Safe Life and Damage Tolerance Concepts of Railway Axles

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Abstract

On July 9, 2008 a high speed train derailed in Cologne main station, Germany at a low speed because an axle was broken. Fortunately, the derailment happened at a low speed so that nobody was injured. The reason for the broken axle was investigated and it turned out that most likely large inclusions located shortly underneath the surface in a T-transition were the origin of the final crack. Basing on that result, a systematic investigation on existing safety assessments of railway axles was performed. This results in an analysis of the production process of axles and in a critical review of existing of existing assessments. Improvements and future developments are outlined.

Keywords railway axles, derailment, service loading fatigue, inclusions, safety assessment

1. Introduction

A hollow axle of a German high speed train broke on 9 July 2008. Fortunately, the train derailed at low speed after change of running direction when crossing a Rhein bridge in Cologne. The failure occurred when the axle was in service 3.09 million kilometers which refers to 10^9 loading cycles. A more detailed report on the failure investigation is provided in [1]. Because the fracture surfaces were heavily destroyed no definite answer could be given to the question of the initiation site. However, non-metallic inclusions of unacceptable size were found nearby the crack origin. The investigators assume a similar inclusion to be responsible for fatigue crack initiation. Basing on this event, a critical review of state-of-the-art design is presented and the further development is basically revealed.

2. Safe Life and damage Tolerance Concepts: State-of-the-Art and Necessity of Improvements

2.1. Overview

The design and operation of railway axles are based on a two-stage safety concept comprising “safe life” and “damage tolerance” methods. Figure 1 schematically illustrates the state-of-the-art concept and extends it by further options which are presently under development or offer additional potential in the future. The figure is taken from an extended discussion on axle safe design which the authors of this paper and others presented in [2]. This shall not be repeated here in detail. Instead a number of selected issues shall be briefly discussed which, as the authors think, promise potential for further increasing the safety level of axles. These are:

(a) Limiting the projected lifetime as a consequence of features such as damage accumulation, potential very high cycle (VHCF) effects and corrosion. A specific concept is the “one-million miles axle” based on a worst case scenario including fatigue crack propagation;

(b) Taking into account the most common reasons for fatigue crack initiation, corrosion pits, damage due to flying ballast impacts and non-metallic inclusions in the material by advanced design rules, and;

(c) Improving the reliability of non-destructive testing (NDT) with respect to its probability of detection (PoD)-crack size characteristics.

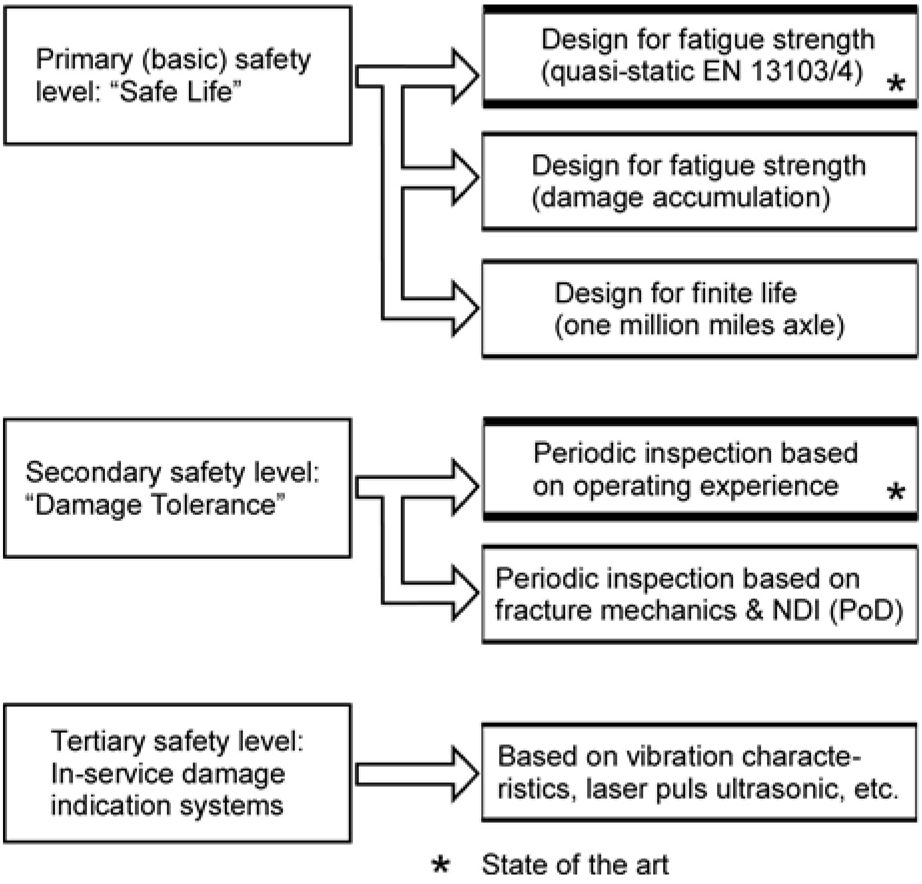

Figure 1: Components of a safety assessment of railway axles. All options not marked with a * refer to present or future development.

