

Research Paper

Comparative Fatigue Failure Analysis of Axle Shafts in Two Front Wheel Drive Vehicles

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Abstract

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Axle shafts are critical components of vehicle powertrain systems, providing torque and load transfer between the differential system and the wheels. Common causes of axle shaft failures include manufacturing and design defects, lack of maintenance, raw material-related problems, material processing errors, and user-induced effects. In this study, damage and fracture analyses were performed on broken front axle shafts from two different automobiles. It was determined that the examined axle shafts separated into two pieces under service conditions. The aim of the study is to determine the failure mechanism of the broken front axle shafts and to reveal the factors contributing to the damage through detailed fracture analyses. In this context, chemical composition analysis, metallographic examinations, hardness measurements, scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDX) analyses were performed. The results obtained showed that axle shaft fractures are primarily related to fatigue damage developing under cyclic loads, and that cross-sectional changes and notch effects play a significant role in crack initiation and propagation.

Keywords: Powertrain; AISI 4140; Fatigue fracture; Drive shaft failure; SEM fractography

1. Introduction

The axle is a critical component that connects a vehicle's body to the wheels through the suspension system. Axle shafts support the vehicle's weight, transmit forces and torques bidirectionally between the vehicle body and the wheels, and play a vital role in maintaining vehicle stability during operation. **Figure 1** illustrates the powertrain configuration of a front-wheel-drive vehicle.

The front axle plays a crucial role in the overall performance and safety of a vehicle. During operation, the front axle is subjected to dynamic loads and stresses, making its structural integrity essential for ensuring vehicle safety and reliable

performance throughout its service life. Failure of the front axle can lead to severe safety risks and undesirable operating conditions. Therefore, understanding the service life and failure mechanisms of the front axle is of great importance for improving vehicle design and preventing potential failures [1].

Fatigue damage is a common type of failure, usually occurring due to repeated loading and unloading cycles, and is a frequent failure pattern for automobile axles. To ensure the safe and reliable operation of vehicles, axles must undergo extensive testing and analysis to evaluate their performance under dynamic conditions. These tests typically include vertical, longitudinal, and

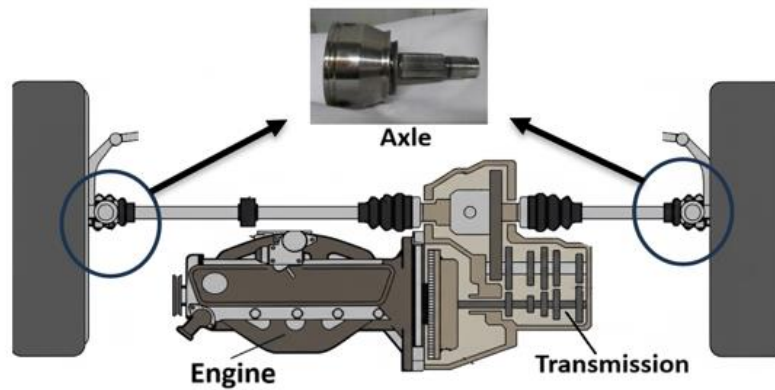


Figure 1. Elements of a front wheel drive power transmission system

horizontal fatigue tests, aiming to predict the axle's behavior under continuous stress by simulating driving conditions. The results of these tests help determine the maximum load the axle can withstand and identify weak points that could lead to failure [2].

Automobile front axles are critical components of the vehicle suspension system, supporting the vehicle and payload while providing structural support for the steering mechanism. During service, front axles are subjected to varying loading conditions and environmental influences, which may lead to fatigue damage and fracture over time. Such failures reduce vehicle reliability and performance while increasing maintenance and repair costs [3].

One of the most common causes of front axle fractures is fatigue damage caused by bending and torsional vibrations. Furthermore, it has been determined that loads under different conditions significantly shorten the axle's service life and increase the risk of fracture [4]. Errors in front axle structure design, inadequate material selection, and defects in manufacturing processes are also among the main causes of such failures [5].

The front axle is one of the vital components of an automobile. It requires high strength, rigidity, and good fatigue resistance, and is typically subjected to a combination of shear stress and bending stress [6]. Most failures result from crack growth due to fatigue loading, and these cracks propagate, leading to failure. Front axle fracture failure can lead to serious safety accidents due to its unexpected occurrence [7], [8]. Therefore, studying the failure mechanism of the front axle of automobiles is important in reducing the rate of accidents. Strength, hardenability, impact toughness, and fatigue performance vary

depending on the material type, and these differences significantly affect failure behavior. Front axles are generally manufactured with 42CrMo, 40Cr, and other micro alloyed steels. Many studies have been conducted on the effects of front axle materials.

Studies on the effects of different steel alloys on front axle materials show that material properties shape failure behavior. The usability of vanadium alloy steels in automobile front axles demonstrates that these steels can meet the front axle requirements of vehicles [9]. It has been reported that the surface layer obtained by nitriding of 42CrMo steel increases wear resistance and that the dynamic mechanical behavior of the material can be described using material behavior models [10], [11]. In addition, the effects of quenched and annealed 42CrMo steel on hot cracking in circular weld joints have been investigated [12].

