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Dakar Rally Drive Shaft Failure

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1 Introduction

The Dakar Rally puts very high loads on the vehicles, especially on the drivetrain. The drive shafts on both team cars failed completely during stages four and five. When the shaft broke, the car could not move and had to retire. The team believes this is linked to a recent change of aluminium supplier.

The aim of this lab is to test an aluminium sample in tension and use the results to help explain why the drive shafts failed. In this work I will:

1. Carry out a tensile test on an aluminium specimen.
2. Use the data to find an approximate Young's modulus, yield strength and an estimate of the ultimate tensile strength (UTS).
3. Compare the lab results and theory with the known maximum shaft stress of 90 MPa.
4. Suggest likely reasons for the failure and possible ways to avoid it in future.

2 Literature review

2.1 Properties needed for an aluminium drive shaft

A drive shaft must transmit torque without permanent deformation or fracture, even under harsh off-road conditions. For an aluminium shaft, the key properties are Young's modulus, yield strength, ultimate tensile strength (UTS), ductility and fatigue strength. Young's modulus for most aluminium alloys is about 69–72 GPa and does not change much between different alloys and tempers (Matmatch, n.d.). This means stiffness is mainly set by the material type (aluminium vs steel), not the exact alloy.

Yield strength is the stress where plastic deformation starts. Above this stress, the shaft will not fully recover its shape when the load is removed. UTS is the maximum stress reached in a tensile test before necking and fracture. (Matmatch, n.d.).

Ductility and toughness are also important for a drive shaft. Ductility (often given as % elongation at fracture) shows how much the material can stretch before it breaks, while toughness is related to the energy it can absorb. Common structural aluminium alloys often have elongations between about 8% and 20%, depending on the alloy and heat treatment (Callister and Rethwisch, 2020). A ductile material with reasonable toughness is better able to cope with surface damage, misalignment and stress concentrations without sudden brittle fracture.

Because the Young's modulus of aluminium (~70 GPa) is much lower than that of steel (~210 GPa), an aluminium shaft must usually have a larger cross-section to achieve similar stiffness and to keep deflections within limits (AZoM, 2012). If the shaft is too flexible, this can increase bending stresses and vibration, which in turn can reduce fatigue life.

2.2 Tensile testing and property determination

The standard way to obtain E , yield strength and UTS is a uniaxial tensile test. A machined specimen with a known original cross-sectional area A_0 and gauge length L_0 is loaded in tension until it yields and usually until it fractures. Engineering stress and strain are calculated from the measured force and extension:

$$\sigma = \frac{F}{A} \qquad \varepsilon = \frac{\Delta L}{L}$$

where F is the tensile force and ΔL is the change in gauge length (Callister and Rethwisch, 2020). The initial straight part of the stress–strain curve is the elastic region, and the slope of this region is Young’s modulus, $E = \Delta\sigma/\Delta\varepsilon$.

2.3 Fatigue and failure of aluminium shafts

In real service, a drive shaft is loaded in torsion and bending many times, not just once. It experiences torque reversals, gear changes, bumps and jumps. Under these conditions, fatigue behaviour is just as important as static strength. For many aluminium alloys there is no clear fatigue limit, so even stresses below yield can eventually cause failure if the number of cycles is high enough (Hutchinson, 2019). Typical fatigue strengths at 10^7 cycles are roughly 30–50% of the UTS (Hutchinson, 2019).

Fatigue performance is strongly affected by surface quality, internal defects and geometric stress raisers. Features such as shoulders, spline roots, keyways, and welds act as local stress concentrators, and small cracks often start from these locations (Hutchinson and Hutchinson, 2017). Material defects such as porosity or inclusions also reduce fatigue life. A change of material supplier can change defect levels, grain structure and residual stresses, even if the quoted yield and UTS values are similar. This can lead to unexpected fatigue failures in components like drive shafts if the new material is not properly qualified and tested under realistic loading conditions (Hutchinson and Hutchinson, 2017).

Because of this, it is not enough to know only the tensile properties of an aluminium alloy. For safety-critical rotating parts, designers should also consider fatigue strength, surface finish, heat treatment, and inspection methods when choosing the material and validating new suppliers.

