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FAILURE ANALYSIS OF A TRACTOR FRONT AXLE

ANALIZA POŠKODBE PREDNJE TRAKTORSKE OSI

Ibrahim Yavuz
Faculty of Technology, Afyon Kocatepe University, Afyon, Turkey

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Tractors, high-power, low-speed traction vehicles and power units are similar to trucks or automobiles but designed for use off-road. They are defined as motor vehicles with wheels that allow them to hold on to loose terrain and be fitted with trailers. Tractors operate in challenging operating conditions. Therefore, it is possible that they become damaged. In some cases the damage is due to disrupted engineering, but more frequently, it is due to failures in material processing and maintenance, raw material errors, design and manufacturing errors, and user-related errors. This study examined the fractured front axle of a tractor. Spectroscopic, metallographic and hardness measurements of the axle parts were made. Stress analyses were also performed using finite elements to determine the stress conditions in the renewed section. The finite element analysis showed that the broken region was exposed to maximum stresses. Stress analyses using finite elements were also carried out to determine the stress conditions in the repeated section. With the fracture surface analysis, mild fatigue was observed, and it was concluded that the fracture occurred suddenly.

Keywords: fatigue failure, finite element analysis, front axle, tractor

Traktorji oziroma tračna vozila z veliko močjo in majhno hitrostjo so mobilne naprave podobne tovornjakom ali avtomobilom, vendar so oblikovana za vožnjo izven urejenih cestišč. Definirana so kot motorna vozila s kolesi, ki se držijo terena in so prirejena tudi za pritrditev prikolic. Traktorji obratujejo oziroma delajo v zelo težkih pogojih. Zato je možno, da na njih pride do nekaterih poškodb ali okvar. Nekatere okvare so inženirske narave toda nekateri bolj pogosti vzroki so slaba izdelava ali izbira materiala, napake nastale zaradi slabega vzdrževanja, napake osnovnih surovin, oblikovanja in izdelave ter napake povezane z uporabnikom vozila. V študiji so raziskovali vzroke za poškodbo oziroma zlom prednje traktorske osi. Izvedli so spektroskopske, metalografske in mehanske preiskave delov traktorske osi. Opravili so napetostne analize s pomočjo programskega orodja na osnovi metode končnih elementov (MKE) in določili obremenitve obnovljenega dela. Rezultati analize dobljeni s pomočjo MKE so pokazali, da nastopajo maksimalne obremenitve na mestih, blizu katerih se je dejansko zlomila traktorska os. Napetostno analizo MKE so izvedli tudi za pogoje dinamičnih (izmeničnih) obremenitev. Površinska analiza preloma je pokazala, da je prišlo do rahlega utrujanja materiala, zato so zaključili, da je verjetno prišlo do nenadnega (trenutnega) zloma preiskovane traktorske osi zaradi utrujanja materiala.

Ključne besede: dinamična poškodba, utrujanje materiala, metoda končnih elementov, prednja traktorska os

1 INTRODUCTION

Today, the tractor is one of the most critical machines in agriculture. The effect of tractors on agriculture is indisputable.[1] In recent years, the rapid development of technology has led to the modernization of agriculture. Agricultural machines and tractors are important examples of this modern technology.[2–4] The quality of mechanical inputs, land, and labour productivity can vary considerably.[5–7] Tractors carry loads with trailers attached to their backs; they are used for ploughing, planting, and so on. They operate in very harsh conditions.

Tractors are affected by various loads including the above-mentioned land operation and the complex dynamic loads caused by the changing surface of the ground during their use on the farm. The dynamic stress spectrum is a history of loading time that reflects the state of the load of the entire machine structure.[8,9]

The braking and steering systems of tractors are similar to those of the other vehicles. The tractor front axle shaft is the part in a tractor that enables rotation and carries the load. The tractor front axle is one of the most important components. It requires a perfect design so that the entire tractor can operate in extreme conditions. Axle shafts are subjected to axial loads at different angles depending on the site conditions. The road roughness depending on the terrain increases these difficulties and causes axle damage. A schematic view of the front axle system of a 2WD tractor is shown in **Figure 1.**

