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An analysis regarding train derailments caused by cracked wheelsets

Eugen Ghita[1]

[1]Politehnica University, Faculty of Mechanical Engineering, Timisoara, Romania

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* **Correspondence:** eugen.ghita@upt.ro

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ABSTRACT

The wheelset is a critical component of a bogie's rolling equipment, and safety requirements necessitate both static and fatigue analysis of wheelset axles. This paper proposes a comparative analysis of derailments and accidents caused by cracked wheelsets, a topic that is extensively debated among wheelset manufacturers and railway administrations. The central issue under discussion is whether the cause of wheelset axle cracking is attributed to failure in complying with wagon or locomotive loading requirements, leading to increased static stress, or to material fatigue. The answer to this debate may be found through technical expertise that involves analyzing the cross-section of the cracking, stress levels, and the impact of dynamic conditions.

KEYWORDS

Rail, Wheelset axles, Fracture mechanics

1. INTRODUCTION. DESCRIPTION OF THE ACCIDENT

Based on the analysis carried out at the accident site by the research commission [2], it was established that "The breakage of the axle shaft, in the transition (connection) area between the axle shaft and the shutter area, occurred in the distance between Hm Coteşti and CFR Gugeşti Station ..."

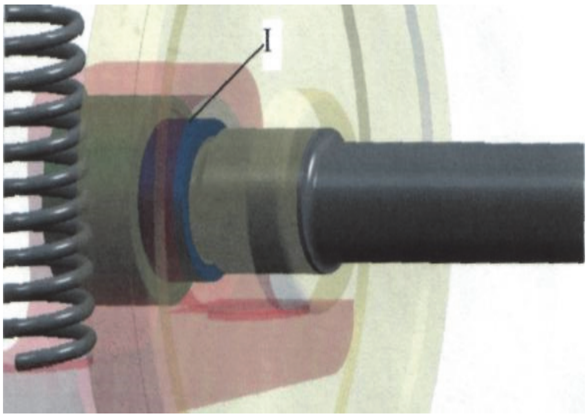

Figure 1: Cracking zone

Photos of the broken spindle after deformation (Fig. 2) confirm the break in the connection area in the obturator, at a distance of 5-10 mm from the obturator diameter. So, the break did not occur in an area where the stress level would have been maximum. According to Navier's formula and the bending moment diagrams, the maximum stress and bending moment would be located in the middle of the axle. The axle was a driving axle that taken over, therefore, and a torsional moment being subjected to a stress composed of bending and torsion which, according to resistance theories, are equated to a single equivalent moment.

Figure 2: Spindle broken in the Gugeşti accident dismantled at SIDEX Galati

The macroscopic appearance of the fracture surface (Fig. 3) indicates a fatigue fracture, starting from a previous defect, which may be a transverse crack. The fatigue fracture zone covers 30-40 % of the total fracture surface. The research report from confirms that "The surface of the fracture section presented the specific aspect of fatigue fracture generated by transverse cracks".

Figure 3: The macroscopic aspect of the rupture section at Gugeşti

According to the instructions for in-service ultrasonic control of mounted axles - AFER (ROMANIAN Railway Authority), [2], it was found "the presence in the breaking section of two radial cracks in the transverse direction of 10 and 15 mm respectively, whose primers (of semi-elliptical shape) extend over an area of 30% of the initial cross-section." Before leaving the grease box, the spindle continued to remain solid with the sealing ring on which it was pressed, deforming in the connection area. ” From the findings, it emerged that the breaking of the axle shaft, in the transition (connection) area between the axle shaft and the shutter area, occurred as a result of exceeding the fatigue resistance limit of the material due to a manufacturing defect. This manufacturing defect was not detected during the controls performed by the manufacturer (respectively by SC SMR SA Balş) nor during operation during the ultrasonic control performed at the CFR Coşlariu station...", [2].

The stiffness of the wheel-axle joint is influenced by a series of factors, the most important of which are :

- maximum pressing force (for cold pressing);
- the value of tightening (in practice it is called “serage”) expressed in %;
- the quality of the surface that comes into contact (roughness of the order of 6.3 -12.5 μm);
- the size of the surfaces that come into contact;
- pressing speed (the higher it is, the lower the strength of the joint), v = 50mm/min.

