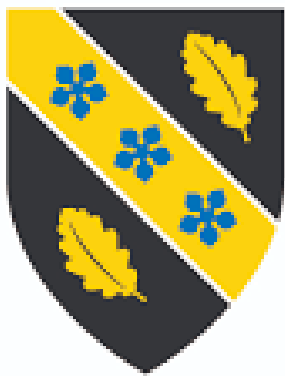


University of Wales Trinity Saint David

Wales Institute of Science & Art



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

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Rebekah Pratt

2400239

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1. Introduction

The reliability of drivetrain components is critical in high-performance motorsport applications, where mechanical systems are subjected to extreme loading conditions, including high torque, cyclic stresses, and dynamic impacts. During the fourth and fifth stages of the Dakar Rally, two vehicles experienced catastrophic failure of their aluminium drive shafts, resulting in complete loss of functionality and forced withdrawal from the competition.

Notably, the failed components were manufactured using established design specifications and production methods that had previously demonstrated satisfactory performance. However, a recent change in aluminium supplier introduces a significant variable, suggesting that material properties may have deviated from required standards. The recorded maximum operational stress of approximately 90 MPa provides a critical benchmark for evaluating the mechanical suitability of the material.

This investigation adopts an experimental and analytical approach to determine the root cause of failure. Tensile testing is conducted to obtain key mechanical properties, including yield strength, ultimate tensile strength, and Young's modulus. These results are then critically compared against expected values for structural aluminium alloys and the operational demands of the application.

The report aims not only to identify the failure mechanism but also to evaluate the interplay between material properties, manufacturing factors, and service conditions. Based on this analysis, evidence-based recommendations are proposed to prevent recurrence and improve the reliability of future components.

2. Literature Review

2.1 Requirements for Drive Shaft Materials

Drive shafts in high-performance automotive applications operate under complex loading conditions, including torsional stresses, bending loads, and cyclic fatigue. Therefore, material selection must prioritise high yield strength, sufficient stiffness, and strong fatigue resistance to prevent deformation and failure.

In motorsport, weight is also critical, so materials with a high strength-to-weight ratio are preferred (Ashby, 2011). However, weight reduction must not compromise structural integrity. The material's yield strength must exceed the maximum operational stress by an appropriate safety factor (Budynas and Nisbett, 2015), as failure to do so can result in plastic deformation and accelerated fatigue damage.

2.2 Aluminium Alloys and Their Limitations

Aluminium alloys are widely used due to their low density, corrosion resistance, and manufacturability. Heat-treatable alloys such as 6061-T6 and 7075-T6 achieve enhanced strength through precipitation hardening (ASM International, 2020).

Typical yield strengths range from approximately 200 MPa to over 500 MPa (Davis, 1999). However, their mechanical properties are highly dependent on correct alloy composition and heat treatment. Any deviation can significantly reduce strength and stiffness.

Aluminium alloys also exhibit lower fatigue strength than steels, making them more susceptible to failure under cyclic loading (Callister and Rethwisch, 2018). As a result, careful selection and processing are required to ensure reliability in applications such as drive shafts.

2.3 Failure Mechanisms in Aluminium Components

Failure in aluminium components can occur through several mechanisms.

Overstress failure occurs when applied stress exceeds yield strength, causing plastic deformation and fracture (Ashby, 2011). Fatigue failure is particularly significant in rotating components and results from repeated cyclic loading, often initiating at stress concentrations such as defects or geometric discontinuities (Callister and Rethwisch, 2018).

Material defects, including porosity and inclusions, can further reduce performance by acting as stress concentrators (ASM International, 2020). In practice, failure often results from a combination of these mechanisms. For example, low yield strength can lead to plastic deformation, increasing stress concentrations and accelerating fatigue crack growth.