The microstructure of a material directly affects its mechanical properties. Therefore, improving the microstructure of the material with reasonable machining and heat treatment technology is of great importance to enhance the quality of the front axle [13]. Research on machining techniques for automobile front axles has investigated the effects of various machining methods. In one study, a 3D thermomechanical finite element model was developed to predict microstructure evolution during hot forging [14]. Another study identified a brittle structure caused by faulty heat treatment in the analysis of a fractured axle shaft [15]. By examining the kinematic relationships between the rolling die surface and the forged part during the forging process, the rolling-forging production technique was defined [16]. An accurate 3D FE model was

developed for the rolling-forging process of the automobile front axle beam [17]. It has been found that the final turning process reduces fatigue life, but induction hardening and tempering processes increase fatigue life by reducing stress residue [18]. Machining challenges of automobile front axles have been analyzed [19]. Various tools and control systems have been used to optimize the forging process [20].

Corrosion, wear, and fatigue are among the main causes of failure in mechanical components. Fatigue damage is the most common type of failure in front axles. In addition to studies on chemical composition and processing techniques, the literature extensively examines failure mechanisms.

Studies have analyzed the possible causes of fracture in the welded front axle tube structure of trucks [1]. Fracture processes in drive shafts and axles have been analyzed experimentally [21]. A fracture mechanics approach has been presented to determine the fracture time of the axle, and a rollover accident has been analyzed [22]. Remaining life and crack depth in induction-hardened S38C railway axles have been analyzed [23]. The causes of cracking in the frame of a mining casting truck have been investigated using finite element analysis, and its design has been improved [24]. Failure modes and design improvements of a pair of front axle steering linkage elements were analyzed [25]. Crack behavior near circular inclusions was investigated, and the effects of crack-inclusion distance were examined [26]. There are also other studies on this topic [27], [28], [29].

Front axle failures can occur due to the influence of multiple factors. In addition to raw material defects, the processing technologies used can also affect such failures. Determining the causes of fracture failures and preventing similar situations is of great importance. However, studies investigating the fatigue failure mechanisms of high-strength steel front axles under actual service. In this study, damage analysis was performed on fractured front axle parts taken from Vehicle 1, which has an approximate service life of 250,000 km, and Vehicle 2, which has an approximate service life of 270,000 km. Spectrometric chemical analysis, hardness measurements, and microstructural examinations were carried out as part of the

damage analysis. The damage characteristics occurring in different front axle materials were discussed comparatively, and recommendations were presented regarding raw material quality and process conditions to reduce crack formation.

2. Methods

Analysis of damage is crucial to prevent repetitive failures, to enhance maintenance processes and business sustainability. This study investigated the damage mechanisms occurring on fractured front axles of two different front-wheel-drive vehicles.

Initially, the components were visually checked for fractures, cracks, wear, deformation, and the like. Then, damage analysis procedures were applied [30]. Following sample selection, preliminary investigations were initiated on the damaged component. This included sample selection, identification, preservation, and cleaning, followed by macroscopic examination and analysis. Subsequently, metallographic sections were prepared, the damage mechanism was evaluated, and chemical analyses were performed. On choosing and preparing metallurgical sections the damage mechanism was identified and chemical analysis were conducted [31]. Simulation and operational testing were conducted as necessary, and the evaluation of all analyses and the reporting the results were finalized.

During the stage of sample preparation, the selection and orientation of the sample are crucial. In-correct cutting techniques may change the material's microstructure and cause false results. In the examination of oxide layers, the cleaning process should be limited to simple methods; Otherwise, the oxide layer on the surface may be removed. Care was taken to avoid cavitation during the cleaning of soft materials. Small or irregularly shaped samples were easily handled during the grinding, polishing, and metallographic imaging stages.

Samples were taken from near the fracture zones using a precision sample cutting device and ground with grit sandpaper of 120, 240, 320, 400, 600, 1200, and 2400, respectively, from coarse to fine. Following grinding, polishing with aluminum oxide was performed, and the samples were prepared for microstructure examination. Etching with liquid nital (5% HNO₃, 95%

C₂H₅OH) was performed for microstructure imaging.

Fracture surfaces were examined using SEM. For SEM analysis, samples were prepared with a diameter of approximately 20 mm and a thickness of 12 mm without damaging the fracture surfaces. In the analyses, a LEO 1430 VP model SEM instrument with tungsten (W) filament was used. Failure analysis was performed using various experimental methods. The chemical composition of the parts was determined by GNR Metal Lab Plus optical emission spectroscopy; material properties were evaluated through hardness tests and metallographic examinations.

2.1. Description of Damaged Axle Shaft Samples

Figure 2 shows a comparative presentation of damaged samples of the axle shafts of Vehicle 1 and Vehicle 2, along with solid models and dimensioned technical drawings created in SolidWorks. The axle shaft of Vehicle 1, shown in Figure 2a, has a total length of approximately 149 mm, and a significant fracture (breakage) is observed at the point where the shaft joins the housing in the physical sample. The length of the milled (toothed) section in the technical drawing of this shaft is measured as 50 mm. The solid model-ing shows that the complex geometry and

toothed structure are represented with high precision.

The axle shaft of Vehicle 2, shown in Figure 2b, exhibits structural differences compared to Vehicle 1, particularly noting that the outer housing has a more convex geometry. Similarly, a damage condition where the shaft separates from the housing is observed in this sample as well. The length of the milled (toothed) section in the technical drawing is given as approximately 36 mm, and the axle shaft has a total length of approximately 174 mm.

