Causes and Probability of Premature Fatigue Cracks in Railway Axles

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***Abstract*—Fatigue is one of the most common forms of damage to structures, moving parts of machines, devices and vehicles. It is estimated that over 80% of all cracks are due to fatigue. The axle is considered to be the most heavily loaded element in a railway vehicle. Despite the fact that there is progress in the field of computational methods and technological processes of axle production and their acceptance, diagnostic methods during inspection, these elements are exposed to fatigue fracture, which is often the cause of serious railway accident. The article presents cases of fatigue cracks in railway axles and discusses their causes.**

***Keywords*—railway vehicle, wheelset, axle, fatigue, cracking**

I. Introduction

Fatigue of materials is the failure due to a crack that slowly develops over time, or cracks under the influence of cyclically changing loads. Fatigue is a dangerous form of failure because it usually occurs below the yield point and occurs suddenly and without warning. Fatigue is one of the most common forms of destruction of structures, moving parts of machines, devices and vehicles. It is estimated that over 80% of all cracks are due to fatigue.

Three types of fatigue failures can be distinguished:

a / for materials (structures) that do not contain preliminary cracks:

- high cycle fatigue failure; occurs at stresses much lower than the yield point and a sufficiently large number of cycles (10^5-10^8),

- low cycle fatigue failure; occurs in structures and components exposed to temporary overload above the yield point and with the number of cycles lower than 10^4-10^5,

b / for large structures containing cracks in the initial state (especially welded structures); the process controlling the failure of such structures is the rate of crack propagation under cyclic loads, not the crack initiation process.

Fatigue failure of metals and alloys begins with the nucleation (initiation) of the crack, followed by the phase of the crack development (propagation, growth). The number of cycles to failure N_f is the sum of the cycles to nucleation N_n of the crack and the cycles during which the crack develops N_p.

$$N_f = N_n + N_p \tag{1}$$

The number of cycles necessary to initiate a fatigue crack, in the case of high-cycle fatigue of smooth laboratory samples, is up to 80% of the number of cycles necessary to failure the material. For low-cycle fatigue at high stress levels, the range of crack propagation ($N_p > N_n$) is dominant. In the case of high stress amplitude, approx. 90% of the element/structure life phase is the fracture development stage. If an element/structure has a pre-fracture (notch), this percentage is even greater.

The following factors affect fatigue strength:

- presence of a notch (cavities, scratches, subsurface non-metallic inclusions or precipitations of hard phases),
- average stresses in the cycle σ_m,
- environment (corrosion pits),
- microstructure,
- residual stresses (due to the influence of the average cycle stress σ_m).

The fatigue life is particularly sensitive to the surface condition and hence most of the fatigue cracks are initiated on the surface of samples/components /structures.

II. Fatigue Failure of the Axles of Railway Wheelsets

Wheelset axles are one of the critical elements of a rail vehicle, decisive for the operational safety of wagons and locomotives. The axle is considered to be the most heavily loaded element in a railway vehicle.

Despite the fact that there is progress in the field of computational methods and technological processes of axle production and their acceptance, diagnostic methods during inspection, these elements are exposed to fatigue fracture, which is often the cause of serious railway accidents, causing significant material losses and fatal accidents.

The axle is designed for high cycle fatigue, which means the axle can operate with unlimited fatigue strength.

Railway axles are designed for high cycle fatigue, with no mileage and no limitations on service life. Therefore, they are used until the inspection proves that the product is unfit for further safe performance of its function.

Due to the distribution of cyclic stresses in rotational bending in the axis, the greatest bending moments occur in the section axle journal – dust collar – wheel seat - a radius of transition from the seat to the body of an axle. This is also where fatigue cracks initiated on the axle surface occur most frequently (Fig. 1). These cracks appear in particular in freight wagons after long use.

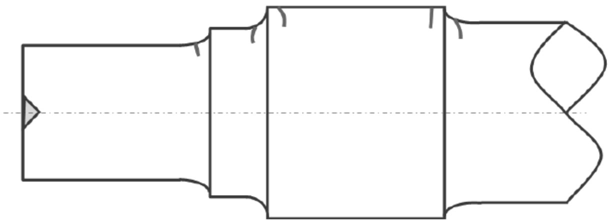

Fig. 1. The places of the railway axle most exposed to the occurrence of fatigue cracks [1]

The sources of the emergence of additional hazards in the operation of the axles of rail freight wagons and the formation of fatigue cracks can be divided into the following groups:

- overloading the wagon,
- dropping the load while loading/unloading,
- corrosion and pitting,
- poor condition of infrastructure (dynamic loads).

A new axle is equally exposed to fatigue cracks as an operating axle, if it has subsurface defects caused in the process of its manufacture, or surface defects such as scratches, microcracks and other discontinuities in materials that appear during operation and are initiation places of fatigue cracks.

Taking into account the service life of an axle showing no defects, the life to failure is an essential part of the overall fatigue life of a wheelset axle. This phase of a wheelset axle service life can be shortened by surface or subsurface defects that occurred during the manufacturing stage and were not detected, or due to damage during operation - by corrosion or mechanical impact - and contribute to the formation of fatigue cracks.