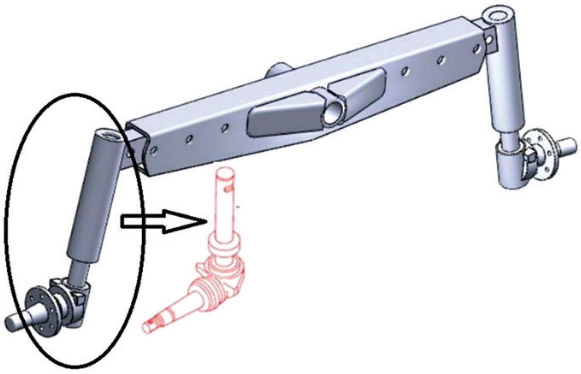

Figure 1: Tractor front axle

*Corresponding author's e-mail:
iyavuz@aku.edu.tr (Ibrahim Yavuz)

Figure 2: Tractor front axle and a broken surface analysis

A damage analysis and prevention are of interest to all engineering branches. A damage analysis is an engineering approach that determines how and why a part or device becomes unusable. When performing a damage analysis, safety, performance and economic use are taken into account. A damage analysis is necessary to prevent damage and understand the progress of the system and product quality. Overall, the goal is to achieve the designs and products that are produced in line with the highest standards and best meet the expectations of users and consumers.

Fracture damage is the most unwanted kind of damage. Therefore, several studies were conducted on broken parts for a damage analysis. In the studies of transmission, axle shafts and joints were examined and it was found that the axle shafts were damaged by heat. Some researchers concluded that the damage was due to some defects in designs.[10–12]

Many studies of the rear axle shafts were conducted. Chemical analyses, examinations of mechanical properties, microstructure and breaking surface (fractography), as well as EDX analyses were carried out as part of damage-analysis examinations. Many researchers also used this method to study models. The failure or fracture of a rear axle shaft can cause death and injuries in transit and significant financial losses. An improper design or other metallurgical causes usually lead to a rear axle shaft fracture.[13–16] Other researchers conducted some simulation studies to estimate the damage. The simulations allowed them to conclude that the damage and stress zones were similar.[17–20]

This study investigated an early failure of an (operating) tractor front axle with similar methods of inspection. Stress analyses were also performed using the finite element method. **Figure 2** shows the tractor front axle and the broken surface analysis.

2 EXPERIMENTAL PART

In this study, a chemical analysis, examinations of mechanical properties, microstructure and fracture surface (fractography), SEM and EDX analyses, and finite element (stress) analysis were used for an in-depth failure analysis.

Samples cut from the front axle were prepared for a chemical analysis. A GNR device was used to obtain the chemical structure of the axle.

The samples were taken from the damaged tractor front axle for a micro-structure analysis. They were polished with 60, 120, 240, 400, 600, 800, 1000, and 1200 sandpaper, and a Forcipol sandpaper machine was used. An alumina-pure water solution was poured and polished on a diaper. At the end of the polishing process, abrasion was carried out and images were taken at 100× and 200× magnifications using an Olympus optical microscope.

The specimens were examined under a scanning electron microscope (SEM) (LEO 1430VP, Carl Zeiss, Jena, Germany) with an energy-dispersive X-ray analysis device (EDS, Oxford Instrument Link ISIS, Oxford, UK) operating at 10–20 kV with a working distance of 10 mm.

A SHIMADZU device was used for the hardness test. The average hardness value determined using the Vickers hardness measurement method under a 1,961 N load was HV 0.02.

3 RESULTS AND DISCUSSION

3.1 Chemical analysis

The average values of the tests performed in three different regions were used for the chemical analysis of the axle shaft. As a result of the chemical analysis, the material of the axle shaft was determined as 50CrMo4 (AISI 4150) steel with a nominal chemical composition, as shown in **Table 1**. This is a low-alloy steel with a medium carbon content, often used in automotive applications and heat-treated to improve the surface mechanical properties.[21]

50CrMo4 steels are also called chromium-molybdenum steels. These steels contain 0.80–1.10 % of chromium and 0.15–0.25 % of molybdenum. Molybdenum inhibits the growth of grains and increases the hard-

Table 1: Comparison between nominal and chemical-analysis compositions

	Composition, *w*/%							
	Fe	Cr	Mg	C	Si	Mo	S	P
Axle	96.13	1.19	0.9	0.5	0.16	0.16	0.018	0.014
50CrMo4	96.6–97.8	0.9–1.2	0.7–1.1	0.48–0.53	0.15–0.3	0.15–0.25	< 0.04	< 0.035