In both examples, SolidWorks solid models provide pre-production geometric verification of parts, while technical drawings detail manufacturing parameters such as tolerances and assembly allow-ances. This comprehensive visualization reflects the entire engineering process, from the design phase to actual use and failure.

3. Result and Discussion

3.1. Spectral Analysis

Samples taken from the axle shafts of vehicles 1 and 2 were prepared for spectral analysis and their chemi-cal compositions were examined. The analysis results are presented in Table 1. Evaluation

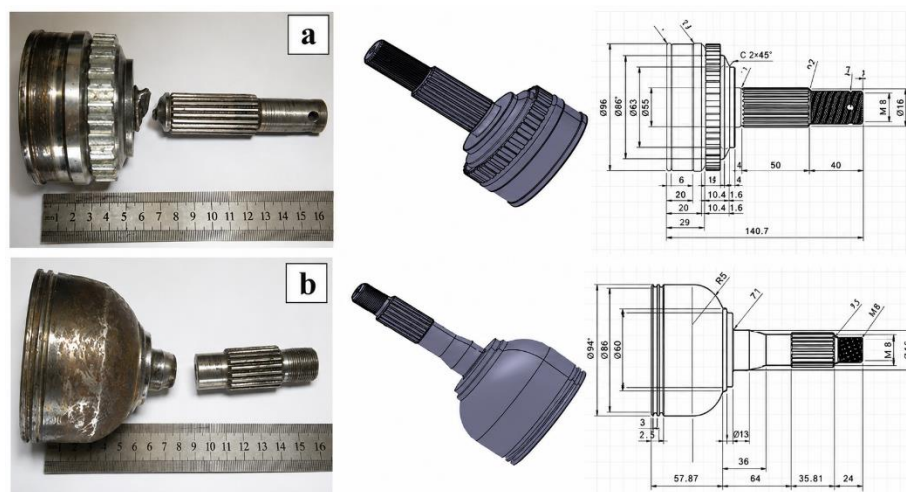


Figure 2. Solid models and dimensioned schematic representations of damaged axle shafts: (a) Vehicle 1, (b) Vehicle 2

Table 1. Chemical analysis composition, wt %

	Fe	C	Cr	Mn	Si	P	S
AISI 4140	96.78	0.30	0.8-1.1	0.7-1.1	0.15-0.30	<=0.035	<=0.040
	97.77	0.43					
Vehicle 1	97.474	0.33	0.790	0.712	0.225	0.019	0.007
Vehicle 2	98.317	0.58	0.55	0.698	0.275	0.012	0.017

of the results shows that the chemical composition of the front axle of Vehicle 1 is compliant with the AISI 4140 steel standard. However, deviations from the AISI 4140 standard were detected in the chemical composition of the front axle of Vehicle 2, particularly in terms of C and Cr elements; therefore, it was determined that the material composition is not fully compliant with the standard.

AISI 4140 steel is a machine manufacturing steel that offers high strength, good toughness and superior temper ability thanks to its medium carbon Cr-Mo alloy structure. Due to these properties, it is widely used in the automotive sector in axle shafts and other drive elements where torsional, bending and impact loads are applied together. Depending on the applied heat treatment, tensile strength of 700–1060 MPa [32], [33], yield strength of 950–1250 MPa [34] and hardness values of 210–400 HV can be obtained [32]. Furthermore, induction surface hardening processes create a hard surface and a more ductile core structure at levels of 520–700 HV, significantly increasing fatigue and wear resistance [35]. Table 1 provides a comparative analysis of the typical chemical composition of AISI 4140 steel and the results of the samples.

Surface chemical analyses were performed to qualitatively determine the alloy composition of the damaged axle shafts and to confirm the presence of other related elements. The analyses showed no significant differences between the vehicles. However, the chromium (Cr) element

present in the axle shaft material, while increasing the material's strength properties, can have a limited but negative effect on ductility and notch strength. Chromium promotes the formation of stable carbide phases in steel, contributing to increased hardness and tensile strength. For vehicle 2, it is thought that the increased hardness and decreased notch strength, depending on the Cr content in the material, facilitate crack initiation, thus contributing to the fracture mechanism.

3.2. Hardness Analysis

Hardness analyses of the axle shafts were performed using the Vickers hardness (HV) test method. According to the hardness analysis results, it was observed that no hardening was done on the outer surfaces of the axle shafts. Table 2 shows the mechanical properties of the material made of AISI 4140 steel.

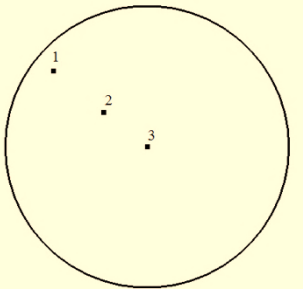
Hardness measurements were taken from the axle shafts at three different points on each sample. The measurement areas were selected to represent the critical load-bearing sections of the axle. The hardness values obtained from these determined points were evaluated comparatively, and the results are presented in tabular form. Table 3 clearly shows both the location of the hardness measurement points and the arrangement of the measurement results.