2.2 Limiting the Projected Lifetime?

Figure 2 gives a brief overview on the various options of fatigue strength and fatigue life design of railway axles.

Figure 2a: The approach followed by the present standards (in Europe EN 13103 [3] for trailing and EN 13104 [4] for driving axles) implicitly assumes a constant amplitude loading with the stress amplitude being conservatively estimated as superimposed maximum loading, i.e., different to reality all loads are assumed to act simultaneously. Unknowns, e.g., a potential reduction of the admissible stresses below the fatigue limit due to the very high cycle fatigue (VHCF) phenomenon (for a service time of 10^8 and more loading cycles) or other features are covered by ample safety margins. The maximum permissible stress in the axle is given by the fatigue limit of the material under consideration (EA1N carbon steel = C35, normalized and EA4T alloy steel = 25CrMo4, quenched and tempered) but it additionally depends on the type of axle (solid or hollow) and the axle section (away from or beneath the press fits, etc.). If the axle is exposed to corrosion some reduction of the permissible stress is required but no detailed rule is given in the standards cited above. However, EN 13261 ([5], Tab. 11), in such a case, specifies a value of 60% of the maximum allowable stresses of EN 13103 and EN 13104. For all other cases, where the axles are not exposed to environmental corrosion, it is assumed that no reduction of the fatigue limit due to some kind of damage occurs during service which implicitly means that protection measures have to be taken which exclude such damage or the damage has to be removed soon after it appears in service.

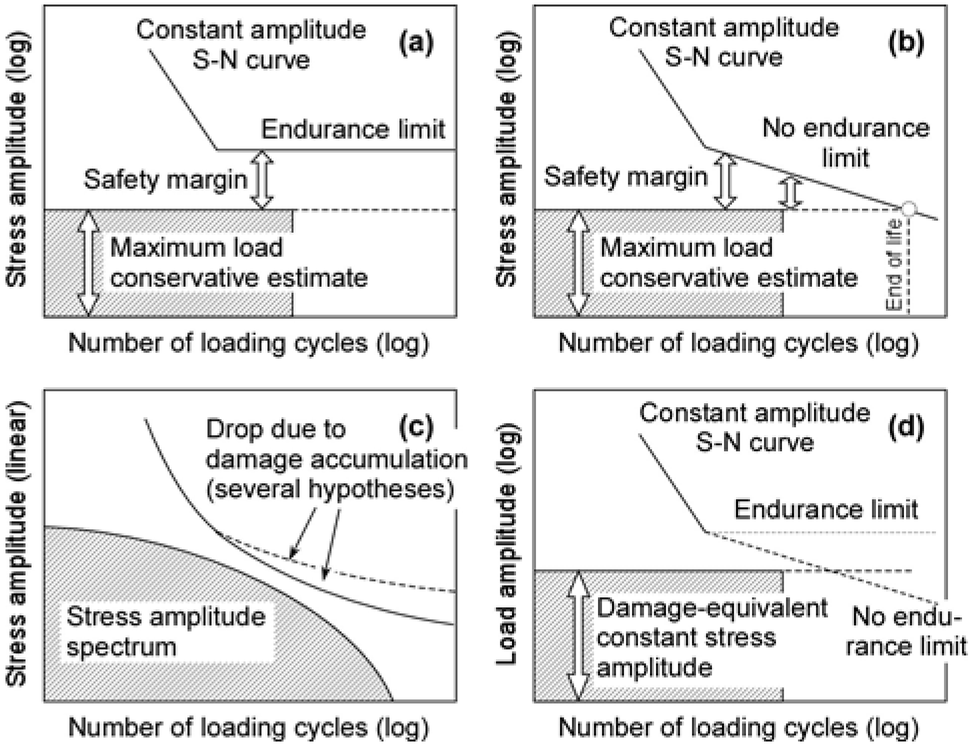

Figure 2: Potential concepts of fatigue strength analysis.

Figure 2b: As an alternative to the standard method, VHCF could be taken into account by replacing the fatigue limit by a sloping curve beyond the knee-point. Sonsino [6], based on the re-analysis of a large body of fatigue data proposes a modified fatigue life diagram with a decrease of 5% per decade loading cycles in logarithmic scales for steels. Note, however, that the author explicitly excludes from this rule cases where environmental or fretting corrosion is present (such as in axle press fits).