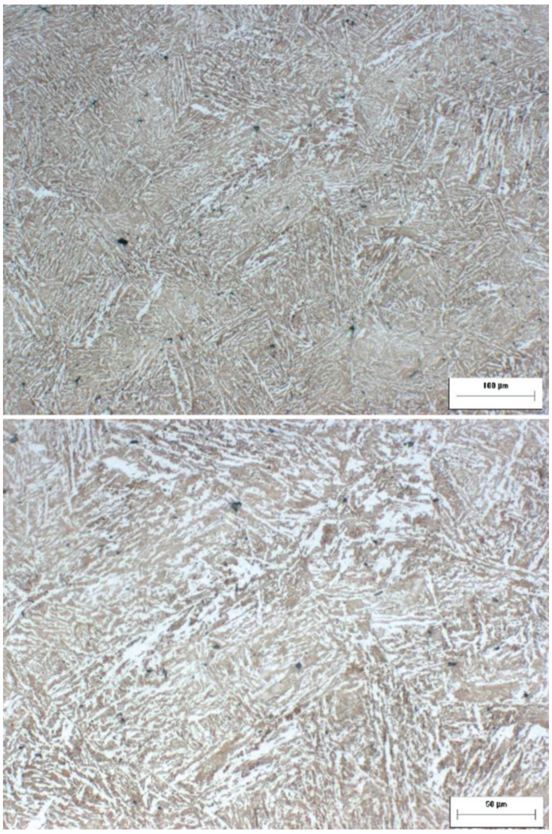

Figure 3: Optical-microscope photographs: a) 50 µm magnification image and b) 100 µm magnification image

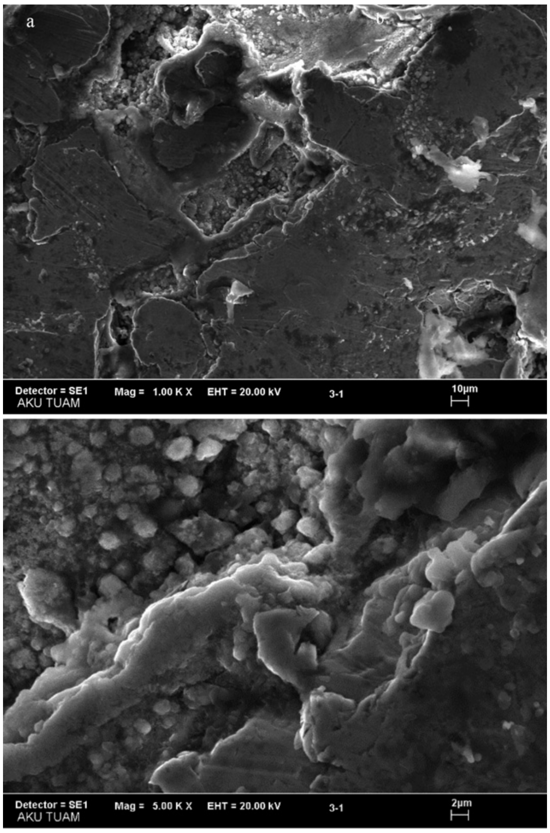

Figure 4: SEM images of the fracture surface: a) 1000× and b) 5000×

enability of steel. Chromium increases the capability of the material to retain stiffness and strength. Tempered steels are used for the production of automobile and airplane parts with a high foam content such as crankshafts, axle shafts and sleeves. A comparison between the nominal composition and chemical analysis is presented in **Table 1**.

3.2 Micro-Structure Analysis

The martensitic and ferritic structures stand out in the microstructure examinations (**Figure 3**). This is one of the steel alloys suitable for tempered steel hardening. As can be seen from the rigidity analysis, the axle was subjected to surface hardening. Therefore, the outer surface is hard, and the inner parts are ductile.

3.3 SEM (Scanning electron microscope) and EDX analysis

The device can perform qualitative and semi-quantitative elementary analyses of images with the point, line, area and mapping methods.

In **Figure 4a**, signs of a brittle fracture of the structure are observed. The fracture surface gradually obtained micro-scale pit characteristics as shown in **Figure 4b.** The reason for this is the martensitic structure.