The effects of different heating conditions on the microstructure and hardness values of AISI 4140 steel have been investigated in the literature,

Table 2. Mechanical properties of AISI 4140 steel [33]

Tensile strength (MPa)	Yield strength (MPa)	Young's modulus (GPa)	Density (kg/m ³)	Poisson's ratio
1158	1034	190-210	7.7-8.03	0.27-0.30

Table 3. Measured hardness values

Hardness measuring points	Axle shafts	HV		
		1	2	3
	Vehicle 1	544	471	434
	Vehicle 2	525	458	423

and high Vickers hardness values have been determined for hardening applications. The Vickers hardness measurement results obtained from the axle shafts investigated in this study are presented in [Table 3](#). The obtained hardness values are consistent with the high Vickers hardness range observed in heating/hardening studies on AISI 4140 [36].

The outer surface becomes too hard, making the material brittle. Inside, the material is softer but relatively rigid when compared to the rest of the material. This makes the material more brittle. Brittleness, on the other hand, causes fractures due to impacts on the material [37].

3.3. Micro-Structure Analysis

Medium carbon alloy steels are a widely used material group in applications requiring high strength and toughness. Thanks to the alloying elements they contain, such as nickel, chromium, and molybdenum, they offer superior mechanical properties and are therefore frequently preferred in engineering applications. Since heat treatments significantly affect the final mechanical properties of these steels, parameters such as tempering temperature, holding time, and cooling rate play a critical role in determining the microstructure. Therefore, knowing which heat treatment protocol the samples have undergone is important for a more accurate microstructure assessment. While the pearlite phase increases the strength of the material, the ferrite phase exhibits a more ductile and smoother transition behavior.

As seen in [Figure 3](#), a microstructure is observed in the sample from Vehicle 1 where cementite phases are embedded in a network structure within the ferrite matrix. This

microstructural appearance suggests that the cementite phase may not be fully spheroidized and retains a reticular morphology in some regions. Such carbide distributions can be considered as microstructural discontinuities that may create favorable regions for crack propagation along grain boundaries. However, since records of the heat treatment history applied to the samples are not available, it cannot be definitively stated that the observed structure resulted directly from incomplete spheroidization annealing.

While this type of microstructure exhibits relatively high hardness values, it may show poor performance in terms of crack resistance and impact toughness. Although no significant decarburization traces are observed on the surface, the discontinuous distribution of cementite in the network structure suggests that the homogeneity of the heat treatment is limited. However, the spherical and homogeneous distribution of the carbide phase within the ferrite matrix is a characteristic result of a successful spherization annealing process applied for a long period at approximately 700–720 °C.

Furthermore, micro-voids and inclusion-like structures observed within the matrix cause stress concentrations, creating crack initiation points. These microstructural weaknesses, combined with the notch effect observed in the axle shaft, lead to preferential crack propagation along grain boundaries under fatigue loads, resulting in earlier fatigue fracture.

[Figure 4](#) presents optical microstructure images of a sample taken from the axle shaft of Vehicle 2 at different magnifications (50 µm and 10 µm). The microstructure generally exhibits a ferrite-

