Failure Analysis of Drive Axle Shaft failed under Torsional Stress

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Abstract. Drive axles are an essential component for power transmission in any automobile. It transfers the power from the differential to the hub of the wheels which drives the vehicle. The axles are subjected to torsional stresses due to the torque from the differential and the resisting torque present due to the frictional resistance from the ground on the wheels. Hence, they are prone to torsional failures under fatigue with and without shock loading. In this paper, a comprehensive engineering failure analysis of the failed drive axle shaft of material EN 24-T, custom designed for a 200kg BAJA SAE all-terrain vehicle was performed. Destructive, non-destructive testing and material analysis along with finite element simulations using Ansys were carried out to better understand the nature and cause of the failure. Failure analysis data hints at the flaws in design considerations and scanning electron microscopy (SEM) images reveal the formation of bainitic microstructures within the component due to improper heat treatment which lowers the ultimate tensile strength of the material.

1. Introduction

The movement of a vehicle happens when the torque produced by the prime mover (here engine) is transferred to the wheels in the desired amount via the transmission. This transfer and modification of torque in a vehicle is called power transmission. It has always been a field of challenges and innovations. Most on-road automobiles today use rigid drive axles to deliver power from a transmission to the wheels but an off-road automobile like an All-terrain Vehicle (ATV) requires a variable length drive axle to accommodate for the vertical wheel travel due to rough terrain.

Most of Original Equipment Manufacturer (OEM) drive axles comprise of either two Constant Velocity (CV) joints or two tripod joints. CV joints give maximum angularity of 40° with no plunge whereas tripod joints have maximum angularity of 23° with a plunge of about 50 mm to account for variable length of drive axle and to accommodate side thrust impacts during cornering. The desire to use a cross-groove joint which is a hybrid of a CV and a tripod joint was to get maximum angularity of 31° along with a plunge of 50 mm. But due to limited track width requirements of the buggy, the wheel side cross-groove joint was custom designed to work as a wheel hub while enclosing the joint within itself. Also, due to the in-board mounting of rear brake rotor, the drive axle shafts varied in length and had to be custom designed and manufactured. These axle rods are susceptible to torsional, shock and fatigue loads which greatly affect the component’s life.

The present work does a systematic failure analysis for a failed drive axle rod, which was a critical failure in terms of the ATV buggy [1]. Bipin's [3], Bhagoria's [6] and Zhao’s [7] papers on failure analysis of axle shaft of an automobile helped us in defining the steps for this comprehensive failure analysis.
2. Methods

Figure 1 shows the powertrain assembly of the buggy consisting of a Briggs and Stratton® OHV 10 HP Engine, CVTech™ continuously variable transmission (CVT), a custom designed constant reduction gearbox which connects with the two drive axles integrated with the wheel hub. The buggy was designed according to the rules published by the Society of Automotive Engineers (SAE) in the rulebook for BAJA all-terrain vehicle championships which take place across the globe.

**Figure 1.** Powertrain assembly of the ATV buggy.

Figure 2 shows the hub integrated drive axle design consisting of an OEM cross groove joint that fits on the splines of the gearbox output shaft. The other end of the axle is another cross groove joint sitting in a customized hub, machined out of Aluminium 7071 block and bolted to the wheel rim.

**Figure 2.** (a) Isometric and (b) front view of complete drive axle assembly.

Figure 3 shows an exploded view of the integrated cross-groove drive axle assembly which helps us determine the loading points on the axle rod at the splined areas.

**Figure 3.** Exploded view of complete drive axle assembly.

Detailed engineering draft of the drive axle rod in figure 4 shows its key features which helps us understand the sequence of manufacturing processes the rod must have gone through.

**Figure 4.** CAD model of the custom designed drive axle.
EN 24-T was chosen as the material for the drive axle rod due to its high tensile strength and other mechanical properties as seen in table 1 [2]. Tempering of the axle rod was carried out by heating it up to 660°C and holding at heat for two hours per inch of total thickness which increases the toughness while reducing brittleness and internal stresses.

### Table 1. Mechanical properties of EN 24-T steel.

| Condition | Tensile Strength (N/mm²) | Yield Strength (N/mm²) | Elongation (%) | Brinell Hardness |
|-----------|-------------------------|------------------------|----------------|-----------------|
| T         | 850 - 1000              | 650                    | 13             | 248 - 302       |

EN24-T has the following chemical composition as shown in table 2 [2].

### Table 2. Chemical composition of EN 24-T steel.

| Min.  | Max.  |
|-------|-------|
| C     | 0.36  | 0.44  |
| Si    | 0.10  | 0.35  |
| Mn    | 0.45  | 0.70  |
| P     | -     | 0.035 |
| S     | -     | 0.04  |
| Mo    | 0.20  | 0.35  |
| Cr    | 1.00  | 1.40  |
| Ni    | 1.30  | 1.70  |

The 20 mm diameter EN 24-T billet was cut in the desired length. 1 mm module splines with 30° pressure angle were splined on both the ends of the rod. After splining, 2 circlip grooves were machined on both the splined areas to hold the cross-groove cage in its place.