3 Methodology

3.1 Specimen and measurements

The test specimen was an aluminium tensile sample supplied for use with the TecQuipment ES6 tensile tester (TecQuipment, n.d.). The central reduced section of the specimen is the gauge length where uniform stress and strain are assumed.

Before testing, I measured the key dimensions with a dial calliper:

- Original gauge length, 30.7 mm
- Original cross-sectional area, 2.2 mm²

These values were used for all stress and strain calculations.

3.2 Test equipment

The tensile test was carried out using the TecQuipment ES6 Engineering Science tensile tester. The main features of this rig are:

1. An upper and lower chuck to grip the specimen.
2. A Load Nut at the top, which moves the upper chuck upwards when turned. One full turn corresponds to 1 mm of movement.
3. Springs supporting the lower chuck, with a total stiffness of 100 N/mm.
4. A Dial Indicator that measures the extension of the springs in millimetres.

The Dial Indicator reading gives the force in the specimen:

$$F = (\text{Dial Reading in mm}) \times 100 \text{ N}$$

The nominal extension of the specimen is obtained by subtracting the spring extension from the Load Nut movement:

$$\Delta L = (\text{Load Nut Movement}) - (\text{Dial Reading})$$

Engineering stress and strain are then:

$$\sigma = \frac{F}{A} \qquad \varepsilon = \frac{\Delta L}{L}$$

Because the ES6 measures movement of both the specimen and the machine, the strain is nominal rather than a very accurate true strain, but it is suitable for teaching and comparison between materials (TecQuipment, n.d.).