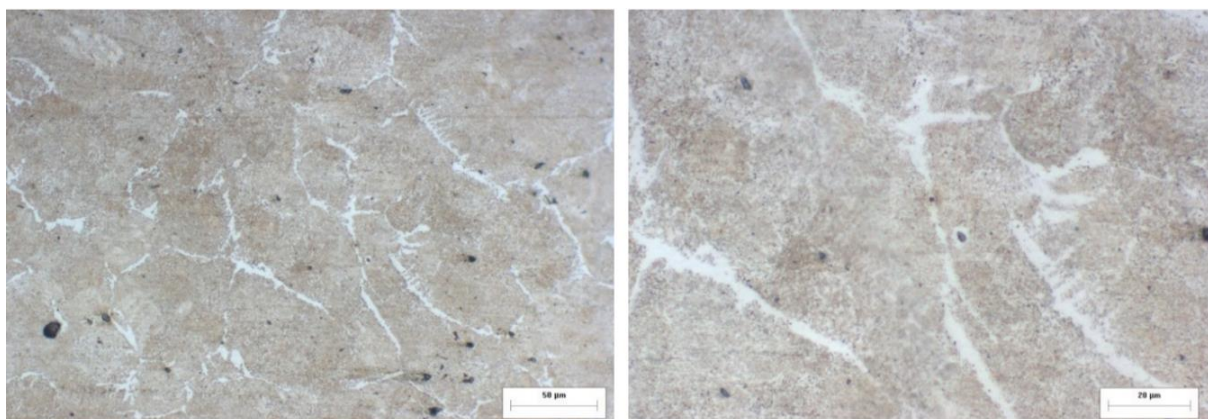


Figure 3. Micro structure of vehicle 1 axle shaft

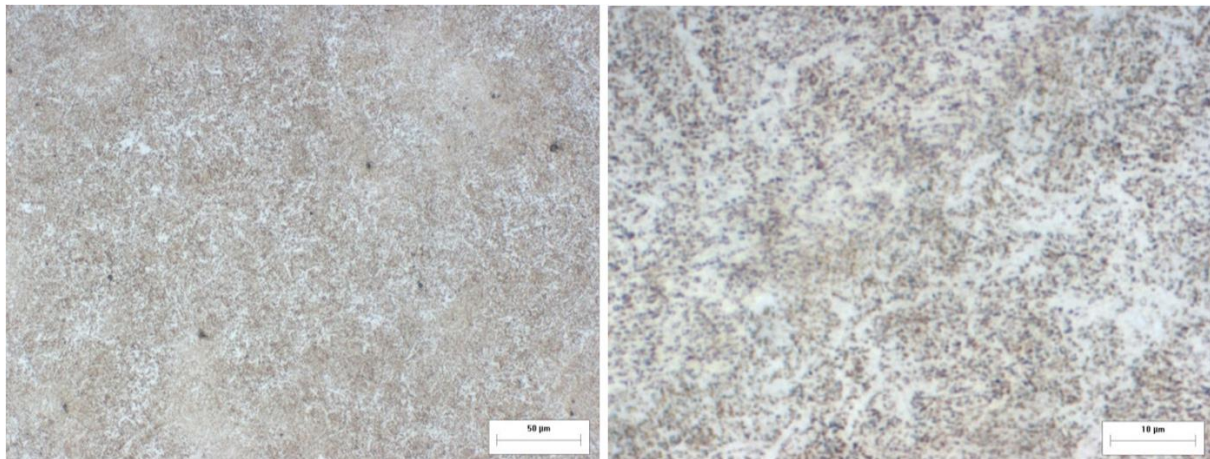


Figure 4. Micro structure of vehicle 2 axle shaft

pearlite-based matrix structure, with widespread and relatively homogeneously distributed fine carbide phases within the matrix. However, discontinuous white network-like phase separations along the grain boundaries and scattered micro-voids and inclusion-like structures have also been detected in some regions. These regions cause stress concentration, creating potential weak areas in terms of fatigue crack initiation and propagation paths.

No significant decarburization effect is observed on the surface, and the structure generally exhibits a more homogeneous distribution compared to Vehicle 1. The finer and more dispersed carbide morphology may allow for greater energy absorption before deformation, supporting a relatively more ductile fracture behavior. However, discontinuous phase separations and micro-defects observed along the grain boundaries may have facilitated microcrack formation in subsequent load cycles, contributing to eventual fatigue fracture [38].

3.4. Scanning Electron Microscope (SEM)

When the fracture surface morphology of the axle shaft of Vehicle 1 is evaluated, it is observed that the crack initiation occurs from the surface and possibly from a stress concentration zone, while the fatigue traces progress regularly and concentrically along the cross-section. These observations suggest that the fracture developed under a fatigue-related mechanism, with crack propagation features consistent with cyclic loading conditions. However, due to the absence of direct stress calculations, service load history, and fatigue striation measurements, the specific stress level and loading mode cannot be

confirmed. After the fatigue crack reduced the cross-sectional area to a critical level, the remaining section ruptured with a sudden and brittle fast fracture, and the fracture surface characteristics show similarities with fatigue fracture features reported in the literature; however, the exact loading condition and stress amplitude cannot be determined without additional mechanical data.

To support these macroscopic findings, microstructural examination was performed by taking SEM images from three different regions of the analyzed axle shaft. These regions are shown in Figure 5 for Vehicle 1. In the SEM images, fracture orientations parallel to the direction of the torsional force and traces of plastic deformation in places were observed, and macro-crack regions, which were assessed to be related to sudden loading, were examined in detail. When the fracture characteristics of the material were evaluated, brittle fracture features were detected in some regions, while microstructural deformation traces indicating ductile fracture were detected in other regions.

SEM images obtained from different regions of the fractured axle shaft are presented in Figure 6. The macroscopic and scanning electron microscopy (SEM) images of the fracture surfaces of Vehicle 1 and Vehicle 2 reveal significant differences in terms of the fracture mechanisms of the materials. In the macroscopic image of Vehicle 1, the fracture surface is observed to be quite rough, bearing distinct crack traces, and the cracks mostly propagate in a planar manner. Such fracture surfaces indicate a tendency towards brittle fracture under sudden loading. In the SEM images shown in Figure 6a to Figure 6c the regions