Figure 2c: A design stress spectrum, i.e., a histogram of the frequency of occurrence of different stress magnitudes, is compared with an S-N curve corrected for damage accumulation. This is obtained by a modified Palmgren-Miner rule according to one of several proposals. Note that, different to Figure 2b, the drop of the S-N curve beyond the knee-point is not caused by the VHCF effect but by damage accumulation. A special feature of variable amplitude loading is that loading cycles with stress amplitudes below the fatigue limit may contribute to fatigue damage when there is a mixture of stress amplitudes above and below this level. This is the case because the high stress amplitudes (above the fatigue limit), due to their damaging effect, cause subsequent lowering of the fatigue limit. Depending on the applied stress spectrum the drop in the S-N curve can be more pronounced than those caused by the VHCF effect because of which one could think about cases where it “covers” the latter in a conservative way.

Figure 2d: A damage accumulation analysis is used to obtain a damage-equivalent constant stress amplitude. This is then used like the maximum stress amplitude of Figure 2a but it actually describes variable amplitude loading. The fatigue strength analysis is performed as in Figure 2a or b

against the constant amplitude S-N curve.
The approaches according to Figures 2c and 2d have been proposed in some recently finished research projects on the safety of railway axles ([7], see also [8], [9]). Note that they require real stress amplitude spectra, e.g., from test runs. Although a number of those has been determined over the last decade (e.g. [7], [8], [9]) there is still need for generally accepted reference loading spectra for the various kinds of railway transportation (high speed, freight etc.) and different track quality (modern high speed and traditional track, significantly curved track, track with switches and crossovers, e.g., at stations, etc.). As long as generally accepted information of that kind is not available the damage accumulation based analyses are hardly an alternative to the fatigue limit based standards discussed at the beginning of this section. But, although it can be argued that these "cover" the damage accumulation effect by its ample safety margins, damage accumulation based approaches, in the opinion of the authors of this paper, point into the right direction for future development. Note, however, that they have to include further effects such as damage due to corrosion and ballast impacts during service (see Section 2.3).

2.3 In-service effects on Fatigue Life

Corrosion pits and notches due to flying ballast impacts develop during service which means that the fatigue strength is not a material and/or component property established once for all but can reduce during the lifetime of the component. Failures of axles in freight wagons are frequently caused by corrosion pits at the axle shafts. Besides the corrosion effect itself corrosion pits act as stress raisers.

With respect to flying ballast impacts a systematic screening has shown that the latter is a rather typical issue of high-speed traffic [10]. Whereas only on 5% of other axles showed impact notches 30% of the high-speed axles were affected. The reason for flying ballast is aerodynamic effects with respect to the high speed which make impact from debris more likely. On 9 February 2006 a passenger train derailed in New South Wales, Australia after an axle completely fractured at the radius relief area between the gear and wheel seats [11]. Whilst the crack initiation site could not be identified on this specific axle, twelve similar axles were found with fatigue cracks at identical axle sections. Five of these were closer examined. In each case the crack originated from small surface indentations with depths between 0.1 and 0.9 mm which, by means of chemical analyses of crystalline material embedded in the indentations, could be identified as the result of ballast impacts.

The average depth of the detected impact notches was 0.8 mm, i.e., significantly larger than that of typical corrosion pits [10]. The 95% upper bound depth of about 2 mm was close to earlier assumptions in [12]. Of course a ballast-induced notch is not a crack although there is some chance of sharp edges from which small fatigue cracks could easily develop. A systematic investigation on the typical and most dangerous impact notch geometry and its effect on the local stress concentration and small crack initiation and on the residual stress field generated by the impact is due in the future. Note, that impact damage also promotes stress corrosion crack initiation by local damage of the coating and the introduction of complex residual stresses.

2.4 Potential effect of on-metallic inclusions

Non-metallic inclusions originate from the steel manufacturing process such as illustrated in Figure 3. When, e.g., aluminium is added for deoxidisation, oxidic inclusions such as Al_2O_3 are formed, silicon oxides can be introduced form mould powder etc. Besides oxides there may also be sulfides such as MnS or other particles. The size of the inclusions is in the order of ten µm up to mm.

During forging or rolling the inclusions can be crushed, this way forming clusters or inclusion “chains”. An example is shown in Figure 4 which belongs to the failure investigation on the German high speed train mentioned in the beginning of Section 1 (for details see [1]).