After SEM images of the damaged-axle sample surface were taken, an EDX analysis was performed. The elemental analysis of the fractured surface is presented in

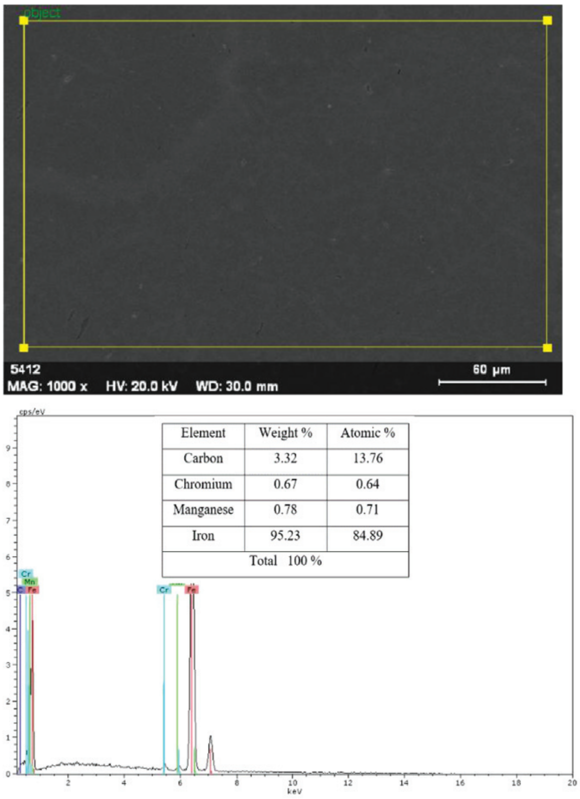

Figure 5: Tractor-axle EDX analysis

Figure 5. In the EDX analysis results, Cr and Mn stand out. Cr makes alloy steels more durable and more rigid than the standard carbon steel. Mn increases the hardenability of steel. The most crucial feature of Mn is that it makes a MnS compound with sulphur and prevents the formation of a FeS compound. FeS causes hot brittleness.

The semi-quantitative chemical analysis with EDX, added to SEM, was performed to qualitatively identify the damaged tractor axle shaft alloy and confirm the presence of any other components. No components that could cause damage were detected with the EDX analysis.

3.4 Hardness Analysis

Measurements were made between the outer side and the centre and the results are given in **Figure 6**.

Figure 6 shows that the hardening takes place on the outermost part and the axis reaches the proper hardness towards the centre. It is noteworthy that the hardness is highest on the outer surface, with a value of 900 HV, decreasing towards the centre of the axis and reaching a core hardness of 323 HV. In the literature review conducted, it was determined that the outer surface hardness is around 700 HV and the inner surface hardness is around 250 HV at the end of hardening.[21]

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 extremely brittle. Brittleness, on the other hand, causes fractures due to impacts on the material.

3.5 Numerical modelling and finite elements analysis

In **Figure 7**, the distribution of the von-Mises stress values for the loading and boundary conditions, the finite element network, and the tractor axle end are shown for the original design condition.

A variable element mesh model was applied to the mathematical model. Thus, critical regions were divided into more frequent elements. The total numbers of nodes and elements were 25345 and 14410, respectively. The vertical part of the axle was anchored, and the forces under the operating conditions were applied in the wheel hub area. The bearing load applied to the tractor front hub seating surface was calculated by considering the average weight of the tractor. The force per front wheel of the tractor was calculated as 5.9 kN. However, loads have a highly variable character for real-road and terrain conditions. These load values need to be taken into account by providing the extreme values encountered by the analyzed component. Afterwards, a static stress analysis was performed for the tractor front axle under damaged design conditions.

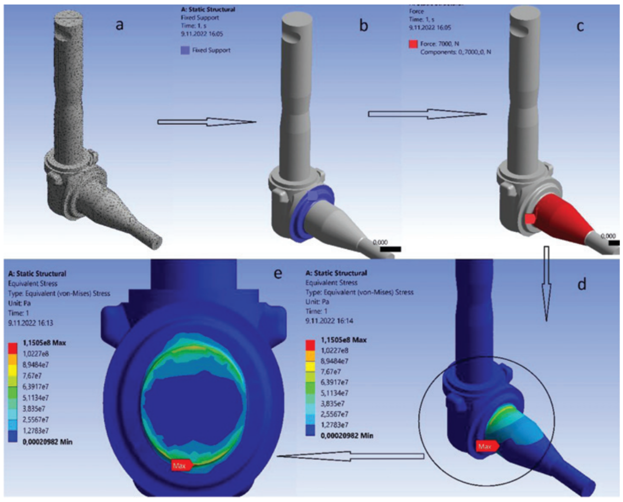

Figure 7: Von-Mises stress distribution for the tractor front axle damaged by fracture