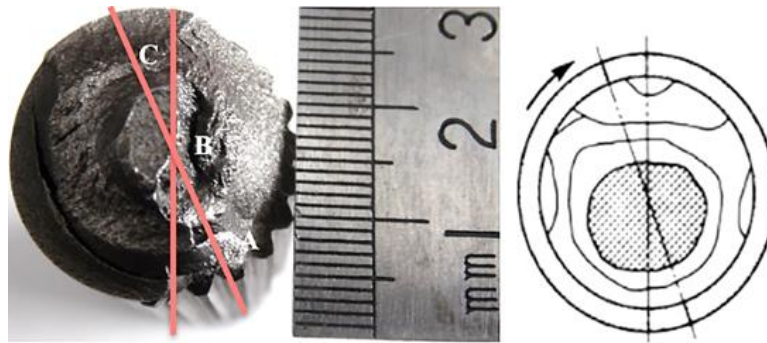


Figure 5. Areas where SEM images were taken by Vehicle 1

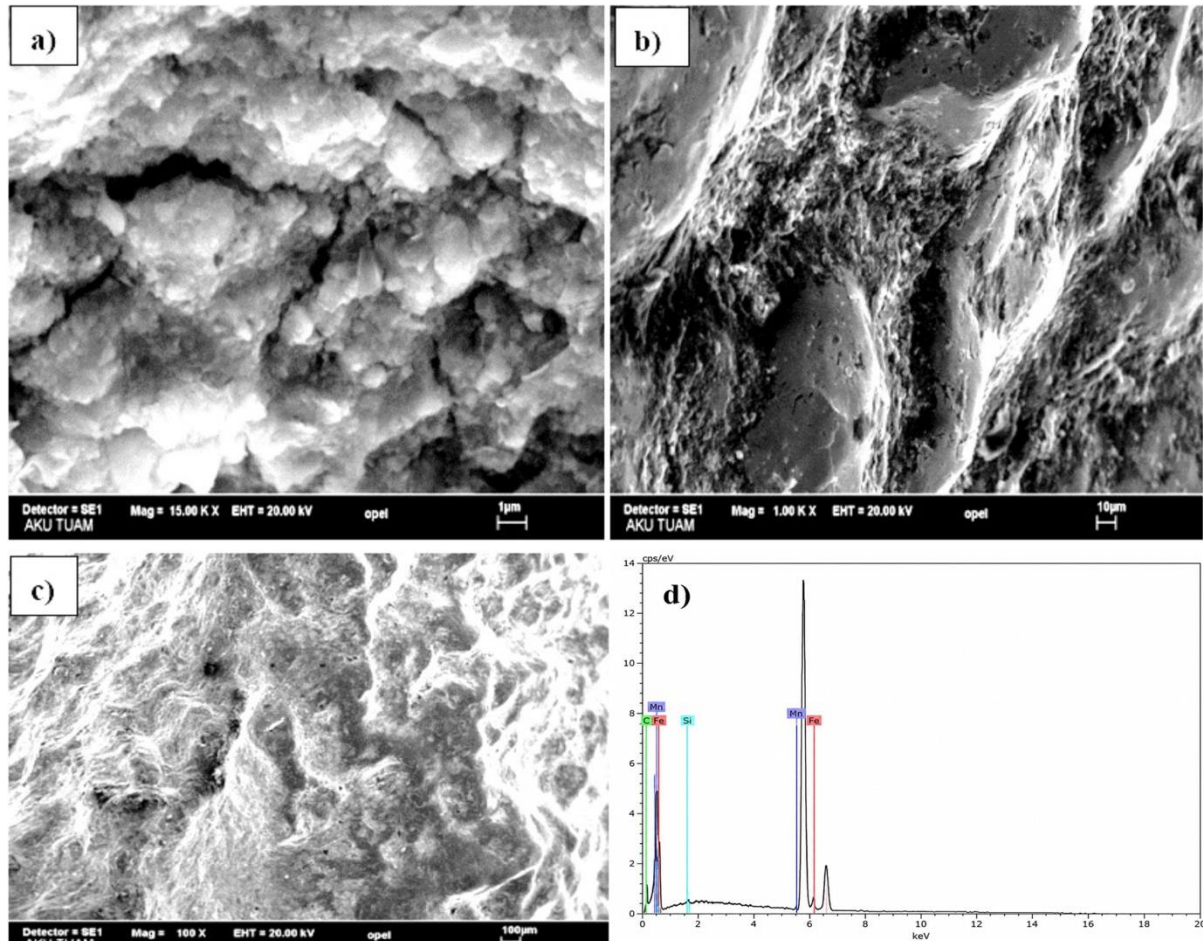


Figure 6. SEM and EDX images of Vehicle 1 fracture surface showing crack initiation region, fatigue crack propagation area, and final fracture region

corresponding to crack initiation and propagation exhibit relatively flat fracture features with limited plastic deformation, whereas the final fracture region displays different fracture characteristics. In particular, image [Figure 6a](#) shows numerous small, massive fracture surface crystals, which indicates a typical brittle fracture morphology progressing along a grain boundary. In images [Figure 6b](#) and [Figure 6c](#), the crack propagates abruptly, with minimal traces of plastic deformation and predominantly flat

surfaces devoid of fibrous structure. Image [Figure 6d](#) is the EDX image of Vehicle 1. These micromorphological features clearly demonstrate that the cementite phases in the network structure present in the microstructure of the sample belonging to vehicle 1 caused crack propagation, and therefore the fracture is brittle.

The fracture surfaces of Vehicle 2 exhibit different fracture behavior compared to Vehicle 1, both macroscopically and microscopically. [Figure 7](#) shows the regions where SEM images were

taken for Vehicle 2. In the macroscopic examination, asymmetric and spiral fatigue propagation traces are noticeable on the fracture surface. When the fracture surface morphology of the Vehicle 2 axle shaft is evaluated, it is assessed that the crack initiation occurred from the surface and from a possible stress concentration region, but the irregular and spiral propagation of the fatigue traces indicates that the fracture developed mainly under rotating bending fatigue, in addition to significant torsional components, and therefore the effective stress amplitude is higher.

Under these conditions, the propagation rate of the fatigue crack increased, the cross-sectional area reached the critical level in a shorter time, and the fracture resulted in a fast fracture region with a sudden and brittle character in the center. The fracture surface patterns exhibit characteristics consistent with rotational fatigue fractures under high stress levels and combined bending-torsion effects reported in the literature.

The macroscopically observed "cup-and-cone" fracture form indicates that the material undergoes a certain amount of plastic deformation before rupture and exhibits ductile behavior in the final stage of fracture. In the SEM images [Figure 8a](#) to [Figure 8c](#), especially at high magnifications, micropore (void) formation, microvoid coalescence resulting from the growth and coalescence of these pores due to plastic deformation, fibrous deformation traces, and distinct plastic yield zones are clearly visible. Furthermore, dimple structures characteristic of a ductile fracture mechanism, developing as a result of the growth and coalescence of micro-void formations starting around inclusions and second-phase particles due to plastic deformation, are clearly observed. These findings confirm that

a ductile fracture mechanism is dominant in the final stage of fracture. Although ductile fracture features were observed in the final fracture region of Vehicle 2, these features represent only the last stage of the fracture process. The overall failure mechanism was initiated by fatigue crack formation at a stress concentration region and continued through fatigue crack propagation under cyclic loading conditions. After the fatigue crack reached a critical size, the remaining cross-section could no longer sustain the applied load, resulting in final overload fracture.

