EVALUATION OF DEFECTS AND CRACKS IN CARRIAGE AXLES USING NON-DESTRUCTIVE TESTING

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ABSTRACT

A company for the maintenance of railway vehicles in Slovenia carried out, in collaboration with the Institute of Metal Structures (IMK), Ljubljana, testing and relevant analyses of the state of carriage axles.
In order to detect cracks at carriage axles and to evaluate the quality of axles surfaced, ultrasonic and magnetic particle testing methods were used. Ultrasonic testing with normal and angle probes was used to detect internal cracks in the carriage axles using the distance gain size (DGS) diagram and the distance amplitude correction (DAC) method for reference specimens.
Additionally, the magnetic particle testing method, with an apparatus permitting the detection of transverse and longitudinal cracks, was used to search for surface cracks.
The tests performed at numerous railway carriages provided results, which make it possible to predict a premature axle fracture in further service.
The non-destructive testing methods used permitted the detection of the cracks present, causes for the crack initiation were established, and the risks of crack propagation were evaluated. A critical evaluation of the carriage axles in terms of crack initiation and size is given. The prediction of the remaining life of an axle with reference to the potential propagation of the existing cracks is given taking into account the load axle acting on the axle and the axle age.

Keywords: carriage axles, non-destructive methods, ultrasonic testing, magnetic particle testing, material fatigue, microscopy, micro-chemical analysis

INTRODUCTION

An umbrella act on assuring safety in railway traffic takes into account the state of a railway track, railway crossings with roads, the state of a railway carriage, the organisation of maintenance in case of extraordinary events in the railway traffic, and protection of railways and railway vehicles [1]. A particular importance is attributed to Article 37 specifying the maintenance and inspection of railway vehicles and requiring that the vehicles should be kept in a state ensuring safe railway traffic. The railway vehicles in service should be regularly maintained and supervised and periodically inspected. The mode of maintenance, the terms of periodic checks, and other conditions are important in the use of railway vehicles in traffic.

More concrete responsibilities for the assurance of safe railway traffic are specified in a Regulation on the maintenance of railway vehicles [2]. The latter specifies requirements for the maintenance of railway vehicles and the mode of authorizing workshops to carry out the maintenance of components, assemblies or vehicles. The maintenance of vehicles should serve as a preventive measure in maintaining a satisfactory technical state providing safe and reliable service taking into account economic and environmental criteria in the vehicle maintenance. The Regulation specifies general requirements and conditions that should be considered by a performer.

J. R. Rudlin and R. Shipp [3] described different non-destructive methods of inspecting railway axles and indicated advantages and disadvantages of the individual testing methods. A probability curve of the detection of surface cracks exceeding 1 mm in size is given too. Probability of detection (POD) data is used, in combination with crack growth data, to give optimum inspection intervals for a given component in service. The interval is set such that an in-service defect that the NDT system would miss cannot grow to a size likely to cause failure before the next inspection. Obviously, more sensitive inspection techniques, which detect smaller defects, will allow for less inspection and are therefore desirable in most cases. A typical POD data curve is given in *Fig.1*.

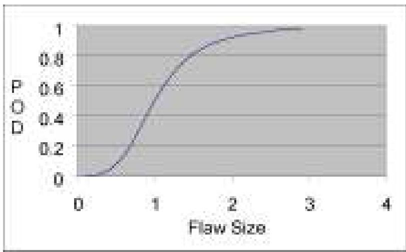

Figure 1. General Shape of Probability and Flaw size.

An expert inspecting railway carriage axles is responsible for the in-operation state and, in turn, for the reliability of operation of railway transportation means and safety of vehicles in operation. In the past few years some failures of carriage axles occurred. This entailed new tasks for the maintenance service in order to ensure safer use of carriages. The maintenance service thus performed immediate inspection of all the carriage axles that might presumably have cracks, which were detected between the past two service inspections.

The requirements set limited the number of testing methods and apparatuses available to experts for the inspection of the carriage axles. The experts thus had to choose the most appropriate testing method and elaborate criteria of evaluation of the state and serviceability of the carriage axles.