2.4 Tensile Testing and Material Characterisation

Tensile testing is used to determine key mechanical properties, including yield strength, ultimate tensile strength, and Young's modulus (ASTM, 2020). The stress–strain curve provides insight into elastic and plastic behaviour, with the initial linear region representing reversible deformation.

These properties are essential for assessing material suitability. In engineering design, the yield strength must exceed operational stress to ensure safe elastic behaviour (Budynas and Nisbett, 2015). However, accuracy depends on correct testing procedures and calibration, as errors can affect the reliability of results.

2.5 Critical Evaluation

The literature indicates that structural aluminium alloys should have mechanical properties well above service stresses. If measured properties are significantly lower, this suggests incorrect alloy selection, inadequate heat treatment, or poor material quality (ASM International, 2020).

Given the sensitivity of aluminium to processing conditions, strict quality control is essential. A change in supplier introduces a risk of variability, making material verification critical.

Therefore, comparing experimental results with established material standards is essential for identifying the root cause of failure and confirming whether the material meets application requirements.

3. Methodology

3.1 Experimental Apparatus

The tensile test was conducted using a TecQuipment ES6 Tensile Tester Kit, designed to evaluate the mechanical properties of engineering materials under controlled loading conditions. The apparatus consists of a manually operated loading mechanism, a dial indicator for displacement measurement, and a calibrated scale for force determination. The setup was securely mounted to a work panel to ensure stability during testing, as shown in the experimental configuration.

3.2 Experimental Procedure

3.2.1 Tensile Test Procedure (TecQuipment, 2012).

1. Measure the specimen's original gauge length, width, and thickness using a vernier calliper and record the values.
2. Calculate the original cross-sectional area from the measured dimensions.
3. Mount the specimen securely in the tensile tester grips, ensuring correct axial alignment to prevent bending stresses.
4. Set the dial indicator to zero to establish a reference point for extension measurements.
5. Record the initial reading on the vertical scale before applying load.
6. Rotate the load nut gradually to apply tensile force in small increments of **0.2 mm** within the elastic region.
7. Maintain a consistent loading rate (approximately equal time per increment) to ensure accurate and repeatable results.
8. At each increment, record the dial indicator reading immediately after applying load.
9. Continue increasing the load using larger increments (1 mm and above) as the specimen enters the plastic region.
10. Record all readings systematically in a results table, including load nut movement and dial indicator values.
11. Continue loading until the specimen fractures, noting any visible deformation such as yielding or necking.
12. After fracture, remove the specimen and carefully align the broken ends.
13. Measure the final length of the specimen to determine total elongation.
14. Convert dial indicator readings into force values using calibration data.
15. Calculate extension by subtracting dial readings from load nut movement.

16. Calculate engineering stress and strain using the measured dimensions and recorded data.
17. Plot a stress–strain graph to determine key properties, including yield strength, ultimate tensile strength, and Young’s modulus