[Figure 8](#) shows the SEM and EDX images of Vehicle 2. [Figure 8a](#) reveals fibrous structures indicating that the material absorbs energy during loading and deforms, and that the fracture is not sudden. [Figure 8b](#) shows microscopic depressions and tearing traces progressing from the center to the periphery, supporting the void growth and coalescence mechanism characteristic of ductile fracture. [Figure 8c](#) shows areas of plastic deformation developed perpendicular to the tensile direction and spread over large surfaces. [Figure 8d](#) presents the EDX analysis result for Vehicle 2, showing a homogeneous distribution of the main alloying elements along the fracture surface.

These fracture surface characteristics indicate that the material exhibits high toughness and good deformation capability, and that the spheroidized carbides in the microstructure play a role in delaying crack propagation. This fracture behavior observed in Vehicle 2 is consistent with the homogeneous and ductile microstructure obtained after spherization annealing.

In axle shafts subjected to varying stresses, the determining factor for fracture is not the maximum stress value, but the number of cycles and the stress amplitude. Cyclically varying stresses

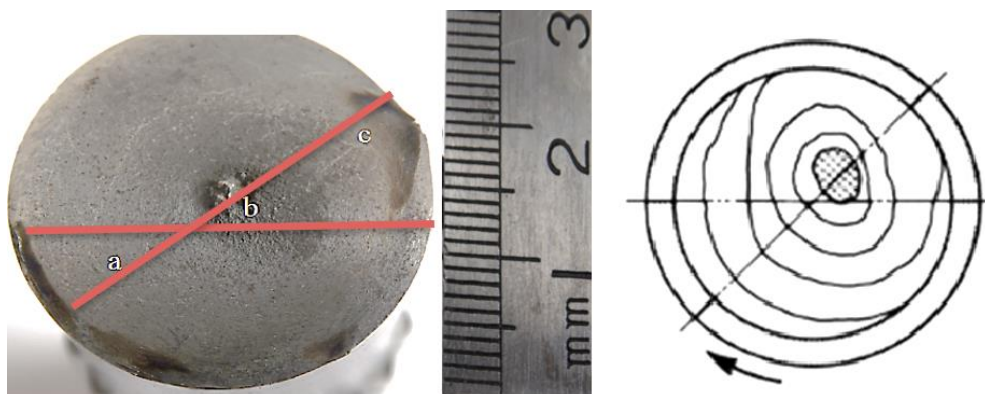


Figure 7. Areas where SEM images were taken by Vehicle 2

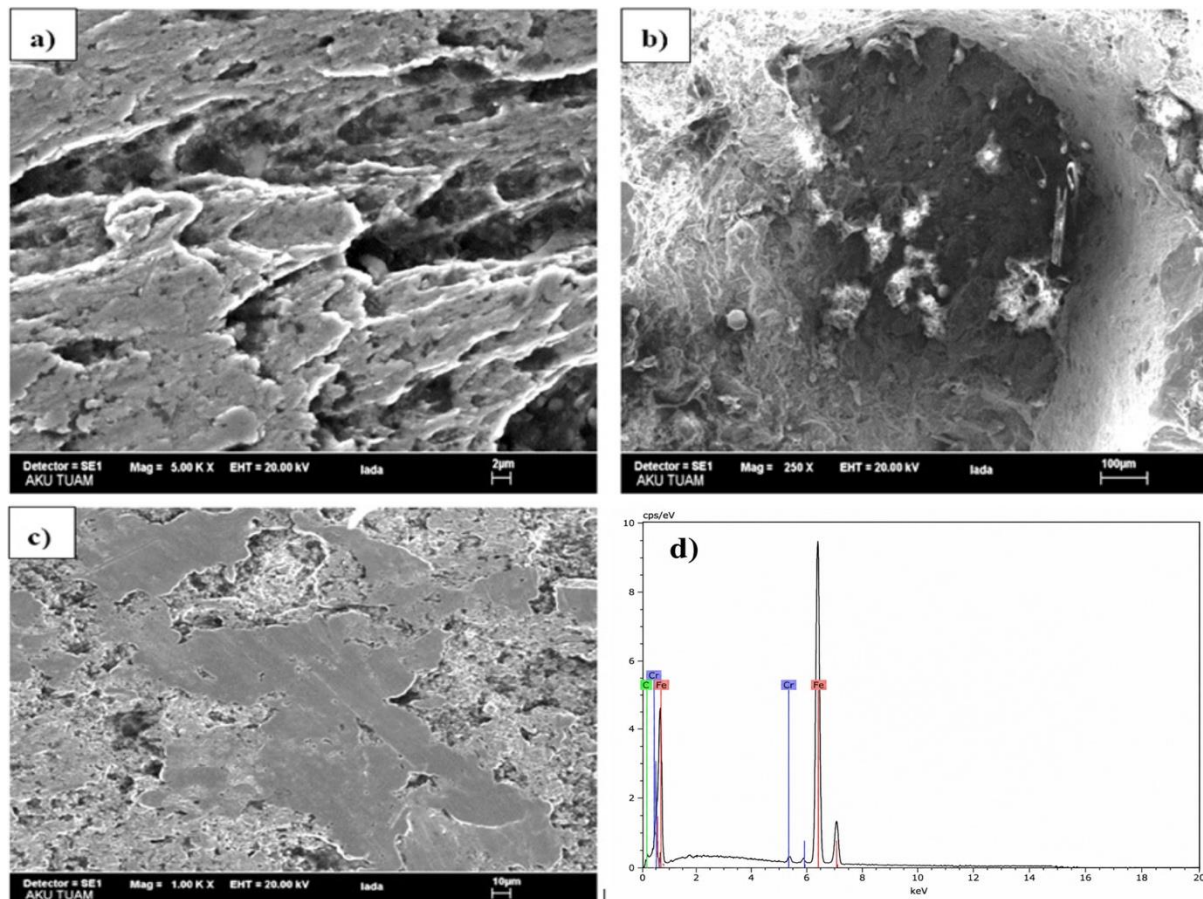


Figure 8. SEM and EDX images of Vehicle 2 fracture surface showing crack initiation area, crack propagation region, and final ductile fracture zone

cause micro-structural damage that accumulates in the internal structure of the material over time, and this often leads to fracture occurring far below the static strength limits. In this context, fatigue damage developing under the influence of varying stresses and the time the material can withstand fracture, i.e., fatigue life, play a critical role in the fracture behavior of axle shafts.

In fatigue, crack initiation usually occurs in stress concentration zones where there are surface irregularities, notches, scratches, hairline cracks, or sudden changes in cross-section. The main factors necessary for crack formation are: sufficiently high tensile stress, a wide range of cyclic stress variation, and a sufficient number of repetitions of this stress. When the damage mechanism observed in axle shafts is evaluated, it is understood that the variable loads on the axle shaft depending on the gear positions, and the fluctuating stresses experienced under different road and driving conditions (idle, partial load, and full load), accumulate fatigue damage over numerous cycles during the service life. Therefore,

it is assessed that the main damage mechanism in the axle shaft fractures examined is fatigue-related, and the fundamental factors affecting this are related to the variable loading conditions described above.

4. Conclusion

Hardness measurementsThe chemical analysis revealed that Vehicle 1 exhibited a composition closer to AISI 4140, whereas Vehicle 2 showed deviations particularly in C and Cr contents. These compositional differences, together with the observed hardness values and microstructural characteristics, may have influenced the fatigue fracture behavior of the investigated axle shafts. The differences in Cr content between Vehicle 1 and Vehicle 2 may have contributed to variations in microstructural characteristics and mechanical behavior. However, these effects should be evaluated together with other alloying elements, hardness values, and microstructural observations.