The sealing ring continued to rest on the bearing in the grease box housing, being pushed towards the wheel hub (Fig. 4).

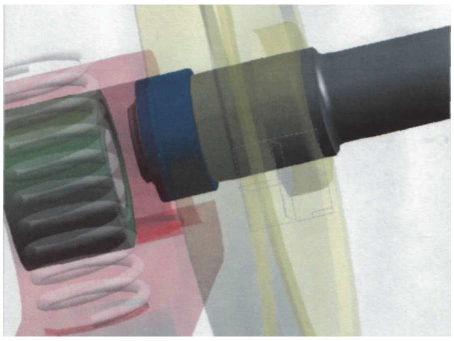

Figure 4: Moving the sealing ring towards the wheel hub and rubbing it on the upper area of the grease box bearing

Pressing the grease box onto the seal ring with part of the weight of the carriage transmitted by the springs (less than 1/8 of the weight, because the grease box has moved down with the difference between the outer and inner radius of the bearings and consequently the springs of this box are less loaded) led, as a result of friction, to the heating of the contact area. Consequently, the grease box continued to descend through the deformation of the contact area, which resulted in the axle end being pressed into the box bearing (Fig. 5) until a channel was formed that allowed the box to fall (Fig. 6).

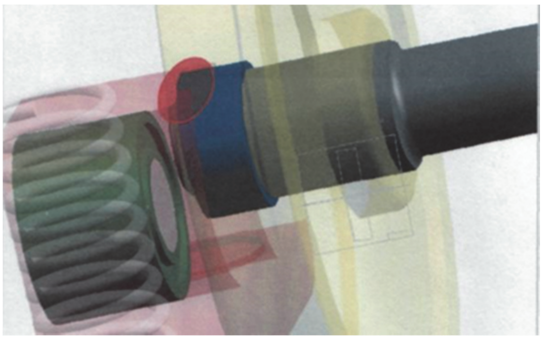

Figure 5: Hot deformation zone of housing, sealing ring and shaft end

Figure 6: Detaching the grease box from the end of the axle

This failure mode was confirmed by the appearance of the grease box after deformation (Fig. 7). Deformation is confirmed by pressing the box vertically from top to bottom on the end of the axle. Simultaneously, the deformation and breakage of the sealing ring occurred, as well as the deformation of the end of the axle (Fig. 8):

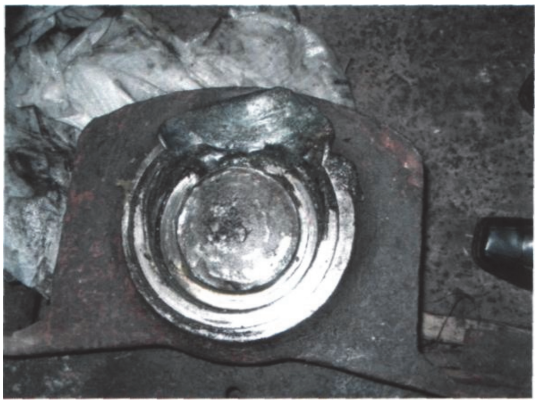

Figure 7: Aspect of the deformed area of the grease box

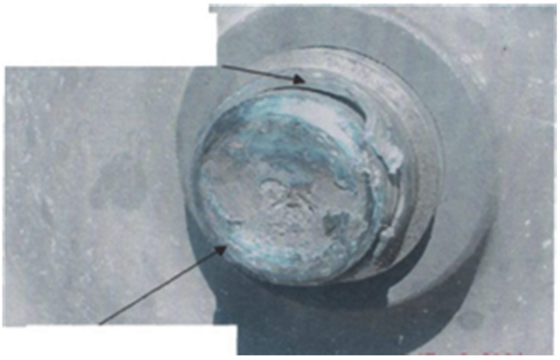

Figure 8: Aspect of the deformed area of the broken axle

This phenomenon was also highlighted in the research report in which it is specified that "Following the friction of the broken spindle pin in the upper edge of the axle box casing, major deformations occurred in the parts in contact, which allowed it to come out of the axle box and rolling friction on the inside face of the bogie frame."