3.3 Test setup

1. The Work Panel was mounted on its supports according to the kit instructions.

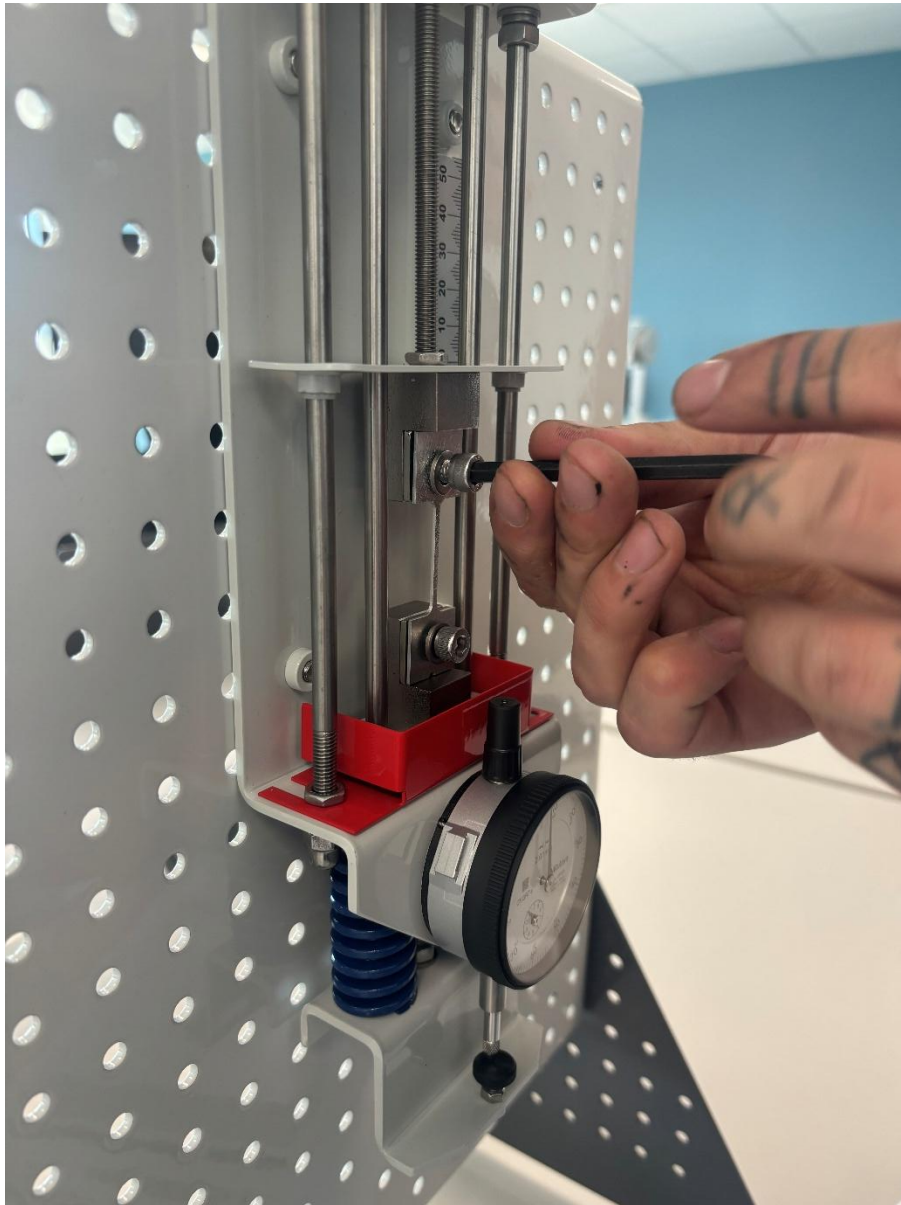


Figure 1 Set up of test equipment

2. The aluminium specimen was clamped between the upper and lower chucks, making sure the gauge length was centred and the specimen was straight.
3. The clear safety guard was fitted over the specimen and chucks.