III. MAXIMUM PERMISSIBLE STRESSES OF AXLES

Railway axles of wheelsets (non-powered and powered) can be classified as highly stressed elements due to the safety factors adopted in their design. According to EN 13103: 2009, concerning the design of the axles of rolling wheelsets, for calculations with static loads for EA1N steel, the safety factor S = 1.2 is assumed (Table 6 on page 28 of the standard).

According to the standard, all calculations are made on the basis of analytical calculations without the use of FEM. The value of the safety factor at the level of 1.2 means that the axis has only a 20% margin to reach the yield point, with the assumed allowable stresses. In the event of unforeseen loads or additional stresses, the yield point can easily be reached locally, which can lead to its permanent deformation (excessive axial runout) or initiation of low-cycle fatigue.

Achieving local stresses in the railway axis close to the yield point of the material may be caused by:

- exceeding the permissible load capacity of a freight wagon,
- one-sided axle overload as a result of asymmetrically distributed loads in the wagon or overcoming bends with excessive speed,
- stresses resulting from operational loads summing up with the stresses resulting from the wheel press-in on the hub, the stresses remaining in the axis after the manufacturing process,
- additional dynamic loads as a result of the interaction of the wheels with the uneven track surface,
- the scatter of mechanical properties of the axle material (especially a yield point) on the cross-section and longitudinal section, which is typical for large-size forgings. In practice, the yield point spread may be from 50 to 70 MPa.

Fig. 2 shows the distribution of the maximum stresses in the tested axle, after applying a load in accordance with the EN 13103 standard, and their reference to the permissible stresses [3]. The diagram shows that the design stresses locally within the wheel seat have reached the level of allowable stresses (the area marked in green).

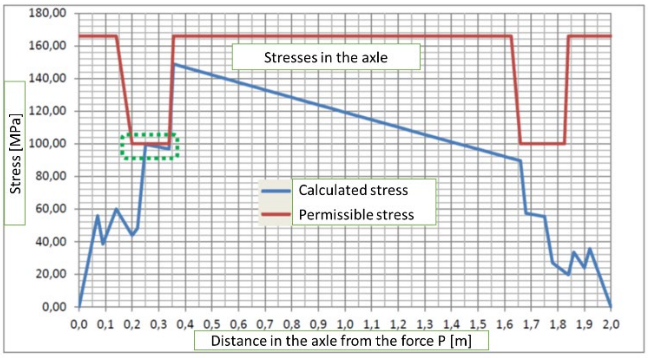

Fig. 2. Stresses in the tested railway axis [3]

Safety factor - a unitless number used in the strength of materials and construction calculations, indicating how many times the allowable stress for a given structure is lower than the dangerous stress.

The dangerous stress for elastic-plastic metallic materials is usually the yield point for static loads, and the fatigue strength for cyclic loads.

The value of the safety factor is assumed depending on the type of metallic material (steel, cast steel, cast iron, aluminum alloys, copper alloys) and the type and responsibility of the structure from the point of view of its operational safety.

The values of the safety factors are given in the relevant standards, and range from 1.1 to 20, for example in typical applications the following values are assumed:

- aviation 1.5
- chains 4.0
- ropes of lifting and hoisting devices 6.0-12.0.

IV. PROBABLE CAUSES OF FATIGUE CRACKING OF RAILWAY AXLES

The causes of fatigue cracks in railway axles include:

- mechanical damage to the axle surface due to errors in assembly and disassembly of axle boxes, bearings, wheels, brake discs,
- mechanical damage to the axle surface as a result of impact during the operation of a railway vehicle,
- initiation of high-cycle fatigue crack as a result of long-term (many years) operation of the axle; in this case, it may be the mechanism of the formation of slip bands in the surface grains, or differences in the deformability of non-metallic inclusions or particles of a different phase and the metallic matrix,

- initiation of low-cycle fatigue crack as a result of axle overload and local stress increase to the yield point.

The probable hypotheses for accelerated breakage of the railway axle between the repairs of the wagon according to the MSD (maintenance system documentation) of a railway wagon and the ultrasonic tests seem to be:

- mechanical damage to the surface during operation (e.g. stone impact from the ballast)
- and/or axle overload.

As fatigue cracks most often nucleate on the surface, the surface condition has a significant influence on the fatigue strength. Increasing the roughness and depth of micro-irregularities reduces the fatigue resistance of the material. Machined scratches and cuts as well as microcracks are especially dangerous when placed perpendicular to the main tensile stress direction as they act as stress concentrators. Deep scratches and dents on the surface dramatically reduce the fatigue life of components subjected to cyclic loads.

V. EXAMPLES OF FATIGUE CRACKING OF RAILWAY AXLES

From 2016 to 2019 twenty three B11 accidents occurred in Poland (Fig. 3) in which the direct cause was the fatigue crack of the axle (data derived from reports of State Railway Accident Investigation Commission). The scope of data submission starts in 2016, as from this year all infrastructure and siding managers are required to report incidents to the Commission.