The previous analysis allows establishing the following partial conclusions:

a) The spindle breakage occurred in the spindle-shutter connection area, as a result of the presence of a manufacturing defect in the superficial layer;
b) The complete break occurred only after reducing the useful section by 30-40%, as a result of the fatigue crack propagation;
c) The broken spindle pin together with the inner bushing with labyrinth rubbed against the grease box after the complete break of the axle;
d) The grease box remained in position after the axle broke, which excludes the break as a result of a box defect.

2. MEASUREMENTS AND ANALYSIS

2.1. Macroscopic analysis

The results of the investigations carried out on the broken axle in Gugeşti

The macroscopic aspect of the surfaces in different areas of the axle allowed the establishment of conclusions partially highlighted in the expert report and the expert supplement, but which were not explained in these two analyses:

1. The end of the axle spindles has a clearance (5 mm x 6°), which is not found in the execution drawing and can be visualized in Figure 9. This clearance (above which the 2 x 45° clearance was also executed) is found in the design of type A I axles, but also in the design of OR 1 axles.

The existence of this channel clearance led to the engineering confirmation of the idea expressed in the report, namely that the type A II axle was obtained by cutting the end of an A I or ORI axle.

A practice of cutting heads was recognized by representatives of the S.M.R. Balş, who invoked its necessity for economic reasons in the conditions of the failure of the vortex threading device, in the case of type AI axles on the manufacturing flow.

Such an operation, which is not included in any approved technological process, is evidence of non-compliance with the technology, which, in addition, leads to a series of disadvantages, since the execution of an axle in this way also requires the restoration of the centering holes for another attachment. This implies that, any eventual clamping on these new centering holes for the processing of some external surfaces, would lead to obtaining some deviations from the alignment with respect to the surfaces already finished on the initial centering holes. Visual analysis of the transition line (LT) between the conical area (ZC) and the cylindrical surface (SC) of the spindle, indicates a variable width of the ZC explained by the fact that it was obtained by clamping on the initial centering holes, and the SC which delimits was obtained by clamping on the subsequently machined centering holes.

There are other spindle locking systems in the CFR (Romanian Railways) park, for example, a wedge channel is milled on the front face of the spindle, the spindles are provided with three threaded holes M 20 x 50 mm, and the locking nut is made in the form of a disc of pressure. Such axes-axes were called OR 1-1 axes and Instruction no. 931 for the repair of axles mounted on railway vehicles in which the axle is mounted OR 1-1.

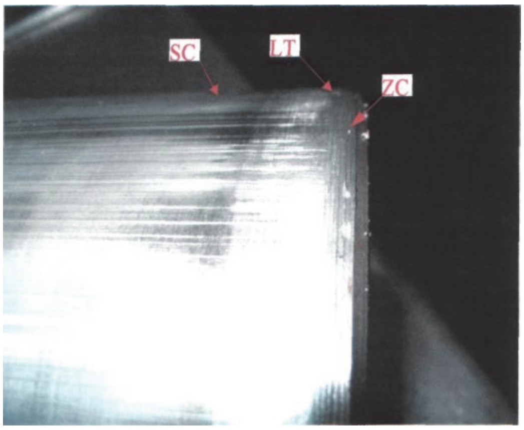

Figure 9: Tapered zone (ZC) on the end of the broken spindle

The existence of the conical surface with an inclination of 6° represents a deviation from the execution drawing, but it is not invoked as the cause of the spindle breaking, but as evidence of obtaining this axis by processing (cutting the ends) from an old one that had, according to the execution drawing, conical surface. The fact that this conical area has a variable width, but possibly highlighted in the expertise) is evidence of the processing at different grips of SC and ZC. Since ZC was machined by snapping to centering holes in the original axle, it follows that SC was machined by snapping to centering holes machined after cutting the ends. Considering the extremely small tolerances of the spindle on the initial axis (between +0.037 and +0.059 mm), any dimensional processing in this area involves increasing the diameter by previously adding a layer of material. Visual analysis allows, in the case of a broken axle, to highlight some circular marks on the surface of the spindle. It is specified that this cutting of the ends has the effect of removing all the markings that allow the identification of the modified axle. Whereas in the points of view of the C.F.R. no reference is made to the marking transfer operation, which is not included in the technological flow of the S.M.R. Balş, this operation cannot be considered as being included in a homologated technology and allows the loss of the identities of the modified axle.