Out of the methods available and suitable for the axle inspection the ultrasonic method was chosen because of two reasons, i.e. first, because it is already in use and favourable experience is available, and second, because the method is practical and rapid. Normal and angle probes were chosen in order to permit the detection of all possible defects in the carriage axles. The choice and use of adequate ultrasonic probes will be described further in the paper.

In accordance with a standard no longer in use [4], ultrasonic testing as performed with 37° angle probes, with which not all possible defects could be detected. The inspection of a carriage axle from the front is not specified but it is possible as an additional inspection to confirm the imperfections already detected in a material. Jemec and Grum [5, 6] first made some calculations to present echograms of sound paths in locomotive shafts when the ultra sound is travelling through the shaft from the shaft front. Because of a specific shaft shape, reflections are obtained at the transitions, which makes the determination of the crack location easier. The signals in an echogram outside the calculated theoretical paths represent a defect in a material if they reach a certain signal height with reference to the height of signal reflection from the back-wall of the shaft. At the Slovenian Railways, there are several geometrically different carriage axles in operation; therefore, for the inspections from the front the locations were calculated with ultrasonic paths. To this purpose self-made software was used, which is a good help in more rapid in reliable detection of defects in a material. The software was elaborated in a way to permit a further development of the automated system for the signal evaluation in ultrasonic testing of axles and shafts.

Hansen and Hintze [7] and Speier [8] described a Phased Array technique, which provides more reliable and rapid ultrasonic testing of axles and shafts. In the Slovenia Railways, however, this technique is not in use yet due to high costs of equipment. A more recent investigation using the Phased Array technique and aided with the assessment of the 11th axles with cracks in Great Britain gives some good results. Rudlin, Muhammed, and Schneider [9] treat analytical methods for determining the periodicity of inspection that require knowledge of load conditions, materials properties and inspection reliability. The Wheelset Integrated Design and Maintenance (WIDEM) Project is being carried out to acquire some of these data and to develop methodologies for axle design. The method estimates the Probability of Detection (POD) of the in-situ inspection technique from the response vs. size method, the size in this case being measured with Alternating Current Potential Drop (ACPD), phased array ultrasonics and time of flight diffraction. The results show that useful information is generated by such methods and a further experiment is planned on a different range of axles to obtain wider applicability of the data obtained.

As the defects in carriage axles most frequently occur at the surface, additional testing is carried out for example with the magnetic particle method as described by Downes [10]. Railway axles are periodically tested for possible surface-breaking cracks. The magnetic particle inspection technique, a semi-automatic system, is used to detect any fatigue cracks on the axle. The wheelsets are conveyed to the machine along floor-laid tracks and lifted on to roller supports by dedicated hoist. The two novel features of the machine are the magnetizing procedure and the programmability of the coil position. High amperage current is supplied to the magnetizing coil from a separate power pack. The system also provides rapid demagnetization from a value of magnetizing current plus 10%. The equipment is supplied with a canopy for the inspection of axles for ultra violet fluorescent indications in subdued light. The canopy can be folded to allow wheelsets to be loaded from overhead.

QUALITY ASSESSMENT OF CARRIAGE AXLES

Periodic inspections of carriage axles using non-destructive methods are almost all performed at the Public Company Slovenian Railways, Unit Dobova. In the Unit Dobova mainly the ultrasonic and penetrant methods are used. The ultrasonic testing method is used to detect primarily transverse surface cracks and cracks at the axle inside. Because of several not clear causes of the axle fractures undetected in regular ultrasonic inspection, additional magnetic particle testing was introduced in 2006. For this purpose the Slovenian Railways have adequate equipment.

Protocols were elaborated for ultrasonic and magnetic particle testing of various carriage axles. The aim of the protocols is to enable as rapid as possible detection of cracks and other defects at chosen carriage axles or at axles after repair surfacing [11].