The rod was heated to its austenization temperature using oxygas flames for flame hardening. It was performed to achieve a surface hardness of around 55-60 HRC and case depth between 0.127 mm and 6.35 mm.

The maximum torque condition coming on the drive axle will be at the moment when the vehicle takes a jump start or cornering at high speeds [3].

- Maximum torque from the Briggs and Stratton® engine ($E_{max}$) = 19 N-m
- Maximum gear reduction of the CVTech™ CVT ($CVT_{max}$) = 2.64
- Constant gear reduction of the gearbox (gb_reduction) = 10.325
- Diameter of the axle rod ($d$) = 20 mm
- Length of the axle rod ($l$) = 486 mm
- Shear modulus of steel ($G$) = 80,000 MPa
- Tensile strength of EN 24-T ($\tau_{tensile}$) = 850 N/mm²

$$T_{max} = E_{max} \cdot CVT_{max} \cdot gb_{reduction} \quad (1)$$

Maximum torque transferred to the drive axles is given by equation (1) and comes out to be 518 N-m.

$$\tau_{permissible} = 0.7 \cdot \tau_{tensile} \quad (2)$$

Maximum permissible stress is given by equation (2) and it comes out to be 595 MPa.

$$\tau_{max} = \frac{16 \cdot T_{max}}{\pi \cdot d^3} \quad (3)$$

Maximum torque transferred to the drive axle rod is given by equation (3) and it comes out to be 330 MPa.
\[ FOS = \frac{\tau_{\text{permissible}}}{\tau_{\text{max}}} \]  

(4)

Factor of safety of the axle rod is given by equation (4) and it comes out to be 1.8.

\[ \theta_{\text{max}} = \frac{594 \times T_{\text{max}} \times l}{G \times d^4} \]  

(5)

Maximum angular deflection of axle rod under maximum torque is given by equation (5) and it comes out to be 0.0115 rad or 0.66°.

After the flame hardening of the axle rod no rusting was observed anywhere for the complete duration of service. The un-splined areas of the shaft usually remained in open and often dust, dirt and mud would accumulate over it which would be easily cleaned with a spray of water or some rugged piece of cloth. The splined area is covered and sealed by a rubber boot or ‘bellow’ which protects the joint and the spline from outside dirt particles and moisture. A grease lubricant of standard OEM grade was filled into the bellows to provide lubrication to the joint and also help in heat dissipation. It was constantly being replenished after about 10 hours of running as the bellows use to either crack and leak or slide open from the joint on the hub side. The axles used to operate for an average of 8 hours after which the axle rods used to break at the same circlip groove location. Axle rods usually used to break after an aggressive start, a jump down from a high location or at attempts of very steep turns at high speeds.

The sample was collected from the testing field where the drive axle failed and covered in dirt, grease and mud. It was gently washed off with water and a piece of cloth. Later detergent water was used to remove the grease. Small samples of the fractured end were cut off by an angle grinder for detailed analysis under optical microscope.

Ansys – Mechanical was used for the finite element analysis of the axle rod. For the design under consideration, finite element mesh is generated using tetrahedral mesh type taking fine size to 1mm and minimum edge length as 0.1mm with 20690 nodes.

3. Results and discussion

As seen in figure 5(a), to replicate the loading condition, maximum torque coming on the axle rod of 518 N-m was applied at one splined end of the drive axle while the other splined end was fixed [3]. Maximum deformation of about 2.34 mm was observed in figure 5(b) under the applied torque.

![Figure 5](image_url)  

(a) Loading of the axle rod and (b) maximum deflection under the load.

In figure 6(a) and 6(b), it can be observed that the regions of maximum stresses of about 5.57GPa are found around the circlip groove area on the edges of the start of the splines and it prevails over to the bottom part of the spline. It is clearly observed that this is the exact point of the plane from where the fracture takes place.
Figure 6. (a) Equivalent (von-misses) stress plot of drive axle, (b) enlarged view.

From figure 7(a) it is visible that the major part of the drive axle (the non-splined part) has an FOS between 1 and 5. It is least around the circlip groove (about 0.12) and it continues to be low till the bottom of the splines as seen in figure 7(b).

Figure 7. (a) Factor of safety plot of drive axle, (b) enlarged view close to the spline.

**Observation of the failed component**

The fractured drive axle was recovered from the vehicle and there was still a lot of grease and dirt articles on it. The smaller portion of the drive axle that broke out was not found. Observed closely in figure 8(a), a slight bend in the drive axle was discovered and after thorough investigation it was found that this bend was observed after the heat treatment process which suggests that flame hardening was not the best heat treatment process for this component. This bend might have caused irregular stresses in the component over its duration of service.