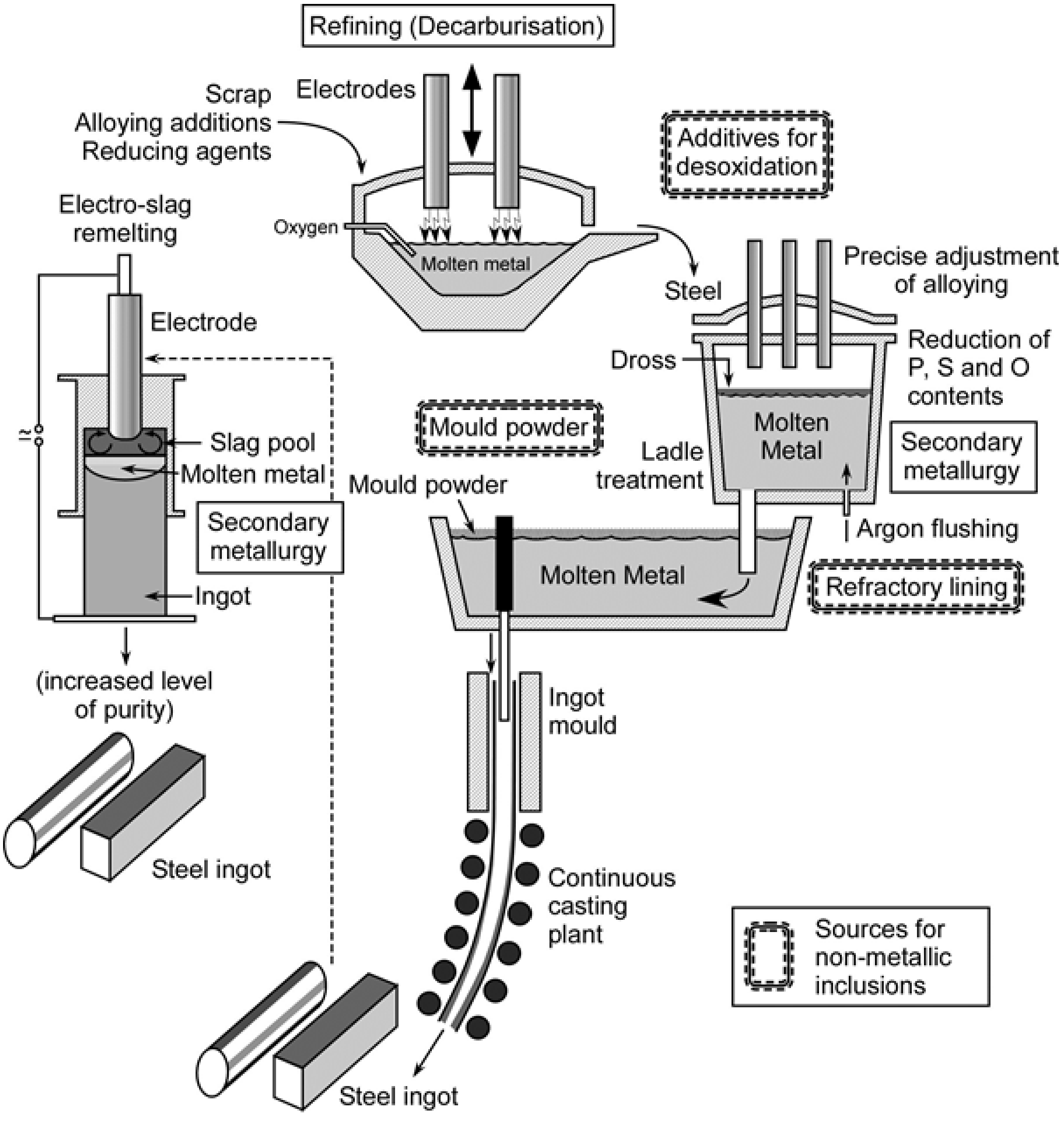

Figure 3: Sources for non-metallic inclusions during steel manufacturing.

In general, the lifetime of a crack consists in the initiation stage, where cracks are formed due to irreversible plastic deformation along slip bands, short crack propagation (up to a size of roughly 0.5 to 1 mm in engineering materials), long crack propagation (beyond that crack size) and final fracture. The effect of the non-metallic inclusions consists in a substantial shortening of the crack initiation stage leaving short crack propagation as the stage which controls lifetime. Inclusions differ from the matrix in several aspects: they have different elastic constants (stiffness mismatch), different strength and hardness properties (strength mismatch) and different thermal contraction coefficients (thermal contraction mismatch). Frequently, they show a square-edged shape which, in combination with the difference in hardness between particle and matrix causes stress concentrations at the corners and, due to this, local damage in the adjacent matrix material when the component is subjected to applied loading. An example of the effect of inclusions on the lifetime of carbon steel is presented in Figure 5. Note that it is the defect area normal to the loading direction (which, in axles, is much smaller than that in axial direction) that correlates with the fatigue life (and strength).