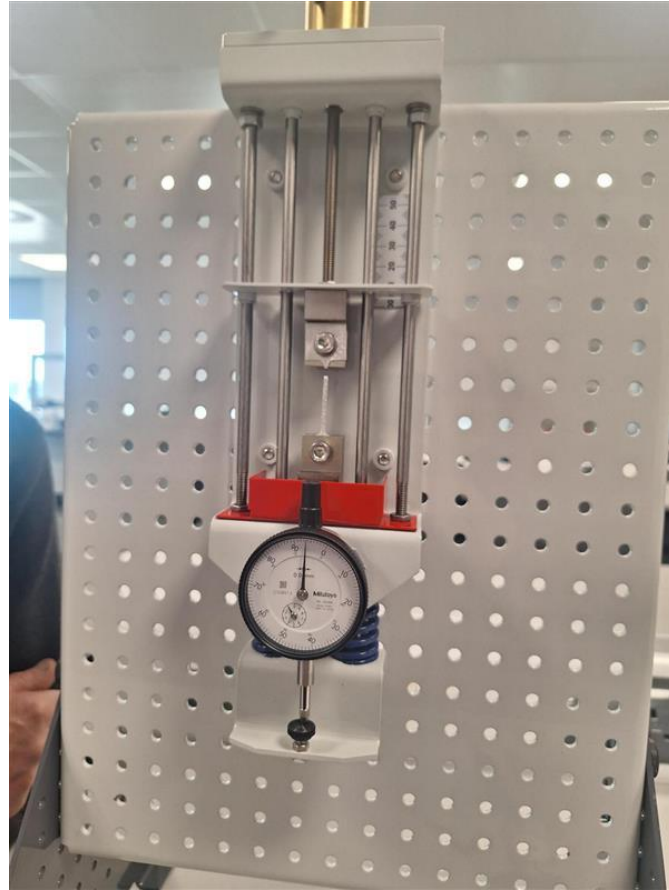


Figure 1: Tensile Tester

4. Test Results

4.1 Overview of Results

The tensile test was carried out on an aluminium specimen using the ES6 Tensile Tester. The load nut movement and dial indicator readings were recorded until the specimen fractured at 5.0 mm load nut movement. The ES6 worksheet states that metal specimens may break between approximately 1 mm and 5 mm extension, so the fracture point observed is consistent with metallic tensile behaviour.

The recorded data was then used to calculate specimen extension using:

$$\text{Extension} = \text{Load Nut Movement} - \text{Dial Indicator Reading}$$

4.2 Results Table

Load Nut movement (mm)	Dial Indicator (mm)	Force (N)	Extension (mm)	Stress	Strain	Cross Sectional Area (mm ²)
0	0.000	0	0.000	0	0.000	62
0.2	0.113	11.3	0.087	0.182	0.002	
0.4	0.270	27	0.130	0.435	0.003	
0.6	0.443	44.3	0.157	0.715	0.003	
0.8	0.608	60.8	0.192	0.981	0.004	
1	0.803	80.3	0.197	1.295	0.004	
1.2	0.970	97	0.230	1.565	0.005	
1.4	1.150	115	0.250	1.855	0.005	
1.6	1.320	132	0.280	2.129	0.006	
1.8	1.495	149.5	0.305	2.411	0.006	
2	1.688	168.8	0.312	2.723	0.006	
2.2	1.860	186	0.340	3.000	0.007	
2.4	2.030	203	0.370	3.274	0.007	
2.6	2.210	221	0.390	3.565	0.008	
2.8	2.373	237.3	0.427	3.827	0.009	
3	2.523	252.3	0.477	4.069	0.010	
3.2	2.633	263.3	0.567	4.247	0.011	
3.4	2.725	272.5	0.675	4.395	0.014	
3.6	2.858	285.8	0.742	4.610	0.015	
3.8	2.914	291.4	0.886	4.700	0.018	
4	3.010	301	0.990	4.855	0.020	
4.2	3.095	309.5	1.105	4.992	0.022	
4.4	3.125	312.5	1.275	5.040	0.026	
4.6	3.245	324.5	1.355	5.234	0.027	
4.8	3.310	331	1.490	5.339	0.030	
5	Break	0	0.000	0	0	

Figure 2: Results Table

4.3 Description of Aluminium Behaviour

The aluminium specimen showed a steady increase in extension as load nut movement increased. This indicates that the specimen progressively elongated under tensile loading. At the beginning of the test, the increase in extension was small, showing that the material initially resisted deformation.

As the test continued, extension increased more rapidly, particularly after approximately 3.0 mm load nut movement. This suggests that the specimen had entered the plastic deformation region, where permanent stretching occurs.

4.4 Fracture Point

The specimen fractured at 5.0 mm load nut movement. The final measurable extension before fracture was 1.490 mm at 4.8 mm load nut movement.

This indicates that the aluminium specimen experienced limited elongation before failure. Compared with highly ductile materials, this suggests relatively low ductility, which may be significant when considering why the drive shaft failed in service.