In July 2006 the Slovenian Railways approved the protocols for the methods specified for testing of surface cracks elaborated by the company's experts. For ultrasonic testing protocols were elaborated for carrying out inspections at critical locations, i.e. transitions at the axles tested with angle probes. In case internal indications in accordance with the DGS diagram with a flaw size exceeding 3 mm are found, then such defects in axles can be successfully detected with the angle probes. Additional checking of the surface cracks of the carriage axles was performed also with penetrant testing. If the defect found exceeds 3 mm, such axles shall be taken out of operation or repaired prior to further service.

In order to detect longitudinal cracks, the magnetic particle testing method was used [12]. In collaboration with the Institute of Metal Structures (IMK) in Ljubljana, first a study of the presence of longitudinal surface cracks was made using the magnetic particle method at carriage axles produced at the Iron Works of Bohumin (Železárny a drátovny Bohumín) by year 1996. Later the carriage axles of the same producer produced by 2007 were tested too. The study of axle testing has not been concluded yet; therefore, only partial results can be presented.
Figure 2 shows a column chart giving results on the defective axles found in the period from June 2006 to July 2007. A total of 2363 carriage axles were inspected. A large number of the defects found with the magnetic particle testing method at the axles/shafts are, to our mind, a consequence of low-quality surfacing performed by the producer in order to repair the defects present.

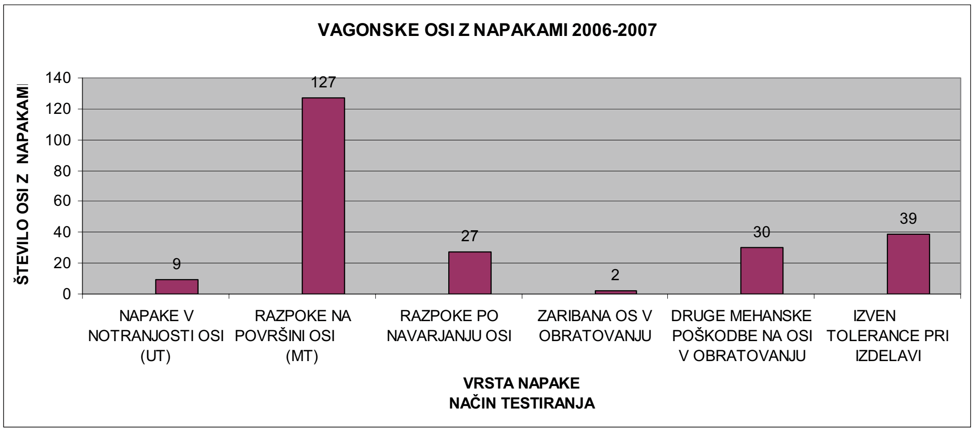

Figure 2. Defects found at carriage axles in ultrasonic and magnetic particle testing.

Testing of the axles and shafts showed transverse and longitudinal cracks. The longitudinal cracks having been unexpected, reasons for their occurrence had to be found. New criteria of acceptability of longitudinal defects with reference to their location at an axle or shaft and their size had to be set as well. With the defects found at axles or shafts, the rate of propagation of a crack between two carriage inspections shall be established as well in order to be able to predict further operation of the axles or shafts concerned. A further question is, in order to secure safe operation, what the synergic effect of a longitudinal crack and a transverse one on material fatigue in case of possible overloads may be. Criteria of acceptability or setting aside of a carriage axle in operation, showing various types, sizes and orientations of cracks, shall be established.
The investigations conducted so far have shown that the main causes of momentary fracture of an axle is a discontinuity in the chemical composition and major differences in the microstructure of an axle, which are a consequence of casting or forging, and presumably also of inadequate conditions of the entire heat treatment.

ULTRASONIC TESTING OF THE AXLES

Ultrasonic testing is performed at the axles of freight carriages having wheels, bearing and sealing rings mounted. In testing of axles the Slovenian Railways take into account a European standard [13] and older railway instructions on testing of axles [14]. The Slovenian Railways have three types of freight-carriage axles. The latter differ in shape and dimensions. Figure 3 shows the most recent axles with their wheels mounted and called wheelsets.

