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INVESTIGATION OF THE CAUSES OF THE FRACTURE OF THE DRIVE SHAFT OF THE ELECTRIC LOCOMOTIVE

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Abstract:
The paper provides a systematic analysis of the origin, spread, and causes of shaft failure in the four-axle electric locomotive series 441. Based on this analysis, recommendations for preventive diagnostic maintenance are provided to timely identify the condition and avoid shaft failure, which is a vital component of the locomotive. Failure to maintain it in a timely manner can lead to catastrophic human, ecological, and material consequences. The paper also presents and explains the fracture surfaces of the locomotive's hollow drive shaft, following a railway incident that caused the derailment of the rail vehicle, resulting in significant material damage. The presented fracture analysis is based on research into the mechanisms of failure, which by their appearance and action cause the formation of an initial crack. The dominant factor in the formation of the initial crack is material fatigue, and the potential presence of inclusions or local initial notches in the material structure formed during the shaft manufacturing process. Research has shown that the measured residual internal stresses after the shaft failure reached up to 470 MPa, significantly exceeding the allowable 300 MPa.

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1. INTRODUCTION

The locomotive drive shaft, along with the wheels, represents a critical component of the locomotive, on which the safety of railway traffic heavily depends [1-4]. Drive shaft failures typically result in vehicle derailments, leading to potentially significant safety risks for passengers, vehicles, and the environment [5]. With the development of railway transportation and various operational modes of trains, especially on mountainous railways, there has been an increase in equipment failures due to heightened material fatigue. A significant portion of incidents in the railway industry related to equipment failure is attributed to the propagation of fatigue cracks in locomotive drive shafts [6,7].

The locomotive drive shaft is one of the most important components of a rail vehicle. In addition to torsional stress, it transmits the vehicle's weight to the wheels, handles both vertical and horizontal loads occurring during static and dynamic movement, and bears both the driving and braking moments [8]. These variable (combined) stresses on the shaft can lead to the development of so-called fatigue cracks, which often occur at notches (local depressions, grooves) [9,10]. Fatigue cracks may be caused by transition radii, non-metallic inclusions, ballast stone impacts, or corrosion [11]. Under mechanical stress during operation, such cracks can begin to propagate and eventually lead to fracture [12,13]. In locomotive drive shafts, cracks are exclusively formed in the radial direction, particularly at seating areas and their radii. The degree of fatigue damage to the locomotive's drive

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shaft is one of the limiting factors in the safety of railway vehicles [14]. The concerns above were the primary motivation for investigating the fracture incident involving the drive shaft of the electric locomotive series 441, which occurred on the railways of the Republic of Srpska in 2023. Given the problem's high complexity, this study aimed to analyze and explain the specific incident – the failure mechanisms of the locomotive drive shaft, which resulted from material fatigue and was aggravated by mechanical, corrosive, and thermal stresses. The aim was to shed light on the contributing factors that initiate micro-cracks, as well as their growth and propagation.

In order to adapt to the anticipated increase in railway travel demands, the railway industry must maintain its status as one of the safest modes of transportation. Selecting efficient maintenance policies is the key to achieving high levels of reliability and competitiveness in railway systems [15], ensuring they retain their status as one of the safest means of transportation [16]. Finding optimal maintenance methodologies while minimizing costs has been a major concern for railway system maintainers [17-19]. In practice, inspections of this critical equipment are linked to the mileage of the vehicles [20]. Based on the conducted research and practical experience, this paper proposes a preventive, diagnostic inspection of the material condition of locomotive drive shafts older than 20 years, which is not defined by national or international railway standards. The fundamental diagnostic inspection relates to damage tolerance, which is the ability of the structure to carry expected loads in the presence of aggressive environmental effects, material fatigue, and incidental damage, up to the detection of damage (either during regular or extraordinary inspections) and its subsequent repair.

2. MATERIALS AND METHODS

This study investigated the drive shaft failure in the series 441 electric locomotive during its operational period. The research was conducted in 2013, with observations covering a total of 20 freight wagons that operated under traction load. All research was carried out on the railways of the Republic of Srpska in Bosnia and Herzegovina.

Fig. 1 presents a technical drawing of the locomotive drive shaft with a central longitudinal hole of 30 mm in diameter, excluding the wheels and reduction gear elements. The shaft shown in Fig. 1 is the subject of this research.

