results obtained on the two considered axles in terms of gain (to reach 80% display level) vs. crack depth (i.e. the crack dimension more relevant for damage tolerance considerations and lifetime calculations). As it can be seen, measurements carried out onto different axles yield very similar results so suggesting that the typical roughness of real surface cracks is not so different. In particular: i) it exists a crack depth (about 6 mm) above which the echoes seem to be saturated since the crack becomes a big reflector; ii) below this value, the relationship between gain and crack depth seems to be linear; iii) such saturation level is the same for both the axles. These info can be very useful for designing axles against fatigue, but more axles should be measured in order to draw some more general conclusions.

3. UT response of different calibration notches

In order to check the performances of different types of notches in representing the echo response of real fatigue cracks, two sample blocks were prepared. These blocks were cut from axles of the same geometry and made in the same material of those fatigue tested on the bench.

On the first block two different types of notches, obtained considering the application of traditional machining and representing typical calibration geometries, were considered: i) saw-cuts (Fig. 3a and b) having depth equal to 0.5, 1, 2 and 3 mm and width equal to 2 mm; ii) drilled holes (Fig. 3a and b) having diameter equal to 3, 4 and 6 mm.

On the second block, other two different geometries of notches, this time representing the shape of typical cracks found on axles, were considered: i) concave defects (Fig. 3c, this shape is typical of cracks due to fretting fatigue at the press-fit of wheels and brakes) obtained by EDM having depth equal to 0.5, 1, 2 and 3 mm and width 0.1 mm; ii) convex defects (Fig. 3d, this shape is typical of cracks found at the body and due to classical fatigue) obtained by EDM having radius equal to 1, 2, 4 and 8 mm and width 0.1 mm.

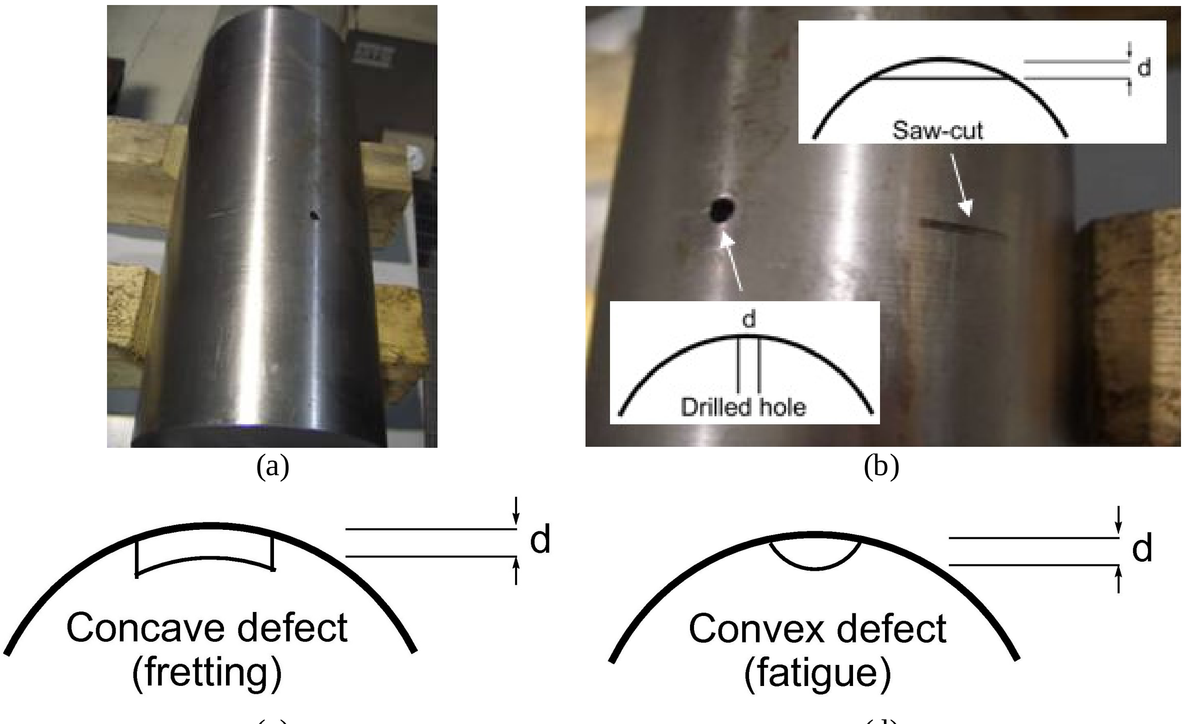


Figure 3 – Notches considered for the analysis: a) sample block with saw-cuts and drilled holes; b) detail of the same block; c) concave EDM notches; d) convex EDM notches.