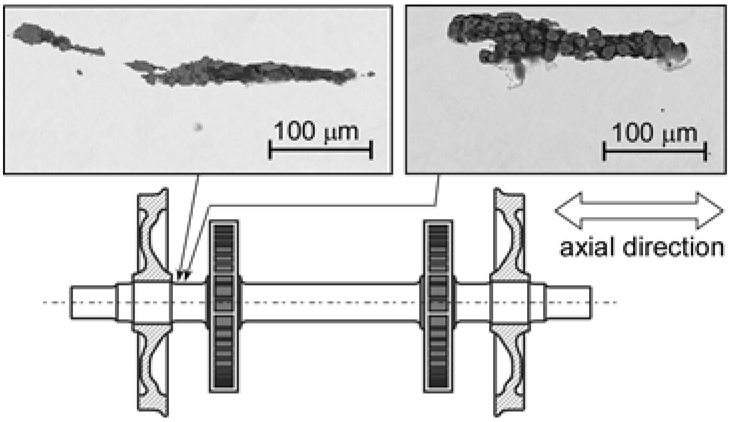

Figure 4: Nearly axially orientated non-metallic inclusions found in sections adjacent to the fracture surface very close to the crack origin in the broken axle of the German high speed train mentioned in Section 1 (according to [1]), axle type shown schematically.

In order to prevent large inclusions EN 13261 refers to the materials standard ISO 4967 which gives rules for maximum tolerable inclusion dimensions between 76 and 436 µm depending on the inclusion type (sulphide, aluminate and silicate globular oxide) and the category of steel quality (1 or 2). The absence of larger particles has to be proven by metallography at a limited (approximately 200 mm2) polished area parallel to the axial direction half-way between surface and centre in solid and between outer and inner surface in hollow axles at the section of the largest diameter (Figure 6). No guidance is given on the number of axles of a batch to be investigated. This is the more problematic as large inclusions at critical positions – which could act as fatigue crack initiation sites – have to be assumed to be very rare in reality; a statement which is obvious at the background of the relative small number of axle failures in reality. It is certainly not consistent to look for seldom events by a very limited sample. In addition, one could ask whether it is meaningful to look for large inclusions in the middle of the wall and not at the potentially critical locations in the axles such as the T notch or other geometric transitions or the press seats.

On one hand microscopic defects in the order of some ten or hundred micrometers which have to be detected by means of metallography based on a very limited sample, on the other hand the exclusion of much larger macroscopic defects in the order of millimetres by NDT screening of the whole component – and in between a gap, at least if one thinks about standard NDT methods.

What could be an alternative to these inconsistent requirements? In [2] the authors proposed to perform a more thorough investigation on a number of carefully chosen axles (e.g. by ultrasonic immersion technique or destructive methods) and to use the result for statistically specifying an upper-bound inclusion size which, by state-of-the-art quality control, will be found with high probability. Smaller defects which could escape its detection have then to be taken as existent even if the NDT record is “negative”. This limit defect size could then be used, in a worst case scenario, for the specification of a general reduction factor for the fatigue strength. The NDT technique has to be developed such that defect sizes larger than the limit are very probably be found by quality control measures which have to be exclusively based on a methodology allowing the complete screening of the mechanically critical positions of the axles.

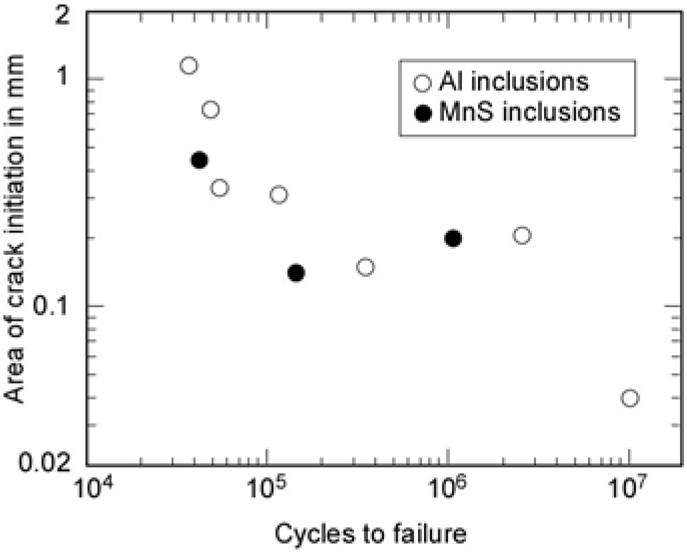

Figure 5: Effect of the defect area normal to the loading direction on the fatigue life of a hot rolled A537 carbon steel at a maximum stress of 260 MPa (according to Ma [13]).