4.6 Summary

Overall, the aluminium specimen displayed typical metallic tensile behaviour, with an initial resistance to deformation followed by increasing extension and eventual fracture. The limited elongation before fracture suggests that the material may not have had sufficient ductility for a high-stress, cyclic loading application such as a drive shaft.

4.7 Calculated Results

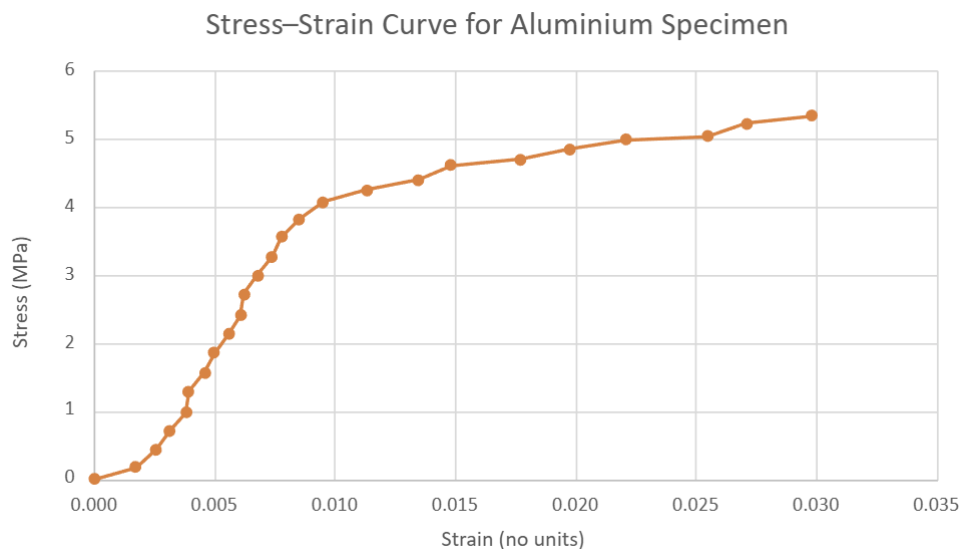


Figure 3: Stress–Strain Curve for Aluminium Specimen

The stress–strain curve (Figure 3) illustrates the mechanical behaviour of the aluminium specimen under tensile loading.

An initial linear region is observed at low strain values, indicating elastic behaviour where stress is directly proportional to strain. In this region, deformation is reversible upon unloading.

As strain increases, the curve begins to deviate from linearity, marking the onset of plastic deformation. In this region, the material undergoes permanent deformation and does not return to its original shape.

The stress continues to increase gradually until reaching a maximum value, after which the specimen fractures. The relatively low maximum stress and limited strain at failure suggest that the material has lower strength and ductility compared to typical structural aluminium alloys.

4.8 Limitations

The original gauge length was not recorded during testing; therefore, a standard value of 50 mm was assumed. This introduces a potential source of error in the strain calculations.

5. Analysis

The tensile test results were used to determine the key mechanical properties of the aluminium specimen, including ultimate tensile strength (UTS), yield strength, and Young's modulus. These values were then compared with the operational stress experienced by the drive shaft (90 MPa) to assess material suitability.

5.1 Ultimate Tensile Strength

The ultimate tensile strength represents the maximum stress the material can withstand before fracture. From the experimental data, the peak stress recorded was:

$$\sigma_{UTS} = 5.339 \text{ MPa}$$

This value is significantly lower than the expected range for structural aluminium alloys, which typically exhibit UTS values between 200 MPa and 500 MPa depending on alloy grade and heat treatment. This

substantial deviation indicates that the tested material possesses extremely poor load-bearing capability.