Figure 3. Wheelsets of freight carriages.

Ultrasonic testing is performed by experts having the qualification of Level 1 for ultrasonic testing in accordance with standard SIST EN 473. Supervision, however, is performed by experts having the qualifications for ultrasonic testing of Level 2 and Level 3. Experts wishing to perform ultrasonic testing shall have a written authorization of their employer.
Ultrasonic testing is performed with the pulse-reflection technique using an ultrasonic device in accordance with standard SIST EN 12668-1. The normal and angle probes used shall comply with the requirements of standard SIST EN 12668-2 in order to ensure transmission of the entire volume of the axles and wheelsets of the freight carriages.
In testing, ultrasonic devices Krautkrämer (GE) USM 35 XS (DGS, DAC) and USL 32, angle probes Krautkrämer WB 45° 2 MHz and WB60° MHz, and B2S with a plexi wedge of 37° and 54° (r = 80 and r = 90 mm), and normal probes MB4S and MB2S using the DGS and DAC methods, a reference planar reflector of 3 mm and a reflector with a drill-hole were used.
Figure 4 shows different techniques of ultrasonic testing of the carriage axles. Figure 4a shows testing with the normal ultrasonic probe of 2MHz or 4MHz, Figure 4b with the 37° angle probe, and Figure 4c with the 60° angle probe.

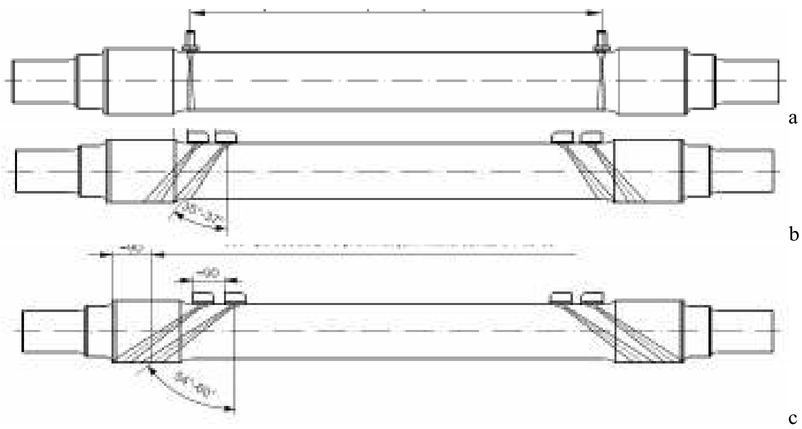

Figure 4. Ultrasonic testing of axles with normal probe (a), 37° angle probe (b), and 60° angle probe (c)

A detailed ultrasonic examination showed defects inside the carriage axle of »a« type at eight locations. Figure 5 shows the carriage axle with locations marked 1 through 6. In testing, defects in the depths between 43 and 82 mm were detected. The locations with the wheels mounted at the carriage axles are marked A and B. Defects were found at location B in the depths between 39 and 57 mm.

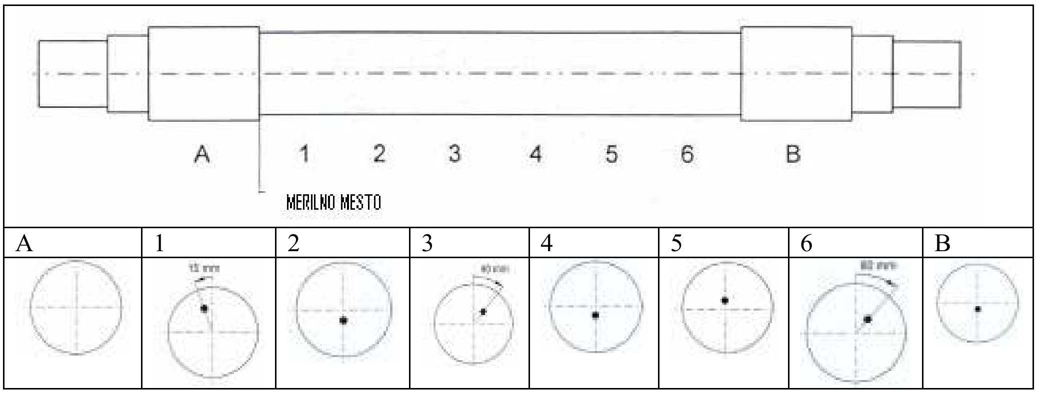

Figure 5. Location of defects inside carriage axles.