Figure 7 shows the distribution of the von-Mises stress values for the tractor front axle for the damaged design condition. As shown in **Figures 7c** and **7d**, it was determined that the maximum von-Mises stress at the critical fracture zone of the tractor front axle end for the original design condition and damaged design condition is σ = 115 MPa. However, the variable character of the applied stress and possible effect of the forces from road-surface irregularities can decrease the fatigue limit.

Consequently, the tractor front axle end should have an infinite life at this loading and the original design condition. However, from the above observations, the fact that the fracture-damaged area and the high-stress concentration region of the axle shaft end occur in the same parts as the damaged crack origin proves that it contributed to the failure (**Figure 8**). The fracture region acts as a stress enhancer and may be an additional factor in the present situation. A fatigue fracture almost always

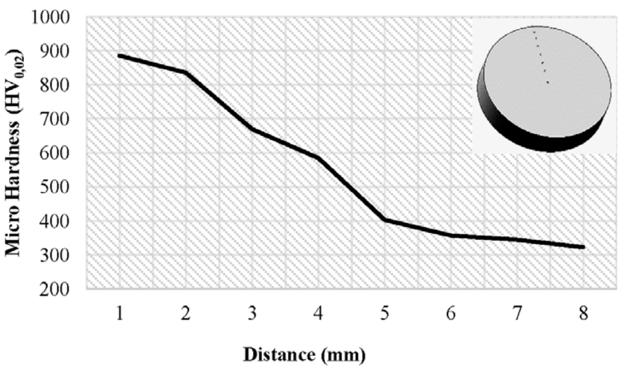

Figure 6: Micro-hardness analysis results

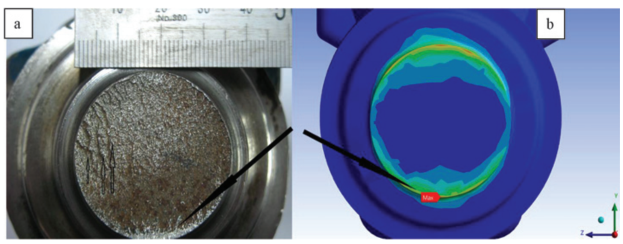

Figure 8: Comparison of the damaged area and stress concentration

occurs in parts such as notches, cracks or other stress concentrations. In the analysis, it was seen that the maximum stresses occur in the critical section of the transition region. It should be considered that this condition causes a high-stress concentration and may lead to the initiation of fatigue cracking during operation.

In brittle fractures, a macroscopic division is observed. It does not matter if the materials are metallic or non-metallic as long as they are brittle. Separation is defined as the breaking of a body on a single surface.[22] As the cleavage will show slight variations at the plane levels of multiple fractures, the surface will show fine crevices called the fatigue pattern that gives the fractures their characteristic aspects with a macroscopic cleavage, as illustrated with the example in **Figure 8**. The propagation exhibits a greater roughness as the crack progresses towards the final split point.

4 DISCUSSION AND CONCLUSIONS

In this study, a damage analysis of a tractor main axle shaft was carried out. The chemical analysis, scanning electron microscopy (SEM), and mechanical test results determined the damaged axle-shaft material. As a result of the analyses, the material was determined as hardened and tempered 50CrMo4 alloy steel. It was believed that there were some defects in the manufacture of the material. In particular, it was observed that the hardness of the material was much higher than average. It was concluded that this increased the brittleness of the material.

Visual inspection showed a typical fatigue fracture with traces of damage. According to the finite element analysis, the most stress occurred on the surface close to the mechanically damaged area. As a result of the finite element numerical analysis, it was concluded that the fatigue fracture of the axle shaft was consistent with the actual fracture. Although the fatigue zone was tiny due to excessive hardening of the material, it was concluded that the axle was damaged due to fatigue. It is thought to have broken suddenly due to excessive hardening.

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