The analysis of the front surface of the broken spindle (Fig. 10) highlighted the fact that several areas can be distinguished on the front surface of the spindle which, by the color of the oxide, prove that they have undergone heating. After this heating the front surface was machined, but with insufficient machining allowance to remove stains from the knife exit area of the threaded holes. at the same time, the conical clearance to protect the centering hole remained unprocessed.

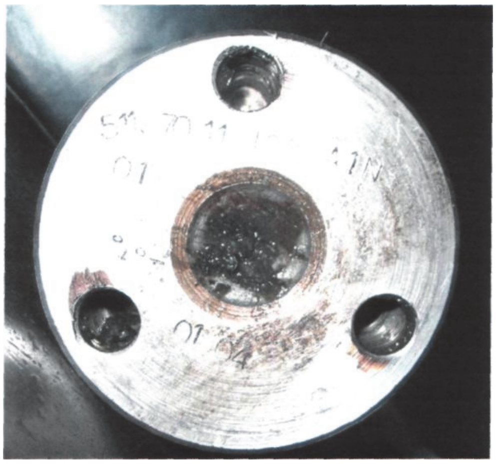

Figure: 10. Traces of heating on the front surface of the broken spindle

The uniform heating of the end of the axle to 255 °C, before the finishing turning of the front surface, cannot be explained by any of the technological operations in the technological flow developed by S.M.R. Balş. This heating can only be explained by the need to carry out a heat treatment (low rebound, stress relief or preheating) applied to the axle. The application of a heat treatment (even at a temperature of 250 °C) is not justified in the final phase of mechanical processing of the axle. Any such treatment should have been applied to the forged blank or roughened axle. The only plausible explanation is that the analyzed axle did not go through these stages (forged semi-finished or roughened axle), it comes from an old, refurbished axle. An old axle does not require subcritical heating, unless the refurbishment operation was required welding operations, which require preheating or stress relief. The application of this operation is to be confirmed by the analysis carried out further. The macroscopic analysis and the analysis with penetrating liquids confirmed the existence of some pores in all connection radii (Fig. 11 and 12).

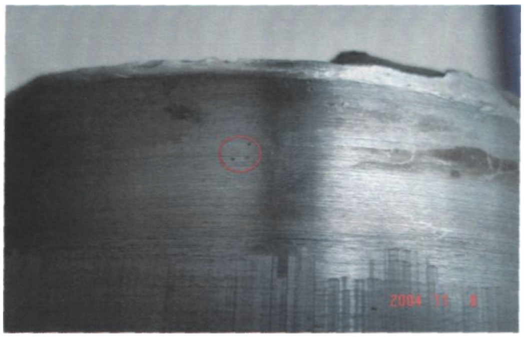

Figure 11: Pores on the surface of the broken spindle

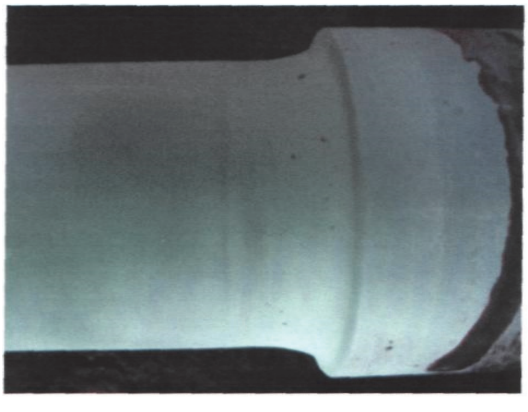

Figure 12: Pores in unbroken spindle junction areas

It is found that the pores are located exclusively in the connecting radii. In addition, the pores have a circular section, which is not characteristic for a forged material where the possible porosities from casting are flattened or even closed.The circular pores indicate the existence of a metallurgical operation, which consists of local melting on the entire circumference of the axle in all connection areas.