Accordin to Polish national act on railway transport "accident" (B) is an unintentional sudden event or sequence of such events involving a railway vehicle, causing negative consequences for human health, property or the environment; accidents include in particular:
a) collisions,
b) derailments,
c) events at level crossings,
d) incidents involving persons caused by a moving railway vehicle,
e) fire of a railway vehicle.

According to Regulation of the Minister of Infrastructure and Construction of 16 March 2016 on serious accidents, accidents and incidents in rail transport – "B11" accident is damage or poor technical condition of the wagon.

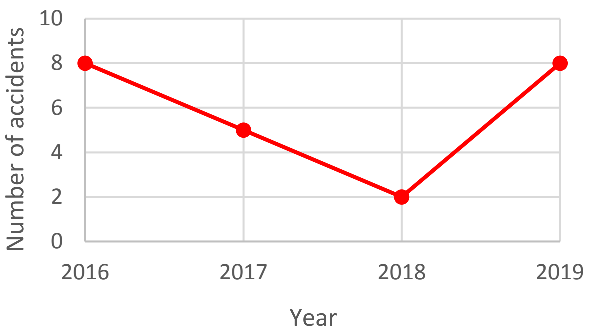

Fig. 3. Number of category B11 accidents, in which the axle fatigue cracking took place

The fatigue crack shown in Figure 4 and Figure 5 derives from the B11 accident of the freight wagon in 2015 [4]. The immediate cause was a fatigue crack in the middle part of the first axle of the first wheelset, while the primary cause was an old surface defect of the axle. A crack has taken place on the axle body. The origin of the crack was the surface defect unnoticed during inspection. The smaller area of the fatigue zone and the larger area of the rapid fracture zone indicate high loads on the axle. The lack of stop and radial lines indicates the rapid development and propagation of the crack that took place on the presented fracture surface. Numerous defects and pitting can be seen on the axle surface, moreover, the shape of the axle is deformed as a result of a derailment of the train.

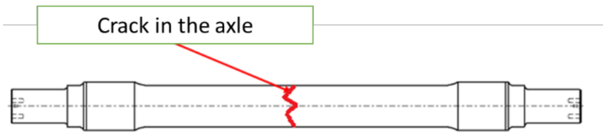

Fig. 4. The place of the axle fatigue crack

Fig. 5. Fatigue cracking surface of the axle of the freight wagon [4]

Another example of fatigue cracking classified as B11 accident is from the derailment of a freight wagon in 2019 [4]. The immediate cause of the incident was a fatigue fracture in the middle of the axle body of the third axle in a wagon. The origin of the crack was the surface defect of the wheelset axle. This axis was subjected to lower bending and rotational loads, which indicates a larger area of the fatigue zone compared to the rapid fracture zone and the presence of stop lines (Fig. 6). The development of the fracture progressed slowly, as indicated by the stop lines.

Fig. 6. Fatigue cracking surface of the axle of the freight wagon [4]

Last example of B11 accident with fatigue cracking is from the derailment of a freight wagon in 2019 [5]. The immediate cause of the incident was a fatigue fracture in the journal of the axle (Fig. 7). It can be seen from Fig. 8 that about 40% of the cross-section is fatigue area, which indicate high loads on the axle. The primary cause is improper machining of the axle surface (Fig. 9), i.e. undercut, which resulted in an unfavorable distribution of stresses in the axle and initiation and development of fatigue crack.

Fig. 7. The place of the axle fatigue crack

Fig. 8. Fatigue cracking surface of the axle of the freight wagon [5]

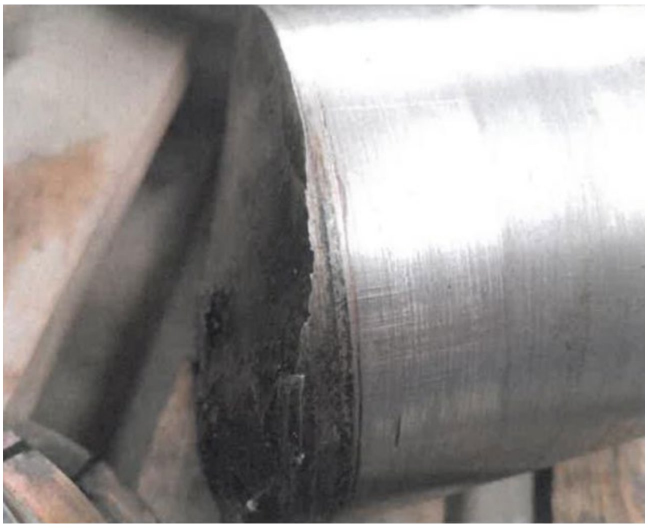

Fig. 9. The fatigue fracture area of the axle journal with visible undercutting [5]

VI. CONCLUSIONS

Despite the fact that railway axles are designed for unlimited fatigue strength, they often fail due to fatigue, which leading to rail accidents.

Fatigue cracking of railway axles is initiated in the places of stress concentration and/or the occurrence of geometric notches.

Notches on the surface are caused by mechanical damage, improper machining, pitting corrosion and fretting.

During inspection and repair of wheelsets, particular attention should be paid to detecting even slight scratches and surface cracks, which may cause initiation and development of fatigue cracks.

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