In railway axles and shafts the most frequent defects are cracks. They are mainly due to dynamic loads they are subjected to. There may be also forming defects that remain in the material such as non-forged oxidised shrinkage cavities or gas cavities in the axle or shaft centre (Figs. 6 and 7).

Figure 6. Radial cracks in axle centre

Figure 7. Volume defects and radial cracks in axle centre

In the cut specimens of the axle, micro porosity and normal porosity, lamination laps, non-forged oxidised spots, impurities in the centre of a forging, segregations, non-forged shrinkage cavities, cracks, and undesired stresses produced in heat treatment due to non-uniform quenching or too high a cooling rate in quenching, cracks due to too sharp grinding resulting in martensite and high residual stresses in the thin surface layer are searched for. None of the above-mentioned imperfections is acceptable according to standards EN 13 261 and ISO 5948 and UIC 811-1.

In case there are major mechanical damages at the surface of a carriage axle, they should be first repaired in order to enable undisturbed surface scanning with the probe. If the repair of the damaged axle is not possible, the axle should be removed from operation.
If a carriage axle surface has been ground too roughly, the signal will show indications of surface roughness. For the state of carriage axles with a rough-machined surface to be evaluated as still acceptable, no signals reflected from the back wall deviating for more than

5% should be detected. In the opposite case, other non-destructive testing methods, e.g. magnetic particle testing or Eddy current testing should be used.

MAGNETIC PARTICLE TESTING OF THE AXLES

For the detection of surface cracks, an apparatus of Advanced Technology Group (ATG) designated Magman 4000 F was used. To make the evaluation of defects or cracks in magnetic particle testing easier and more reliable, testing using fluorescent magnetic particles and UV light for the illumination of the surface were used. The examinations confirmed efficient detection of cracks in the axles with indications in both transverse and longitudinal directions of the carriage axle [15].
The magnetization of the axles concerned can be performed with mobile or stationary devices, which permit efficient detection of both transverse and longitudinal surface cracks at the carriage axles.

In accordance with relevant instructions, a magnetic particle examination is carried out in the following sequence of steps:
- testing of the carriage-axle surface between the wheels mounted to make a wheelset,
- testing of the axle-stud surface in case bearing bushings are not mounted,
- testing of the carriage-axle surface with no wheels, bearing bushings, and sealing rings mounted.
- after magnetic particle testing, the surfaces shall be cleaned, degreased, and corrosion protected in accordance with SIST EN 13261:2003.

Surface preparation for magnetic particle testing:
- the specimen surface shall be first suitably cleaned to show no traces of oil or grease, sand,
- the surface shall have no surfaced areas,
- the axle should show no surface damages such as scratches, notches, tearing-outs or inadequately rough surface,
- a suspension based on oil derivatives, i.e. oil or petroleum, with fluorescent magnetic particles with a grain-size ranging between med 4 μm and 14,5 μm was chosen.

The magnetic particle testing device used shall ensure:
- testing of various types of carriage axles,
- use of a portable magnetizing yoke,
- alternating-current magnetization.