According to Welding Theory and Application Manual TC9-237, US ARMY OPERATORS, localized melting of metal by heating to an appropriate temperature where the filler metal has a melting point approximately equal to that of the base metal but above 427° C, is described by the term WELDING.

Macroscopic images are presented in the expert report, in which the existence of "circular cords" is found in the connection areas, after the application of a "0.2% nitric acid attack". It is also noted that these circular cords have "irregular edges having the shape of arcs of a circle".

The appearance is obviously characteristic of welding seams, confirming the results obtained in the analysis with penetrating liquids. The hardness measurements carried out in the expertise report indicated, without being explained in any way, in the same connection areas, hardness variations in the range of 160...260 HV. These values indicate an inhomogeneous structure or chemical composition over a distance from the spindle surface that can only be obtained by a welding operation.

The microscopic analysis carried out as part of the Report in the area of the so-called "circular cords" indicated the presence of several areas with distinct structures:

- basic structure;
- thermally influenced area;
- the "circular cord" structure.

These areas are the characteristic areas of a welding charge. The existence of welding charges in the connection areas was also confirmed by chemical analyzes that indicated large variations in the carbon content from the base metal to the melt-deposited bead. The definite proof of the existence of welding load cords in the areas of the connection radii required finding the causes that led to the determination of the reason that led to these loads.

The following were taken into account:

- the geometric shape and dimensions of the A II axle and some older axles
- the fact that SMR Balş confirmed the cutting of the threaded ends of the axles without indicating an approved technology and a procedure for transmitting the identification data of the old axle without any doubts.

The analysis performed indicated the following:

- Obtaining the A II axis by cutting the ends of an A I axis on the flow, could not justify the heating traces on the front surface nor the loading with welding, an operation prohibited by the U.I.C. norm. 811-1.
- All the previously indicated aspects explain the fact that the analyzed axle (Fig. 13) was obtained by welding an old OR 1-1 type axle, obtained by cutting the ends of the OR 1 axle (Fig. 14).

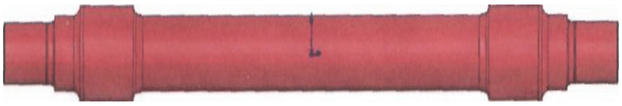

Figure 13: Drawing of axis A II

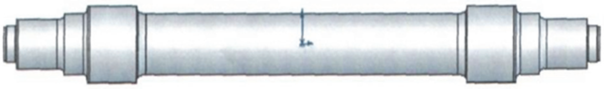

Figure 14: Drawing of the OR 1-1 axis obtained by cutting the ends of an OR 1 axis

If the two axes are analyzed comparatively, the existence of four areas where differences appear in terms of dimensions can be seen (Fig. 15):

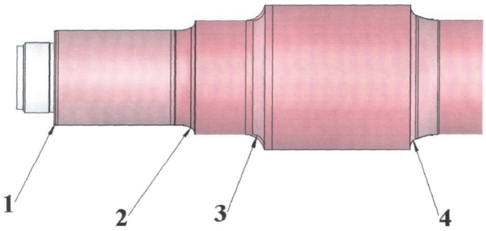

Figure 15: Areas with differences in size

Zone 1 - The difference consists in the existence of an additional clearance on the A II axis (5 mm x 6°), which is only found on the A I and OR 1 axes (Fig. 16).

The role of the clearance and that of the connections at the section transitions is to reduce the voltage level without introducing voltage concentrators that would amplify their level. The larger the connection radius, the smoother the section transition and the lower the stress level. This also has a favorable role in increasing the fatigue resistance of the axles.

Zone 2 - The difference between the connection radii in the spindle - shutter connection area, which imposed the loading by welding the old axle (Fig. 17).