In the axle shaft of Vehicle 1, it was determined that fracture occurred as a result of decreased strength due to the notch effect and the propagation of fatigue cracks under repeated loading. In Vehicle 2, microcracks in the microstructure and sudden geometric changes in the cross-section increased stress concentrations, negatively affecting fatigue performance. Finite element analyses also support the occurrence of high stress concentrations in these regions.

Microstructural examinations revealed a more continuous ferrite structure, particularly along the grain boundaries in sample 1. This indicates more favorable intergranular crack propagation compared to sample 2. This is consistent with the more pronounced notch effect and earlier fatigue fracture observed in sample 1. SEM showed the coexistence of fatigue fracture and fatigue traces on the fracture surfaces. Furthermore, this analysis reveals that ductile and brittle fracture mechanisms occur heterogeneously. The measured hardness values (434–544 HV for Vehicle 1 and 423–525 HV for Vehicle 2) indicate variations in mechanical response across the investigated regions. These differences are consistent with the heterogeneous fracture features observed in SEM analyses.

As a result of Nanawarea's and Pable study, under service conditions, excessive loads trigger crack formation and these cracks are converted into fatigue cracks [39]. In this study, in Vehicle 1, cracks resulting from the reduction in strength due to the notch effect led to fatigue fracture after a certain number of load cycles. In Vehicle 2, it was determined that microcracks and sudden changes in cross-section accelerated fatigue damage and contributed to fracture.

In conclusion, it was determined that the main failure mechanism of both axle shafts is fatigue fracture initiating in critical regions subjected to cyclic loading conditions. Fatigue cracks were supported by stress concentration effects arising from geometric transitions and microstructural features. After the cracks reached a critical size, the remaining section fractured under overload conditions, and the fracture behavior is evaluated in relation to a combination of cyclic bending and torsional loading effects during service conditions. These findings indicate that simultaneous optimization of material composition, heat treatment parameters, and

critical region geometries is necessary in the design and manufacturing processes of 4140 steel axle shafts.

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Author's Declaration

Authors' contributions and responsibilities

Emin Çengelci: Conceptualization, Methodology, Investigation, Supervision. Arif Hakan Yalçın: Methodology, Data curation, Investigation, Validation. Ercan Şimşir: Investigation, Resources, Validation, Data curation. Murat Baraz: Investigation, Resources, Validation. İbrahim Yavuz: Supervision, Project administration, Review & editing.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Generative AI statement

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Additional information

No additional information from the authors.

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