4. The Load Nut was turned slowly until the Dial Indicator just began to move, giving a small preload on the specimen.

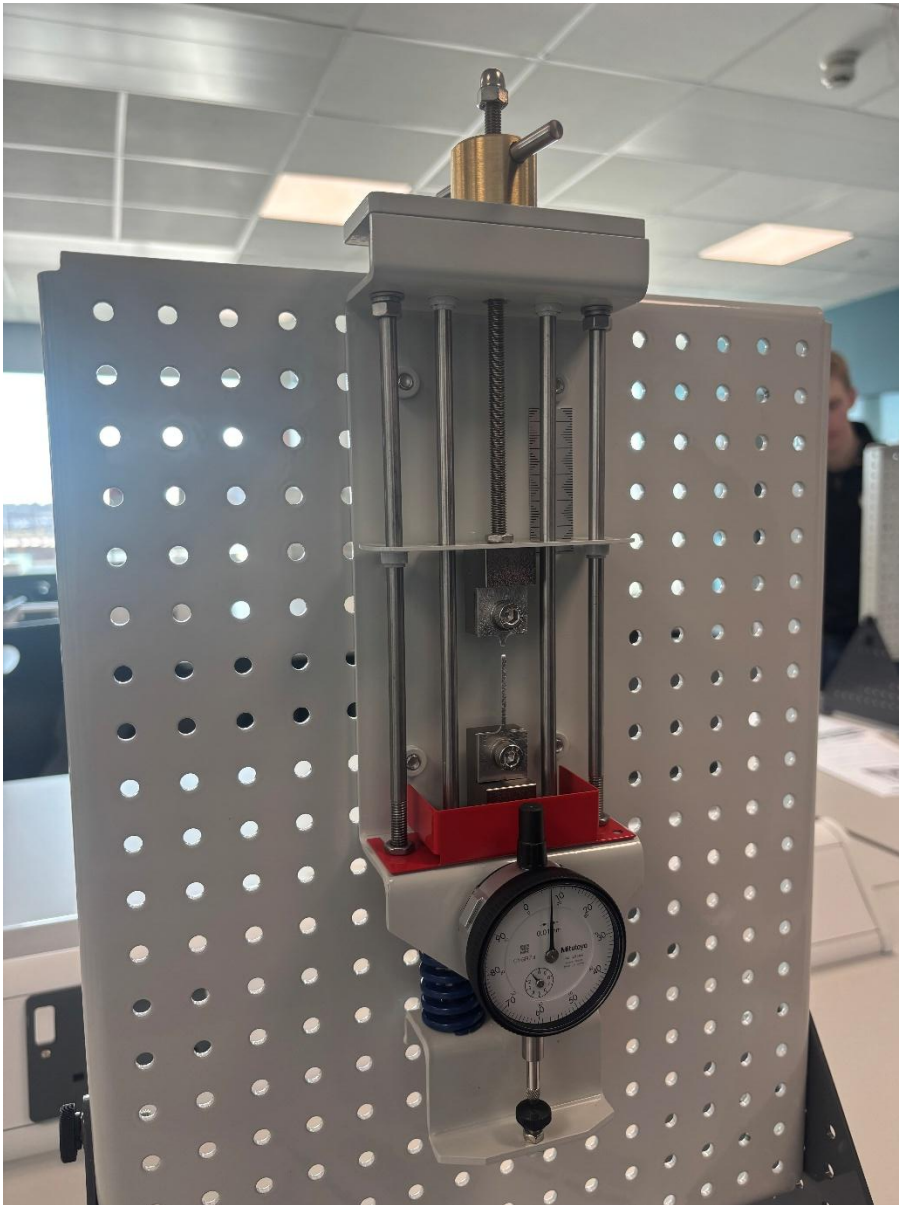


Figure 2 Fracture in the specimen Image

5. The Dial Indicator bezel was rotated so that the pointer aligned with zero.

This setup ensured that the experiment started from a known gauge length with the measurement system zeroed.

3.4 Test procedure

The following procedure was used:

1. With the Dial Indicator at zero, the Load Nut was turned to increase the tensile load in small steps of 0.2 mm movement.
2. At each step, the following readings were taken:
 - Load Nut movement (mm)
 - Dial Indicator reading (mm)
3. The force in the specimen was calculated using the equation found in the section above.
4. The nominal extension was calculated also using the equation found in the section above.
5. Using the measured length and area, the stress and strain were calculated:
6. Data collection continued until a maximum Dial reading of about 3.44 mm (approximately 344 N) was reached. After this point the test was stopped, as the specimen fractured during this run.
7. All values were entered into an Excel spreadsheet, and a graph of nominal stress versus strain was plotted.

This method followed the guidance for using the ES6 tensile tester and provided a full set of load, extension, stress and strain data for the aluminium specimen (TecQuipment, n.d.).

4 Results

4.1 Key dimensions and fracture measurement

Before the test, the aluminium specimen had:

- Original gauge length: 30.7mm
- Original cross-sectional area: 2.2mm^2

After the test, the specimen fractured in the gauge length. By carefully pushing the two halves back together at the fracture and measuring the new distance between the original gauge marks, the final gauge length was found to be:

- Final gauge length: 36.26mm

From this:

$$\text{Elongation} = L_{\text{Final}} - L_{\text{Original}} = 36.26 - 30.70 = 5.56\text{mm}$$

$$\% \text{Elongation} = \frac{5.56}{30.7} \times 100 \approx 18.1\%$$

A percentage elongation of about **18%** shows that the specimen is quite ductile, which is in line with typical structural aluminium alloys that often show elongations between roughly 8% and 20% (Callister and Rethwisch, 2020).