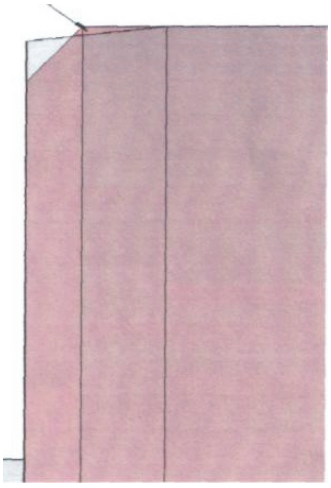

Figure 16: Zone 1

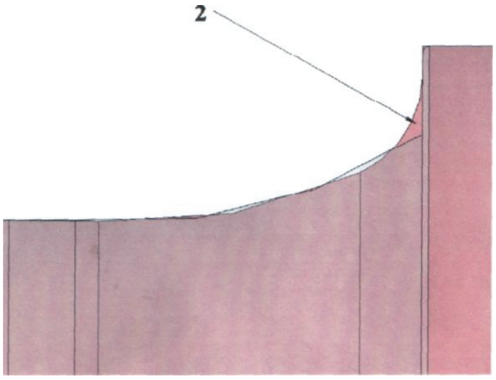

Figure 17: Zone 2

Zone 3 - The difference between the connection radii in the connection area of the mounted shutter, which imposed the loading by welding of the old axle (Fig. 18).

Zone 4 - The difference between the connection radii in the center of the axle, which imposed the welding loading of the old axle (Fig. 19).

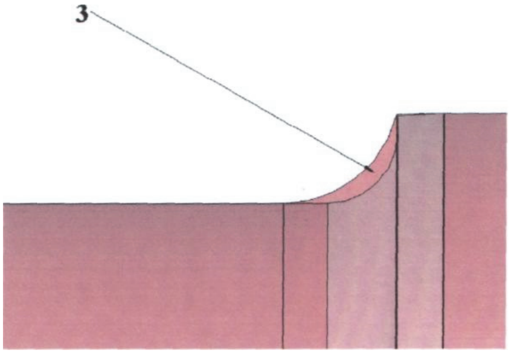

Figure 18: Zone 3

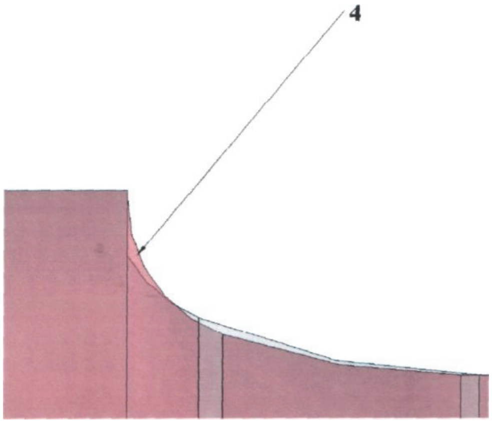

Fig. 19. Zone 4

The obvious coincidence between the areas where weld seams were observed and those where the A II axle has a surplus of material compared to the OR 1 axle, shows that the A II axle comes from an OR 1 axle.

The fact that the centering holes of the analyzed axle have the prescribed dimensions, reveals the fact that the OR 1 axle was previously transformed into an OR 1-1 axle by cutting the ends.

The analysis of the front surface shows that the analyzed axle no longer required the cutting of the ends, but only the removal of the marking, partially by turning, partially by hitting.

The small addition of processing on the front surface (so as not to reduce the length of the spindle), did not allow the removal of the oxide layer from the exit area of the knife from the previous turning. The oxide layer on the protection cone of the centering hole also remained, as the processing of this surface would have led to an even more obvious increase in the diameter of this area (for axis A II the maximum diameter is 40 mm, and for axes OR 1 and OR 1-1, the maximum diameter is 50 mm).

The roughness measurements in the connection areas indicated much higher roughness values than those provided in the documentation (Ra = 5...5.5 m, compared to Ra = 0.8 m imposed by the drawing) (Fig. 20).