Figure 8. (a) Axle rod found to be bent, (b) torsional deflection seen in the splines.

When the other side of the spline was viewed closely in figure 8(b), it was visible how the splines had deformed under the torsional forces.

When the fracture surface was photographed and is shown in figure 9 (a) and (b), the deformations due to torsional stresses were clearly visible which originated from the outer periphery with different
points of fracture initiation and ended up somewhere in between. The shiny and rough patches of the surface indicate towards both tensile and brittle nature of the fracture [1].

![Fracture Initiation Points](image1)

![Fracture End Point](image2)

**Figure 9.** (a) Fracture initiation points (b) fracture end point.

Rockwell hardness test was conducted to check for the hardness of the component at two different locations and the EN 24-T hardness ranged from 248-302 BHN (table 1) and will be helpful to know the quality of the heat treatment process.

**Table 3.** Hardness values from rockwell hardness test.

| Hardness at the centre | Hardness at the periphery |
|------------------------|---------------------------|
| 30 HRC = 286 BHN       | 54 HRC = 543 BHN          |

The hardness value from table 3 is well within known range of hardness of the material and also helped to verify the application of the heat treatment processes along with the material hardness characteristics.

A tensile test was conducted on a specimen machined from the centre region of the bar based on ASTM E8 Standards with a strain rate of $4 \times 10^{-4}$ S$^{-1}$.

**Table 4.** Tensile test values

| Property                        | Values from test | EN 24-T, flame hardened [2] |
|---------------------------------|------------------|------------------------------|
| Yield Strength                  | 665 MPa          | 1110 MPa                     |
| Ultimate Tensile Strength       | 916 MPa          | 1294 MPa                     |
| Elongation                      | 12.8 %           | 14 %                         |
| Reduction of Area               | 52.6 %           | 50 %                         |

The values in table 4 reveal the imperfection in heat treatment processes applied on the axle rod as it could not achieve the desired values as per design considerations.

**Optical microscopic analysis of the component**
As seen in figure 10, optical microscopy at about 3000X magnification revealed the formation of bainitic microstructure in the material sample. Hence it was decided to go for Scanning Electron Microscopy for more understanding [4].
Figure 10. Presence of bainitic microstructure detected.

SEM analysis of the component
Detailed observation of the fracture surface was made by scanning electron microscopy (SEM), as shown in Figure 11. The images were made at specific points: close to the edge, at a quarter-radius from the edge, mid-radius and at centre of the fracture surface.

Figure 11. Fracture morphology: (a) close to the edge, (b) at a quarter-radius from the edge, (c) midway between edge and centre and (d) at the centre.

It was observed from the scanning electron microscopy images in figure 11 that part of the surface was damaged due to rubbing. However, a significant part of the fracture was preserved and dimple morphology was evidenced [5]. The elongated dimples close to the surface, as shown in figure 11(a) are observed by and associated with the larger shear deformations in that region. Besides the elongated dimples, secondary cracks were observed.

Figure 12. (a) Secondary cracks observed on the fracture surface close to the edge (yellow arrows) (b) spline region with intense transverse cracking and a longitudinal crack at the base of the spline root (red arrow).
Figure 12 shows a lateral image of the spline close to the fracture surface revealing several small transverse cracks and a large longitudinal crack emanating from the spline root.

![Image of a lateral image of the spline close to the fracture surface]

**Figure 13.** Transverse view of the drive-axle close to the fracture surface (a) large cracks emanate from the roots of the splines and the wear of the splines (yellow arrows), (b) secondary cracks (red arrows) observed inside a crack.

It is possible to see in figure 13(a) that the tips of the splines treads were worn away from the component. It’s also evidenced from figure 13 that cracks emanating from the spline roots are associated to fatigue process due to torsional loading [5]. Similar results can be corroborated by another study too [7]. Bibin et al study points out the effect of bainitic structure and the same was observed in the current failure analysis too. The FE study helped in identifying the design changes that are required to avoid future failure.

### 4. Conclusion

The above conducted failure analysis of the fractured drive-axle reveals the following:

- The design considerations did not take into account of the circlip groove which was a high stress concentration area and the primary reason for fracture.
- The material EN24 T selected for the application was appropriate but the heat treatment process applied on the drive axles lead to bainitic microstructure which lowers the yield and ultimate tensile strength of the material. Also, improper heating and clamping lead to slight deformations in the component.

A detailed failure analysis of the drive axle rod was conducted using destructive and non-destructive testing as well as microscopic analysis was done. It showed that there were some flaws in the design considerations and improper heat treatment processes were applied which led to the formation of bainitic microstructure. Due to which the brittleness of the component increased and its tensile strength decreased leading to the failure.

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