All the notches were inspected by the same "2nd leg" methodology used onto full-scale axles (Fig. 2b) and the dB level for the 80% display level was recorded. Fig 4a shows the comparison of the results obtained from axles and notches. Some interesting conclusions can be drawn: i) the EDM convex notch seems to yield results very similar and comparable to real fatigue cracks; b) EDM concave notches and saw-cuts behave in very similar way and are more sensible (i.e. less dBs are needed at the same depth) than real fatigue cracks; c) drilled holes present a behaviour completely different from the other notches since also the slope is significantly different.

The choice to plot the results against crack or notch depth is due to the fundamental importance which this dimension holds in the railway field as the most relevant cause of fatigue failures. Also POD curves for railway axles are usually plotted in terms of crack depth. Fig. 4b shows an alternative approach: the response of real fatigue cracks and notches is plotted against the reflecting area. As it can be seen all the resulting curves collapse on a single one, so suggesting the possibility to design sample blocks in a more straightforward way without any influence of the notches shape.

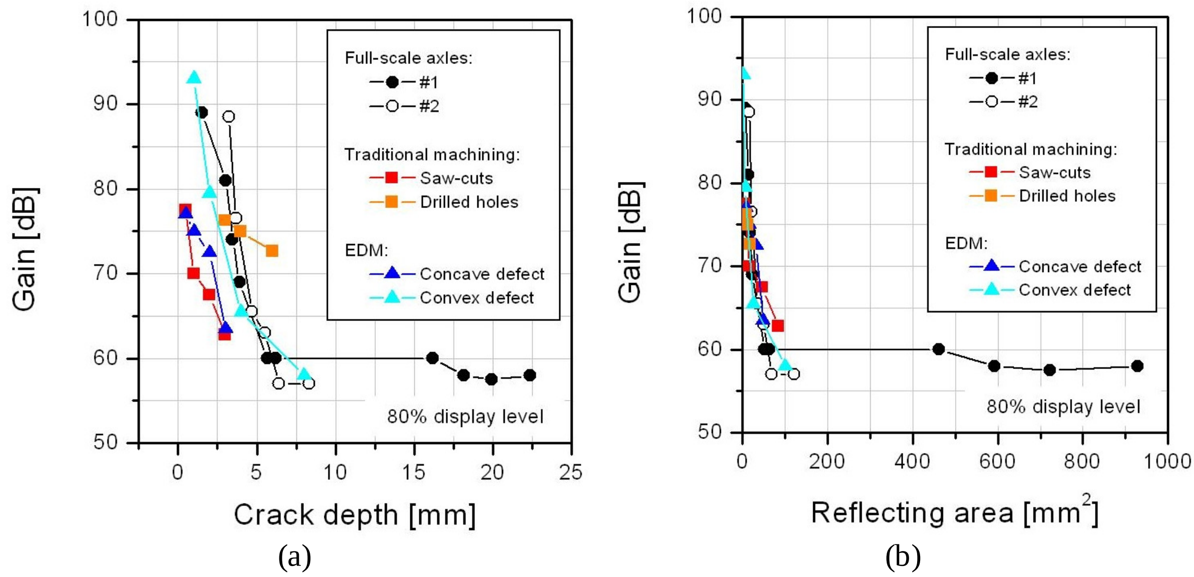


Figure 4 – Cracks and notches responses in terms of crack depth (a) and reflecting area (b).

5. Concluding remarks

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

- UT measurements carried out on two different railway axles have shown a repeatable response behaviour of propagating fatigue cracks obtained from rotating bending conditions. In particular, such behaviour showed a linear trend between gain and crack depth until a certain crack depth value followed by a constant saturated level;
- the comparison between responses coming from real fatigue cracks and artificial notches showed that the most similar results can be obtained adopting EDM convex notches, while the other considered geometries are not so well suited for designing sample blocks;
- considering the relationship between gain and reflecting area permits to loose the influence of the notch or crack shape on UT responses.

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