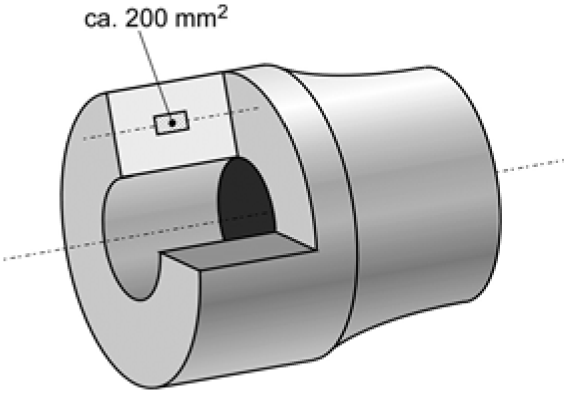

Figure 6: Location for the metallographic proof of the absence of inclusions larger than permissible with respect to ISO 4967 and EN 13261 (not in scale).

2.5 Reliability Issues of Non-destructive Testing (NDT)

A science-based inspection regime consists in two major elements: facture mechanics based residual lifetime and the probability of detecting (PoD) a crack of a certain size. Combining both types of information, the probability to find a potential crack in due time, i.e., before it becomes critical can be determined as a function of the inspection interval. No discussion on the fracture mechanics part shall be provided here, see, however the detailed discussions of the authors in [2].

Non-destructive testing is usually performed by ultrasonic (US) (shorter interval) and magnetic particle inspection (MPI) (larger interval). It seems likely, that MPI is the most cost-effective NDT technique for a bare axle (the wheels, bearings, brake discs etc. are removed) during its overhaul. Note, however, that there might be the risk of scratching during dismantling. Unfortunately fatigue cracks may be initiated and grow to failure in less time than needed to wear out the wheels. Therefore, costly and disruptive axle inspections in between overhauls have to be carried out which are usually based on US as a compromise between a limited intrusiveness, which disrupts train service, and a lower PoD compared to MPI.

With respect to ultrasonic inspection it has to be distinguished between:

- far end scan (the axle is inspected from the end of the axle to mid-span or further)
  near end scan (the axle is inspected from the end of the axle to an adjacent seat)
  and high angle scan (the axle is inspected from the axle body across the seat),
- inspection from the outer surface in solid axles and from the bore in hollow axles,
- manual or automated testing, and
- standard or sophisticated test and analysis methods such as phase array, synthetic aperture focusing technique (SAFT) etc.

PoD-crack size curves for railway axles have first been determined by Benyon and Watson [14] in 2001 (see also the subsequent discussion in [15]). The by now most up-to-date and most systematic study of PoD on railway axles has been performed in the European WIDEM project [16]. In Figure 7 some of these data are shown along with the data of [14]. Note that none of the curves can be generalised because they belong to specific test setups.

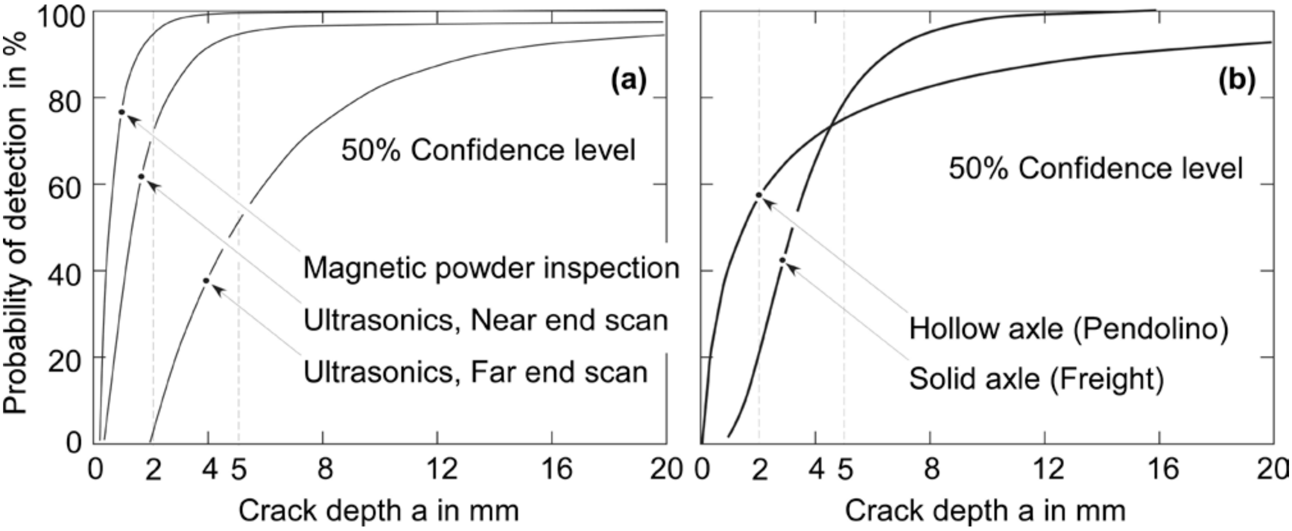

Figure 7: Probability of detection (PoD) of cracks as a function of crack depth. (a) Data obtained by magnetic particle inspection and ultrasonic techniques (according to [14]; 50% confidence level; solid axle); (b) Comparison between ultrasonic near end scan data for solid axles and ultrasonic data obtained from the bore of hollow axles (according to [16]; 50% confidence level).