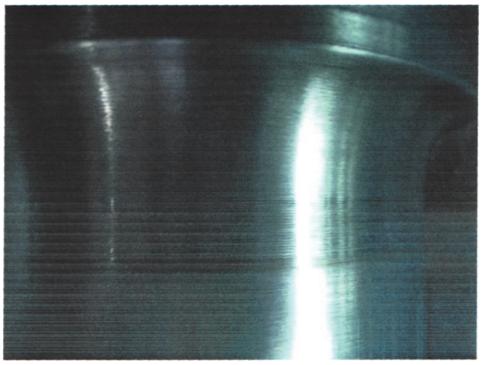

Figure 20: High roughness in the connection area

Partial conclusions:

1. The axle does not respect the dimensions in the drawing (spindle ends and centering holes).
2. by welding. This fact leads to the induction of internal tensions and the weakening of the structure.
3. The roughnesses in the connection areas are higher than those provided, which contributes to the reduction of the fatigue resistance of the axle.
4. For both axles, A.F.E.R. indicated identical conclusions, namely:
5. The roughness of the surfaces of the spindles and the connection areas "do not fall within the provisions of the reference documentation and of the execution drawings, being able to become stress concentrators, leading to the breaking of the axle".
6. In the area of the spindle - shutter connection, traces of impacts and microcracks were highlighted, which can become primers for breaking due to fatigue.
7. The material of the axles does not fall within the provisions of the reference documents, on their surface there is a material deposited by welding, starting from the connection of the spindle with the sealing area until the connection of the sealing surface with the mounting surface, material that has a different composition and other metallographic characteristics.
8. Based on the comparative analysis of the axes presented, the following partial conclusions can be drawn:
9. All type A II axles broke due to fatigue in the connection areas where welding load cords and roughness values higher than the values in the documentation could be highlighted.
10. The chemical composition of the analyzed axles differs from the chemical composition of liquid steel. The difference is greater than the maximum value allowed by the UIC 811 standard for batching.
11. Corroborating the data presented previously, it can be concluded that the axles A II indicated as being part of actually old OR 1 or OR 1-1 type axles loaded by welding.

3. ANALYSIS OF a cracked AXLE TYPE A II

A 3D model of the AII axle was made using a mechanical design software (Solid Works). Constraints, static or dynamic loads were applied to this model (Fig. 21) in order to be able to determine the value of the von Mises stresses by numerical methods.

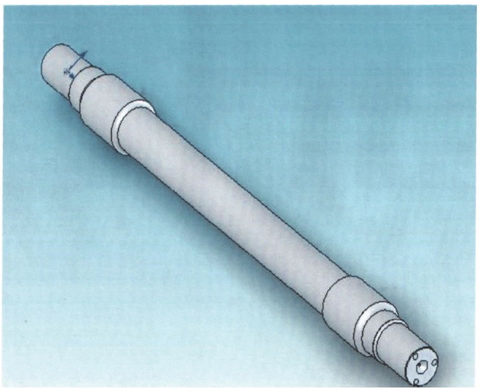

Figure 21: 3D CAD model of axle type A II

Also, a maximum load of 100000 N was applied to both ends of the axle (Fig. 22). Two estimates were made: an estimate of the stresses that appear in the axle in the case of applying the nominal static load and a second estimate of the stresses that appear in the axle as a result of dynamic stresses in curves, with the axle not braked.

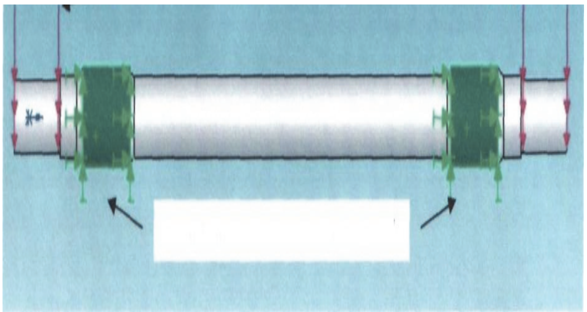

Figure 22: Constraints and loads applied to the 3D CAD model of the type A II axis

After the finite element discretization of the 3D CAD model of the type A II axle, the numerical calculations were performed and resulted in a maximum von Mises stress value of 80.14 MPa), which is well below the breaking limit of the material used for production of axles (Fig. 23), value between 550 and 700 MPa (according to the U.I.C. 820 sheet).