After the detailed examinations of numerous carriage axles, only one of the critical carriage axles showing numerous cracks both in transverse and longitudinal directions will be described. At the axle concerned as much as eight (8) cracks were detected, of which seven (7) ran in the longitudinal direction and one (1) in the transverse direction, as shown in Figs. 8 and 9.
The cracks in the longitudinal direction were quite unexpected. To our mind, they were not initiated during operation but in the phase of production of the carriage axle. The cracks in the longitudinal direction occurred during heat treatment due to rapid cooling of the surface during the formation of martensite-ferrite microstructure after hardening. The thermal and microstructural stresses during the cooling process in heat treatment affect the crack initiation at the surface. High temperature difference between the surface and the core in the initial cooling phase up to the temperature of martensite transformation can produce high tensile stresses at the surface, which may, in turn, produce plasticizing or even failure of the axle surface. Consequently, correct design and performance of the entire heat treatment process for the long carriage axles of large diameters are of major importance in order not to produce

too high internal stresses during the quenching process. This can be controlled by correct heating up to the austenitizing temperature and correct hold time at the temperature concerned, correct choice of a quenching agent and of adequate quenching technique. The choice of the medium and cooling conditions shall correspond to the critical cooling rate in order to produce as low as possible internal stresses during the quenching process.
Another cause of the occurrence of the longitudinal cracks may be the presence of surface and sub-surface defects in the material due to casting or forging. Forging or additional mechanical treatment of the carriage axle may provide homogeneous chemical composition throughout the carriage axle and efficient performance of heat treatment.
At the second carriage axle chosen, four longitudinal cracks at the axle surface were detected (Fig. 9). The most critical seems to be the surface crack in a length of as much as 300 mm, which exceeds the critical depth of 3 mm. This crack was also a subject of a further analysis of causes for the occurrence of the crack with reference to its location. Figure 10 shows the crack location that was confirmed with the fluorescent magnetic particle method.

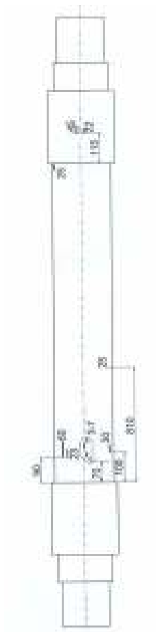

Figure 8. Locations and sizes of transverse and longitudinal cracks at first carriage axle.

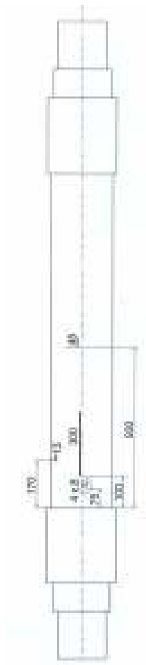

Figure 9. Location and size of longitudinal crack at second carriage axle.


a

b

Figure 10. Photos of carriage-axle surface in testing with fluorescent magnetic powder. Longitudinal crack (a) and transverse crack (b).

EVALUATION OF THE DEFECTS AND CRACKS DETECTED

The defects and cracks detected by ultrasonic and magnetic particle testing were to be verified with macroscopic and microscopic examinations. In testing, the rejected carriage axles shown in Figs. 8 and 9 were used. They were cut from large axles at the locations of the defects.

In ultrasonic testing, cracks were detected in the central part of the axle in the depths between 30 and 80 mm. In magnetic particle testing, the cracks were detected below the hub and the central part of the axle in a depth where the crack size amounted to 3 mm and with a length of some millimetres up to around 300 mm. Figure 11 shows a macrograph with a crack in a depth of 4 mm. Similar macrographs were obtained with the other macro sections. The macroscopic examination confirmed the size and location of the defects or cracks detected at the carriage axles.

Figure 11. Depth of transverse crack in axle shown in macro section.

Possible causes of the occurrence of defects and cracks:
- heat treatment or cold treatment during the manufacture of the carriage axles,
- uncontrolled cooling during the casting process or inadequate quenching conditions in the heat treatment of the carriage axles,
- stronger deviation in the chemical composition after forging and subsequent heat treatment of the axles,
- the choice of incorrect heating to the austenitizing temperature,
- transverse cracks due to dynamic loads and material fatigue.

Some of the cracks were found already in a visual examination. They were related to casting or thermo-mechanical treatment (rolling, forging) relevant to the manufacture of the carriage axles.