The overall probability of non-detection (PoND) as the complement to the POD is identical with the probability that an axle with an initial crack of 2 or even more millimeters depth (such as assumed in the fracture mechanics analysis) fails because the crack was not found in due time. This has to be distinguished from the failure probability of an arbitrary axle in the fleet which is smaller by magnitudes since a pre-existing crack of that size is very unlikely.

Besides the fracture mechanics based residual lifetime the steepness of the PoD-crack size curve is the second key parameter for establishing inspection intervals. This is illustrated in Figure 8. The failure probability of the axle, i.e., the probability that the crack will not be found in due time, increases for a larger inspection interval but it significantly reduces for a shorter one, i.e., with any additional inspections before potential failure (Figure right). The PoD of a specific inspection becomes larger when the crack is more extended and when the PoD-crack size curve is steeper (Figure 8 left). Therefore, measures for improving the PoD-crack size curve [in the figure from (1) to (2)] are of paramount importance for reaching an optimum between safety and cost-efficiency.

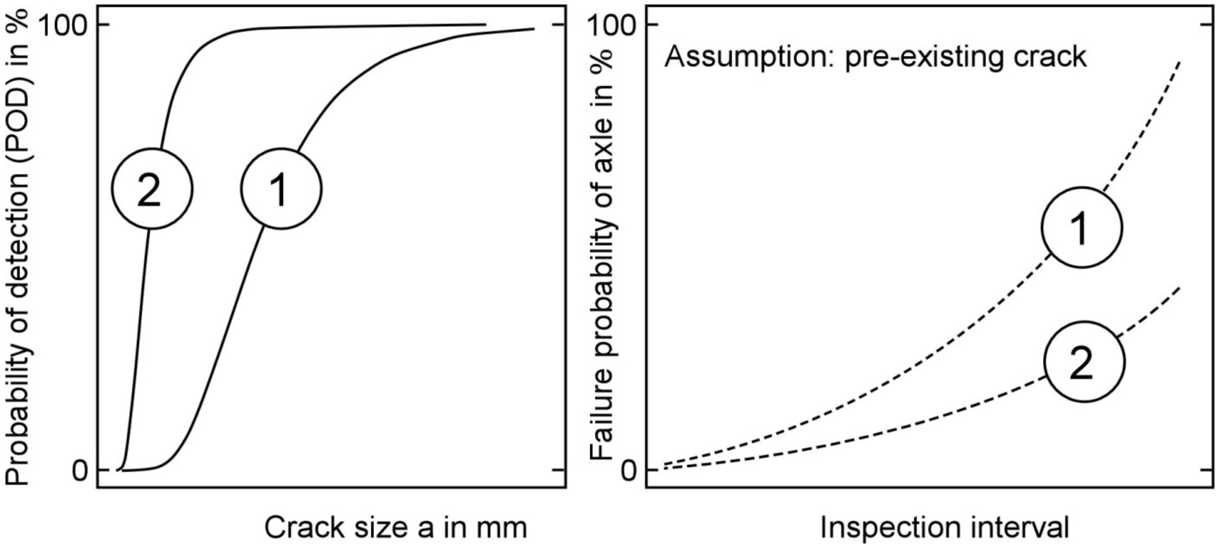

Figure 8: Schematic correlation between the PoD-crack size characteristics of a NDT method, the inspection interval and the failure probability of an axle with a pre-existing crack.

No detailed discussion on options for improving the PoD-crack size characteristics shall be given here because this is a subject of ongoing and future research activity, see however the remarks in [2]. Certainly increasing automation will lead to improvements in NDT quality since, this way, human factors such as the level of training and experience of the inspectors and others which significantly contribute to the variability in manual inspection results are eliminated. Another measure is the application of more sophisticated test and analysis methods, e.g., for US, the application of the phase array or synthetic aperture focusing technique (SAFT). Note, however, that the challenge is not just to have more reliable NDT methods but to optimize these for railway axles with respect to the inspection time needed such that cost-intensive intrusiveness, which disrupts train service, is kept as small as possible.