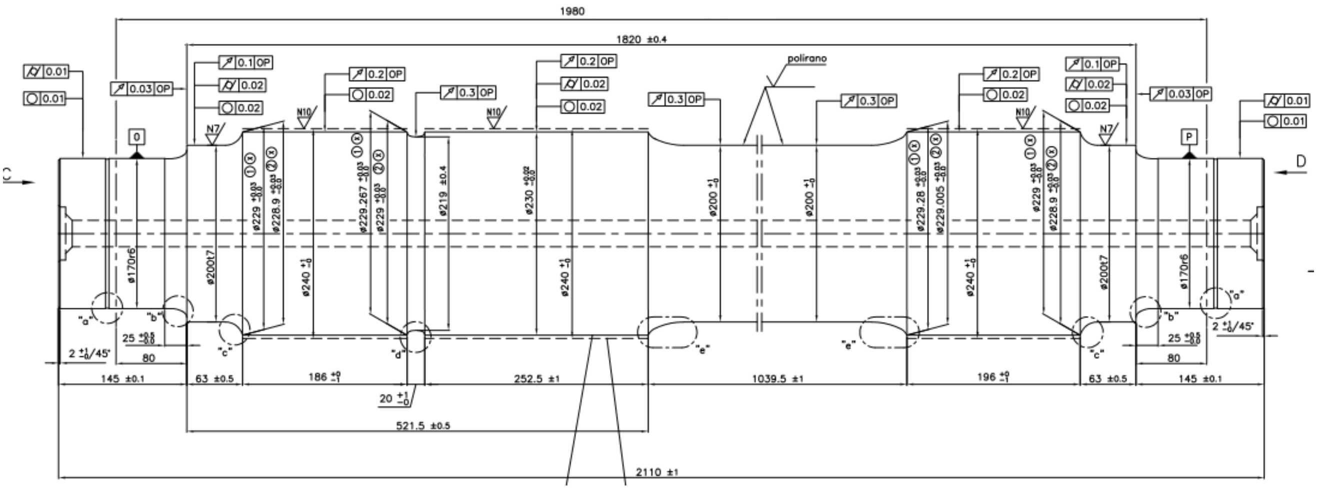


Fig. 1. Drive shaft of a locomotive, series 441 [21,22]

2.1 Location, Identification of the Failure, and Measurement of Residual Stresses

The locomotive axle assemblies consist of four main components: the shaft, wheels, reduction gear, and bearings. A significant number of incidents, including the case described in this study, involve the failure of the drive shaft due to crack propagation in areas with excessive stress concentration. For the observed drive shaft of the series 441 electric locomotive (42CrMo4 or the alternative 26NiCrMoV14-5), fatigue strength was estimated in critical regions of the shaft under working stress. The various loads applied to the components lead to cumulative mechanical failures. The observed electric locomotive drive shaft bears all loads from its own weight, the torque transmitted by the reduction gear mounted on the shaft, the forces arising from wheel-rail contact, the traction load of the entire train, and the braking forces.

As partially depicted in Fig. 2, the crucial role in initiating cracks in the locomotive drive shaft is played by forces caused by the traction torque and by static and dynamic vertical and horizontal forces acting near each end of the axle via the bearings, while a reaction force (also in the vertical direction) acts at the contact surface between the axle (wheel) and the rail [23]. Furthermore, on curved sections of railway tracks, a lateral (side) force generated by wheel-rail contact acts toward the outer rail. The locomotive drive shaft is subjected to typical rotational torsion and bending stress [24,25].

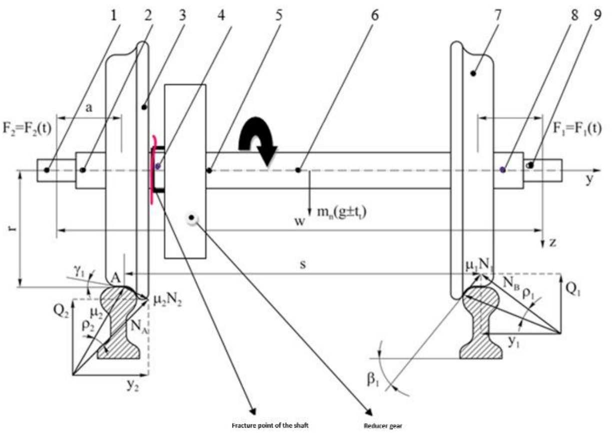
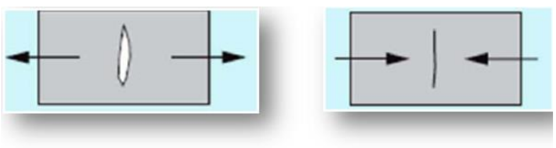


Fig. 2. Measurement locations of residual stresses in the shaft after fracture

Residual stresses in the transmission component, i.e., in the railway vehicle's axle assembly (composed of the shaft, monoblock wheels, and reduction gear), can be either compressive (negative) or tensile (positive), as shown in Fig. 3.



a) „+"　　b) „–"

Fig. 3. Internal stresses a) tensile (positive) and b) compressive (negative)

To predict the behavior of traction locomotive shafts under operational conditions, it was necessary to assess the dynamic durability of the critical regions of the shaft where high stresses prevail. The proposed concepts for assessing the dynamic durability of shafts that have been in service for 20 years or more are based on scientific recommendations and standards, which need to account for the actual loads encountered by rail vehicles in natural working conditions.