5.2 Youngs Modulus

Young's modulus was estimated from the gradient of the initial linear (elastic) region of the stress–strain curve, giving:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}$$

Using two points from the elastic region:

Point 1: X = 0.006 and Y = 2.411

Point 2: X = 0.715 and Y = 0.00314

$$E = \frac{2.411 - 0.715}{0.006 - 0.00314}$$

$$E = \frac{1.696}{0.00296}$$

$$E = 572 \text{ MPa}$$

This is considerably lower than the expected value for aluminium (~70 GPa). This discrepancy is likely due to experimental limitations, including manual loading, potential calibration inaccuracies in the testing apparatus, and the assumption of gauge length. Therefore, while the calculated value is not quantitatively accurate, the trend still indicates low stiffness relative to expected material behaviour.

5.3 Yield Strength

The yield strength is defined as the stress at which the material transitions from elastic to plastic deformation. From the stress–strain curve, yielding appears to occur at approximately:

$$\sigma_y \approx 2.4 \text{ MPa}$$

This suggests that the material begins to deform permanently at very low stress levels. In a drive shaft application, where cyclic loading is dominant, such a low yield strength would result in early plastic deformation during normal operation, leading to rapid accumulation of damage.

5.5 Comparison with Operational Stress

The drive shaft was subjected to a maximum operational stress of:

$$90MPa$$

The measured UTS of the tested aluminium sample was:

$$5.339MPa$$

Since:

$$90MPa > 5.339MPa$$

This demonstrates that the applied stress far exceeds the material's maximum strength. Under such conditions, immediate failure would be expected, even without considering fatigue effects. Furthermore, since the operational stress also greatly exceeds the yield strength, the material would undergo plastic deformation almost instantly during service.

5.6 Failure Interpretation

The results strongly indicate that the aluminium used in the drive shaft was not suitable for the application. Given that previous iterations of the component performed successfully using the same design and manufacturing processes, the failure is most likely attributable to a material-related issue rather than a design flaw.

The most probable causes include:

- Incorrect aluminium alloy selection with insufficient strength
- Improper or incomplete heat treatment, resulting in reduced mechanical properties
- Poor supplier quality control leading to material defects such as porosity or inclusions

The extremely low yield strength suggests that the shaft would plastically deform under normal operating conditions. This deformation would introduce stress concentrations, accelerating fatigue

crack initiation and propagation under cyclic loading conditions typical of motorsport applications. Ultimately, this would lead to catastrophic fracture, as observed during the Dakar Rally stages.

6. Conclusion

The investigation into the failure of the aluminium drive shafts has demonstrated that the primary cause of failure was inadequate material performance. Tensile testing revealed that the specimen exhibited extremely low mechanical properties, with an ultimate tensile strength of approximately 5.339 MPa and a yield strength of approximately 2.4 MPa. These values are significantly below the expected range for structural aluminium alloys and are insufficient for a high-load application such as a drive shaft.

When compared to the operational stress of 90 MPa, it is evident that the material was subjected to stresses far beyond its capacity. This would have resulted in immediate plastic deformation followed by rapid failure, particularly under cyclic loading conditions where fatigue effects would further accelerate crack growth.

Although some discrepancies in the measured values can be attributed to experimental limitations, such as apparatus accuracy and assumptions in strain calculation, the magnitude of the difference between expected and measured properties strongly supports the conclusion that the material itself was fundamentally unsuitable.

Given that the design and manufacturing processes remained unchanged from previous successful components, the most likely cause of failure is a material issue associated with the recent change in aluminium supplier. This may include incorrect alloy specification, inadequate heat treatment, or poor material quality control.

To prevent recurrence of such failures, it is recommended that strict material verification procedures are implemented. These should include certification of alloy grade, validation of heat treatment processes, and mechanical testing of incoming materials. Additionally, the use of higher-strength aluminium alloys, such as 7075-T6, should be considered to ensure sufficient safety margins under operational loading conditions.

Overall, this investigation highlights the critical importance of material selection and quality control in engineering applications, particularly in high-performance environments where component failure can have significant consequences.

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