3. SUMMARY

Starting with an axle failure case and a failure statistics for Europe the paper gives a brief overview on selected issues of existing and potential innovative safe life and damage tolerance methods for railway axles which, as the authors think, promise some potential for further increasing the safety level of axles. The issues addressed comprise questions of limiting the projected lifetime as a consequence of features such as damage accumulation, the potential very high cycle fatigue effect and corrosion including the “one-million miles axle” concept and in-service effects on the fatigue life such as corrosion pits and flying ballast impact notches. Special attention is put on the potential effect of non-metallic inclusions on fatigue strength and lifetime. A gap in the existing quality regulations has been identified. As an alternative it is proposed to carry out a throughout investigation of the as-is state and to correct the design fatigue strength with respect to a limiting defect size which will not be found with acceptable probability in quality control. Defect sizes above this limit have to be found with high reliability by innovative NDT techniques. Finally, the improvement of the PoD-crack size characteristics of NDT has been identified and discussed as a paramount goal for reaching an optimum between safety and cost-efficiency.

REFERENCES

[1] Klinger, C. and Bettge, D.(2013): Axle Fracture of an ICE3 High Speed Train, Engineering Failure Analysis, http://dx.doi.org/10.1016/j.engfailanal.2012.11.008

[2] Zerbst, U., Beretta, S., Köhler, G., Lawton, A., Vormwald, M., Beier, H.Th., Klinger, C., Černý, I., Rudlin, J. Heckel, T. and Klingbeil, D. (2012): Safe life and damage tolerance aspects of railway axles – a review. Submitted to Engng. Fracture Mech.

[3] EN 13103 (2001): Railway Applications – Wheelsets and Bogies – Non Powered Axles – Design Method. European Committee for Standardization (CEN), Brussels, Belgium.

[4] EN 13104 (2001): Railway Applications – Wheelsets and Bogies – Powered Axles – Design Method. European Committee for Standardization (CEN), Brussels, Belgium.

[5] EN 13261 (2009): Railway applications. Wheelsets and bogies. Axles. Product requirements. Annex A. European Committee for Standardization (CEN), Brussels, Belgium.

[6] Sonsino, C.M. (2007): Course of SN-curves especially in the high-cycle fatigue regime with regard to component design and safety. Int. J. Fatigue 29, 2246-2258.

[7] Traupe; M., Meinen, H. and Zenner, H. (2004): Sichere und wirtschaftliche Auslegung von Eisenbahnfahrwerken. Final Report BMBF Project 19 P 0061 A-F; in German.

[8] Beretta, S. and Carboni, M. (2008): Endurance design procedure of wheelsets based on reliable load spectra and reliable Wöhler curves. D5.1.3: Design procedures for axles. European Project “Wheelset Integrated Design and effective Maintenance” (WIDEM), http://www.widem.org/file.php?id=50&save_dialogue=1.

[9] Lütkepohl, K., Esderts, A., Luke, M. and Varfolomeev, I. (2009): Sicherer und wirtschaftlicher Betrieb von Eisenbahnfahrwerken. Final Report BMWi Project 19 P 4021 A-F; in German.

[10] British Railway Safety and Standards Board (RSSB): Project T728: Impact of corrosion upon the high cycle fatigue properties of GB axle Steel.

[11] Australian Transport Safety Bureau (2007): Derailment of XPT passenger train ST22 Harden, New South Wales 9 February 2006; http://www.atsb.gov.au/media/24374/rair2006002_001.pdf

[12] Gravier, N.; Viet, J. J. u. Leluan, A.(1998): Predicting the life of railway vehicle axles. in: Proc. 12th Wheelset Congress, Quigdao, China, 133-146.

[13] Ma, J., Zhang, D., Han, E.-H. and Ke, W. (2010): Effects of inclusion and loading direction on the fatigue behaviour of hot rolled low carbon steel. Int. J. Fatigue, 32, 1116-1125.

[14] Benyon, J. A. and Watson, A. S. (2001): The use of Monte-Carlo analysis to increase axle inspection interval. Proceedings of the 13th Int. Wheelset Congress, Rome, Italy.

[15] Rudlin, J. R. and Shipp, R. (2002): Review of techniques for rail axle inspection. Report for railway safety; also Rudlin, J. R. and Shipp, R. (2003): Review of rail axle inspection methods. Int. Seminar on Fatigue of Axles, Imperial College London, 25-26 Sept. 2003.

[16] Wei, L. (2008): Procedure to define NDT periodicity as function of vehicle service profile; D7.1.8: Results of probabilistic analysis. European Project “Wheelset Integrated Design and effective Maintenance” (WIDEM), http://www.widem.org/file.php?id=54&save_dialogue=1.