Stress measurement in the locomotive shaft was performed at diameters and in the zones of transitional diameters where stress concentrations are particularly high, as shown in Fig. 2. The purpose of this measurement was to understand the distribution of stress in these critical areas. For the research, a diagnostic device for residual stress measurement, DEBBI, was used. Figs. 4 a) and b) shows the process of measuring residual stresses in the locomotive shaft assembly following a failure, which was crucial for understanding the factors contributing to the failure.

a)

b)

Fig. 4. Measurement of residual stresses on the locomotive shaft assembly after fracture

3. RESULTS AND DISCUSSION

3.1 Investigation of Fracture Mechanisms

The investigation of the fracture mechanisms of the locomotive shaft revealed that the fatigue of the hollow shafts of the electric locomotive was caused by complex loads (as partially explained in this study), which led to the formation of an initial crack around the shaft's central hole.

During the research period, a fracture occurred on a 28-year-old traction shaft. The disassembly of the traction shaft confirmed the expected failure, i.e., the fracture of the shaft occurred at the transition diameter of the axle bearing journal and the journal of the reduction gear, as shown in Fig. 2 of the axle shaft assembly.

3.2 Cause of the Fracture

Upon examining the fracture location based on the presence of the initial crack and the stress state diagnosis of the entire locomotive shaft, as well as considering the operational period, it can be reliably concluded that the cause of the fracture was a result of complex mechanical stress over long-term exploitation, which led to excessive material fatigue.

By conducting a comprehensive analysis of the service life of the shafts, primarily operated on mountainous railway tracks characterized by extreme slopes, ascents, and curves, it can be concluded that all complex mechanical stresses, particularly torsional and dynamic-vibrational, were involved.

Considering the facts mentioned above, it can be concluded that the cause of the fracture of the electric locomotive's driving shaft is primarily due to material fatigue produced by complex mechanical stress and excessive residual stresses. Under such operational conditions, extreme torsional stresses and dynamic oscillations were generated, and the geometry and dynamic characteristics of the tracks also played a significant role in the failure.

It is known that material fatigue represents a gradual degradation process caused by the initiation and growth of cracks under prolonged cyclic loads, which are significantly lower than static loads. Based on the material fracture structure, it is evident that the fatigue process leading to the fracture occurred in three distinct phases:

1. Initiation of the initial crack;
2. Crack propagation;
3. Complete fracture of the shaft across its cross-section, caused by the initial crack.

3.2.1 Initiation of the Initial Crack on the Shaft

The initiation of the initial crack on the electric locomotive's driving shaft is the result of material fatigue caused by complex stress loads during operation. The research showed that such initial cracks typically appear at critical locations, i.e., transition diameters with high stresses. In this case, the initial crack was located centrally around the longitudinal hole in the shaft, at the transition diameter of the wheel hub journal and the diameter where the reduction gear was installed. This is visible in Fig. 5, on the side of the reduction gear, and Fig. 6, on the wheel side of the shaft. In this location, extremely high stresses were present, and further exploitation under complex combined loads created the conditions for further crack propagation.

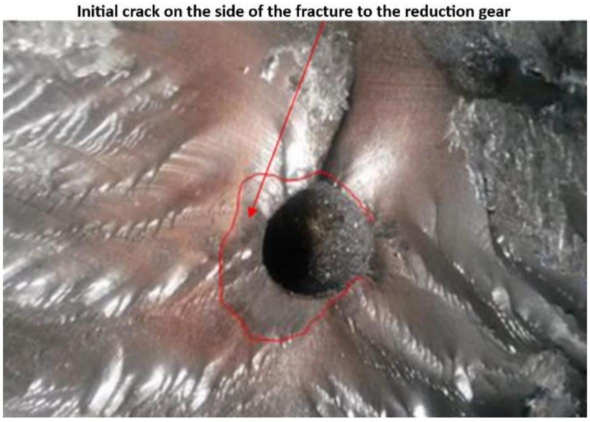


Fig. 5. Position, shape and structure of the initial crack to the reduction gear

Fig. 6. Position, shape and structure of the initial crack to the drive wheel

3.2.2 Crack Propagation in the Shaft

Given that the material of the locomotive's driving shaft is improved and has high strength and toughness, it has the characteristic of withstanding high static and dynamic loads. The fine-grain structure of the material clearly indicates that the propagation of the initial crack due to combined loading is an inevitable mechanical process. The crack propagation zone is very smooth (roughness at the level of crystal grains), as shown in Figs. 7 and 8.