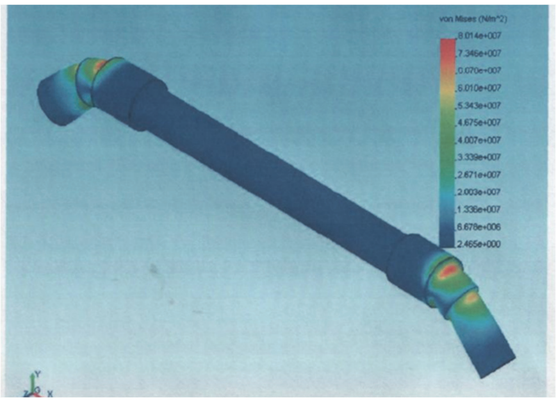

Figure 23: The von Mises stresses resulting from finite element calculations on the 3D CAD model of the type A II axis, in the case of static stresses

The maximum stress thus calculated, considering the dynamic stresses in curves, with the axle not braked, is 110.7 MPa (Fig. 24).

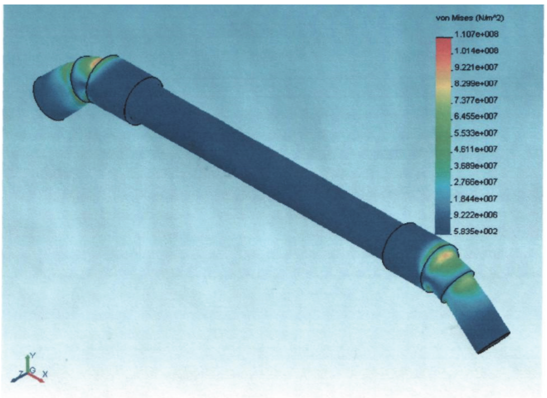

Figure 24: The von Mises stresses resulting from finite element calculations at the 3D CAD model of the axle type A II, in case of dynamic stresses

3. GENERAL CONCLUSIONS

a) The spindle breakage occurred in the spindle-shutter connection area, as a result of the presence of a manufacturing defect in the superficial layer;

b) The complete break occurred only after reducing the useful section by 30-40%, as a result of the fatigue crack propagation;

c) The broken spindle abutment together with the inner bushing with the labyrinth rubbed against the grease box after the axle was completely broken;
d) The grease box remained in position after the axle broke, which excludes the break as a result of a box defect.
e) The execution documentation of the type A II axle - SMR Balş project shows many non-conformities with the UIC 811-2 sheet. The axle does not respect the dimensions in the drawing (spindle ends and centering holes).
f) The execution and control technology (and CFR reception) presents important deficiencies, due to non-conformities in the execution drawing.
g) There is no homologated execution and control technology, which allows the transition during manufacturing from AI-type axles to A-II axles.
h) The structure in the connection areas is modified as a result of welding loading. This fact leads to the induction of internal tensions and the weakening of the structure.
i) The roughness in the connection areas are greater than those provided in the execution drawing, which contributes to the decrease in the fatigue resistance of the axle.
j) All type A II axles broke due to fatigue in the connection areas where welding load cords and roughness higher than the values in the documentation could be highlighted.
k) The chemical composition of the analyzed axles differs from the chemical composition of liquid steel. The difference is greater than the maximum value allowed by the UIC 811 norm for batching.
l) Corroborating the data presented previously, it can be concluded that the axles A II indicated as being part of batch no. 511970 are actually old OR 1 or OR 1-1 type axles loaded by welding.
m) Depositing a weld bead on an axle will lead to a dramatic decrease (by a factor of at least 1/10) in the number of cycles until breaking and implicitly in the number of kilometers traveled or the life time.
n) The larger the value of the pre-existing crack in the connection area, the shorter the number of cycles until breakage and implicitly the number of kilometers traveled or the life time.
o) In SMR Balş, the manufacturing technology of the A II axle was not respected, there is a possibility that the axles of type A II, obtained by reconditioning some old axles, will be marked with the number of some axles belonging to a random batch.
p) The type A II pseudo-axles do not fully meet the conditions established in the execution documentation and in the reference documents of the type A II axle, approved by SNTFM "CFR MARFĂ" S.A. and the Romanian Railway Authority - AFER and for which a Preliminary Railway Technical Approval Certificate of manufacture, for ROLLING APPARATUS drawing ZFF 04/1.0. N, which has as its composition wheelset TYPE A II.

ACKNOWLEDGEMENT

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