In dependence from thermal effects on a material during heat treatment due to thermal and phase stresses at the carriage axle, axle deformations and residual stresses will occur. Combined with the torsional and bending stresses in the axle, they give a true stress state in the axle loaded. Due to dynamic stresses material fatigue will occur and, consequently, the initiation and/or propagation of cracks. The carriage axle has the following chemical composition: 0.40 C, 0.50 Si, 1.20 Mn, 0.30 Cr, 0.30 Cu, 0.08 Mo, 0.30 Ni, and 0.06 V. The tensile strength of the carriage axle is, due to its mass, relatively low and does not exceed 650 N/mm^2.
To this end the specimens for an examination with a scanning electron microscope (SEM) were used to examine the surface. Figure 12 shows the image of a longitudinal crack at the carriage axle having a very agitated appearance. A macroscopic examination and a chemical analysis of the carriage axle were made at the crack location and its surroundings. The characteristic columnar cracking of the material was found whereas at the axle surface no material fatigue effects could be noticed. At the surface only oxides were found, which means that the crack occurred at an elevated temperature in the presence of oxygen. A more detailed microchemical analysis, however, showed that oxidation and surface decarburization occurred. The occurrence of decarburisation is related to an austenitizing temperature too high

chosen in the heat treatment, which is confirmed by the crack occurring during the quenching process. Because of the large axle mass, the quenching process is slow and the thin oxide layer at the surface can crack in a fine-grained form.

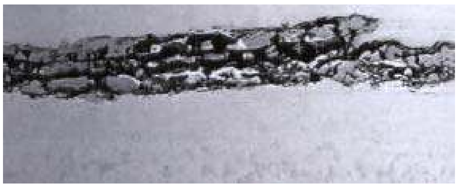

Figure 12. Crack obtained with scanning electron microscope.

The detailed metallographic and micro-chemical examinations of the surface around the crack showed that the crack slowly propagated in depth and ran mainly through crystals (columnar crystals). It was additionally found that the crack surroundings from the surface to a smaller depth were also decarburized to pearlite-ferrite microstructure [16]. The decarburization found indicates that the crack occurred due a too high temperature, which is confirmed by the crack initiation during heat treatment, which was done with inappropriate surface protection. Figure 13 shows the entire, relatively long longitudinal crack at the carriage axle (a) and the appearance of the magnified crack (b) showing obvious decarburization at the surface next to the crack.

a

b

Figure 13. Longitudinal crack at axle (a) and a surface section with crack and visible decarburization (b).

Figure 14. EDS analysis in crack surroundings.

Figure 14 shows the energy dispersion spectroscopic analysis (EDS) of the crack suroundings, which confirmed the presence of pearlite-ferrite microstructure and an additional influence of oxygen at the elevated temperature with the oxide layer and decarburization of the surface in the crack surroundings. The decarburized steel in the crack surroundings has a stronger tendency to material fatigue and cracking leading to the final carriage-axle failure due to lower strength of ferrite. Ferrite has lower dynamic strength; therefore, the axle portion surrounding the crack is more sensitive to alternating load and micro-deformations, which increase material fatigue. This phenomenon around the crack may be very dangerous at those axle locations where a high notch effect is produced by the crack, which produces rapid crack propagation or even carriage-axle fracture. The study and material analysis made in the crack surroundings show that the carriage axles having cracks deeper than 3 mm shall be rejected because a momentary, increased load close to the crack may produce additional increase in stress concentration and, consequently, a fatigue fracture.

CONCLUSIONS

Non-destructive testing with ultrasonic and magnetic particle testing methods showed a high level of reliability in the detection of defects and cracks. It can be stated that the evaluation of the state of carriage axles after the manufacture and in operation can be efficient if the testing procedures are the right ones and the criteria of evaluation of the axle state are available. The right criteria may help to predict the crack propagation, define the testing periods and reject the damaged and critical axles. Additionally, the metallographic analysis was made, which confirmed that the prediction of defects and cracks at the carriage axles using the non-destructive methods is correct and efficient. The cracks detected in the transverse direction of the axle result from an axle overload with very dangerous, combined bending-torsional dynamic stresses. The longitudinal cracks found result from the axle manufacture, particularly heat treatment or repair surfacing.