Fig. 7. Propagation of the initial crack in the shaft, position on the side of the resulting fracture to the reduction gear

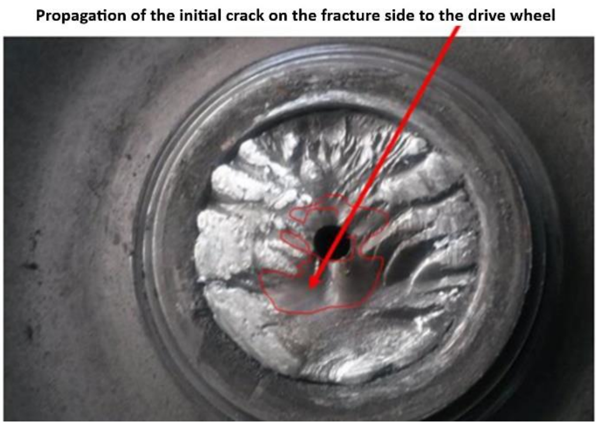


Fig. 8. Propagation of the initial crack in the shaft, position on the side of the fracture to the drive wheel

3.2.3 Complete Fracture of the Shaft across its Cross-Section Due to the Initial Crack

The fracture of the locomotive's driving shaft can be defined as the macroscopic separation of the material, which led to the loss of the shaft's load-bearing capacity. The fracture's physical cause is cyclic bending and torsional stresses, which brought the shaft to a critical state, resulting in a complete fracture. This stress occurred during the locomotive's startup from a stationary position when extreme torsional stresses arose. The fracture structure shows this clearly, as evidenced by its coarse surface, which is characteristic of a static fracture.

Figs. 9 and 10 show the destructive atomic bond of the radial shaft fracture structure, characterizing it as a torn structure oriented toward the shaft's rotational movement.

The driving technique of the locomotive, i.e., starting the locomotive from a stationary position, did not significantly affect the outcome of the shaft fracture, given the described state of the shaft. In such cases, the fracture typically occurs at lower speeds, i.e., during startup or stopping of the train, when torsional stresses are higher. Figs. 9 and 10 clearly show that the shaft's crystal lattice was instantaneously torn apart when the driver increased the train's speed. Thus, increasing torsional stresses, combined with the weakened shaft due to the initial crack, led to a complete fracture.

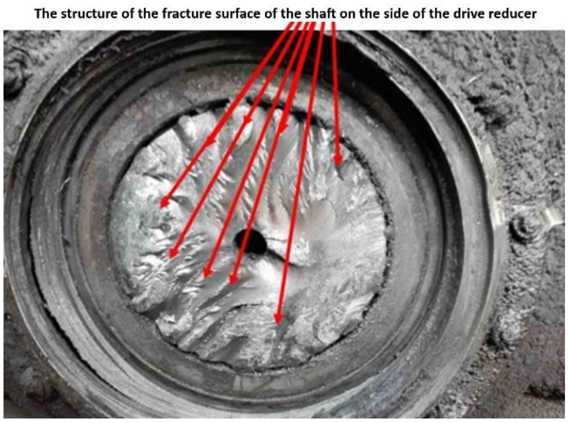


Fig. 9. Relief of the tearing structure in the drive locomotive shaft on the side of the reducer

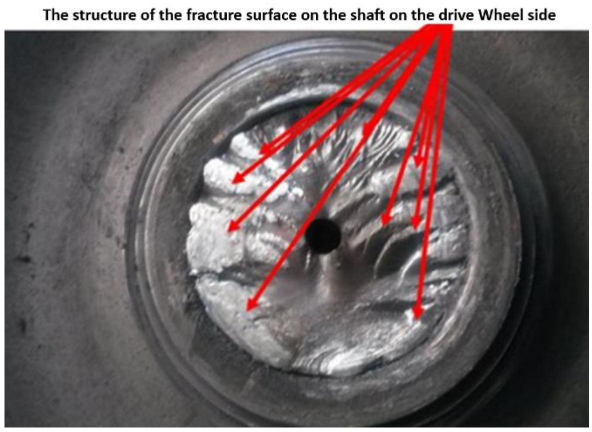


Fig. 10. Relief of the tear fracture structure on the drive locomotive shaft on the wheel side

3.3 Influence of Residual Stresses on the Stability of the Locomotive's Driving Shaft

Various sources in the shaft material generally induce residual compressive stresses during the manufacturing and operational processes. Residual stresses can result from deformation, heat treatment, machining, or other production processes that alter the material's properties. Stresses can originate from numerous sources and may be present in raw, unprocessed material, introduced during machining, or developed during operation. In hollow locomotive driving shafts, tensile residual stresses are generally harmful, as they contribute to, and often cause, material fatigue and cracking.

It is of utmost importance to ensure that all stress levels are kept within the designed limits, typically up to 300 MPa. This prevents the stresses from exceeding the limit of plastic deformation, which could lead to destructive material deformation.

In this specific case, the residual stresses surpassed the allowable (designed) levels of internal positive and negative stresses, accelerating the fracture process. The permissible internal stresses in the locomotive shaft were 300 MPa, while the measured residual stresses after the fracture reached up to 470 MPa at position no. 4 (Table 1). This underscores the critical role of timely diagnosis of residual stresses in the shaft as a key technical parameter that can indicate the shaft's stability and the locomotive's entire technical system.

Table 1. Measurement of residual stresses at characteristic points of the driving locomotive shaft after fracture

Observed values	Residual tension in shaft parts after fracture (MPa)								
	Measuring points								
	1	2	3	4	5	6	7	8	9
Max. allowed value	±300	±300	±300	±300	±300	±300	±300	±300	±300
Measured values	+205	+218	+238	+470	+430	+202	+235	+210	+202

4. RECOMMENDATIONS FOR PREVENTIVE DIAGNOSTIC MAINTENANCE

The driving shafts of all locomotive series are critical safety elements, as their failure includes the risk of the locomotive derailing and, in many cases, the entire train. Therefore, locomotive shafts are considered critical components of the technical system, and professional attention must be given to ensuring the operational stability of both the locomotive and the entire train system. The research conducted over one year and previous studies have shown that most locomotive shaft fractures are almost identical in terms of crack initiation points and their progression to complete failure. To prevent future fractures of locomotive driving shafts and the associated potential catastrophic consequences, certain technical activities should be undertaken to implement diagnostic techniques and technologies for periodic maintenance of shafts, including the following:

1. Creation of identification cards for diagnosing locomotive shafts aged 20 years or older, containing specific diagnostic parameters outlined below;
2. Diagnosis of shaft material homogeneity (using ultrasonic devices), mainly focusing on the appearance of initial surface linear indications (cracks), with particular emphasis on transition diameter zones;
3. Surface hardness measurements (Rockwell method) on both ends and around the middle of the locomotive driving shaft;
4. Endoscopic inspection of the entire internal bore length, with photographing of characteristic details;
5. Visual dimensional inspection of the central, accessible part of the shaft from the outside;
6. Measurement of the stress state in the locomotive shaft (using diagnostic devices for residual stresses), particularly in transition diameter zones where stresses are highly concentrated;
7. Diagnosis of the internal surfaces of the central hole using magnetoflux particles in zones opposite external diameter changes;
8. Ultrasonic diagnosis using longitudinal waves of the shaft's central part, measuring attenuation and wave velocity;
9. Ultrasonic diagnosis using longitudinal waves on both ends, based on pre-calculated echogram positions determined by the geometry of the shaft's ends;
10. Ultrasonic diagnosis using transverse waves from the central free part of the shaft, with probes directed toward both ends;
11. Ultrasonic diagnosis using transverse waves at a 45° angle, scanning the entire length and 100% of the shaft's circumference.

5. CONCLUSION

This research focused on the causes of the fracture of an electric locomotive's driving shaft. The study presented a specific case of shaft fracture in a locomotive of the 441 series. The issue of crack formation in the shaft and the influencing factors that alter the amplitude of shaft load were further analyzed. When operating loads exceed the designed dynamic durability, initial cracks form and propagate under static and dynamic loading and shaft torque. The mechanical and metallurgical factors, which were professionally analyzed and caused the shaft fracture, predominantly occur in traction shafts of locomotives that are 20 years old or older. The presented analyses of fracture causes and recommendations in the form of certain diagnostic measures should contribute to these systems' reliable and safe operation.

Conflicts of Interest

The authors declare no conflict of interest.

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