The fatigue cracks occurring at one of the carriage axles were detected in the hub radius. The crack was detected with ultrasonic testing and confirmed with magnetic particle testing. All cases of defects and cracks found at the carriage axles are suitably documented, the critical locations are additionally metallographically analysed with reference to the axle surface. The results of the measurements of cracks and crack propagation between the examinations are statistically monitored so that repair or rejection could be made.

At suitable specimens cut out from carriage axles, the macro examination and metallographic analysis showed not that only cracks occurred at the surface but also gas porosity in the form of flakes and cavities at the central part of the cast axles. These internal defects found in the carriage axles shall be subjected to additional criteria given in SIST EN 13 261, ISO 5948 and UIC 811-1.

If the criteria of acceptability are not given in a contract, at least a railway standard UIC 811-1 should be taken into account.

The investigations confirmed that inspection of carriage axles should be performed periodically depending on the type and size of the axle. The periodicity of inspections should be adjusted to the state and age of the axles and the anticipated remaining life of the axles.

REFERENCES

[1] Zakon o varnosti v železniškem prometu (ZVZP-UPB1) (Act on Railway Traffic safety), Official gazette of RS no. 102/2004 of 21 Sept., 2004

[2] Pravilnik o vzdrževanju železniških vozil (Regulation on maintenance of railway vehicles (203) (Official gazette of RS, no. 53/2002)

[3] J. R. RUDLIN & R. SHIPP**:** Review of Rail Axle Inspection Methods, International Seminar on Railway Axles, Imperial College, London, 25-26 Sept. 2003

[4] Internal standard (Workshop standard) (in Slovene) JŽS V3.006

[5] GRUM, Janez, JEMEC, Viktor, BECI, Anton. Experimental system for ultrasonic testing of axle sets of diesel-engine trains. *Insight (Northamp.)*, 2000, vol. 42, no. 12, pp. 782-788

[6] GRUM, Janez, JEMEC, Viktor. Ultrasonic testing of axle sets of diesel-engine trains. In: 15th World Conference on Non-Destructive Testing WCNDT, Rome, Italy, October 15-21, 2000

[7] W. HANSEN1, H. HINTZE, Ultrasonic Testing Of Railway Axles With Phased Array Technique Experiences During Operation, 16th World Conference NDT, Montreal 2004
[8] SPEIER, Peter: Traditional and new opportunities in the railway industry GE inspection technologies, Bonn, 2004
[9] J. Rudlin, A. Muhammed & C. Schneider: Inspection reliability and periodicity for rail axle inspection, Insight Vol,48, No.6, pp.348-351, June 2006
[10] Downes, G.W.: Magnetic particle inspection equipment for testing railway wheelsets, Insight (May 1994) 36, (5), pp. 316-317
[11] Navodilo za ultrazvočne preglede TN UZ 01.11.01 in navodilo za magnetne preglede TN MT 01.01.01 (Instructions for ultrasonic testing TN UZ 01.11.01 and instructions for amgnetic particle testing TN MT 01.01.01), Ljubljana, 2006
[12] SIST EN ISO 3059:2002 - Non-destructive testing - Penetrant testing and magnetic particle testing - Viewing conditions (ISO 3059:2001)
[13] SIST EN 13261:2004 - Railway applications - Wheelsets and bogies - Axles - Product requirements
[14] UIC 811-1 Technische Lieferbedingungen Radsatzwellen fur Triebfahrzeuge und Wagen
[15] SIST EN ISO 9934-1:2002-Non-destructive testing - Magnetic particle testing - Parts 1 to 3
[16] Preiskava razpok na oseh kolesnih dvojic tovornih vagonov (Examination of cracks at wheelsets of freight carriages), Report P-27051-1L, IMK, Ljubljana, 2006