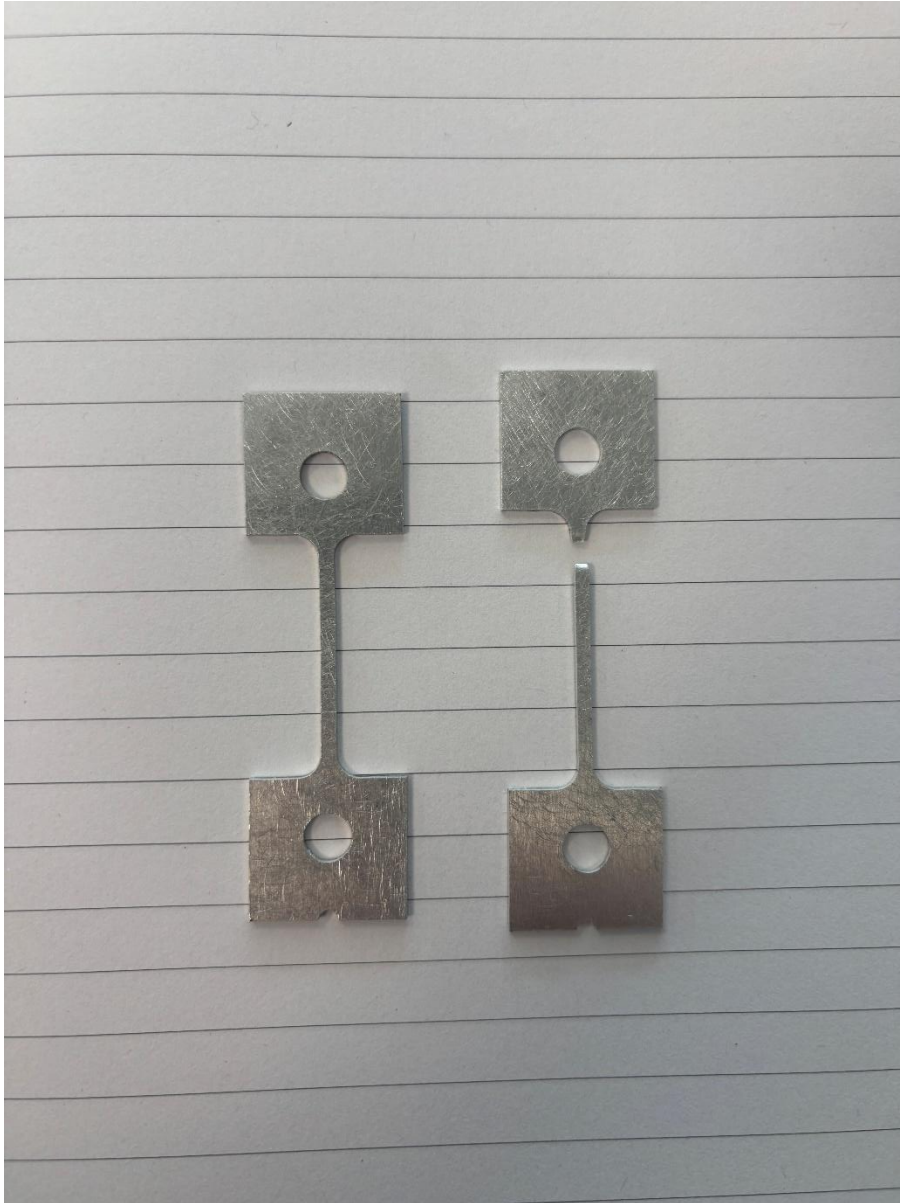


Figure 3 Specimen against Original

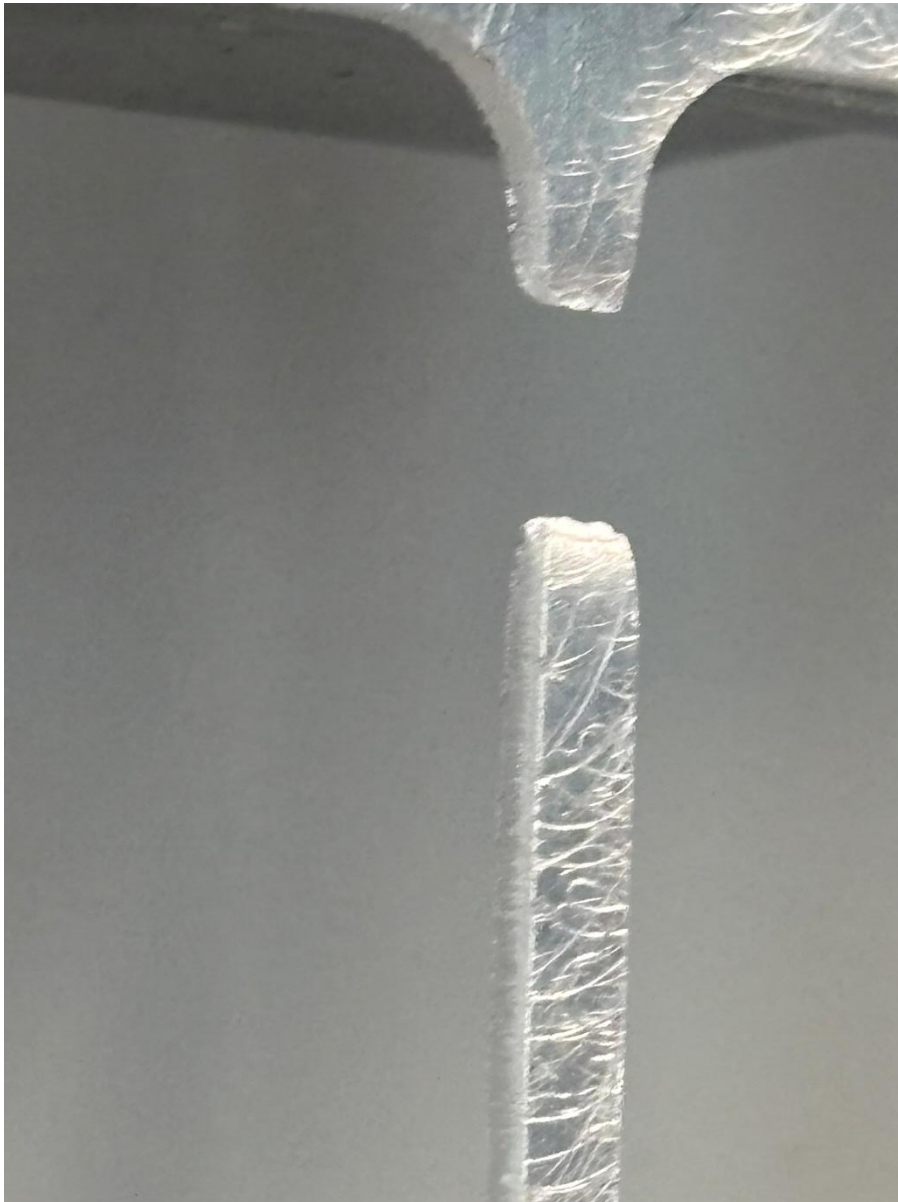


Figure 4 Fracture of specimen - Close up

4.2 Data table

A shortened version of the tensile data, including calculated nominal stress and strain, is shown in Table 1. These data were used to produce the stress–strain graph.

Table 1 Graph of Experiment Results and Calculations

Load Nut Movement (mm)	Dial indicator (mm)	Force (N)	Extension (mm)	Stress (Mpa)	Strain
0	0	0	0	0	0
0.2	0.2	20	0	100	0
0.4	0.39	39	0.01	195	0.00033
0.6	0.57	57	0.03	285	0.00098
0.8	0.75	75	0.05	375	0.00163
1	0.91	91	0.09	455	0.00293
1.2	1.08	108	0.12	540	0.00391
1.4	1.26	126	0.14	630	0.00456
1.6	1.44	144	0.16	720	0.00521
1.8	1.6	160	0.2	800	0.00651
2	1.76	176	0.24	880	0.00782
2.2	1.92	192	0.28	960	0.00912
2.4	2.09	209	0.31	1045	0.0101
2.6	2.26	226	0.34	1130	0.01107
2.8	2.42	242	0.38	1210	0.01238
3	2.57	257	0.43	1285	0.01401
3.2	2.7	270	0.5	1350	0.01629
3.4	2.82	282	0.58	1410	0.01889
3.6	2.94	294	0.66	1470	0.0215
3.8	3.01	301	0.79	1505	0.02573
4	3.1	310	0.9	1550	0.02932
4.2	3.18	318	1.02	1590	0.03322
4.4	3.26	326	1.14	1630	0.03713
4.6	3.33	333	1.27	1665	0.04137
4.8	3.38	338	1.42	1690	0.04625
5	3.44	344	1.56	1720	0.05081

4.3 Stress–strain curve

The nominal stress–strain curve for the aluminium specimen, plotted from the data in Table 1, is shown in Figure 3.

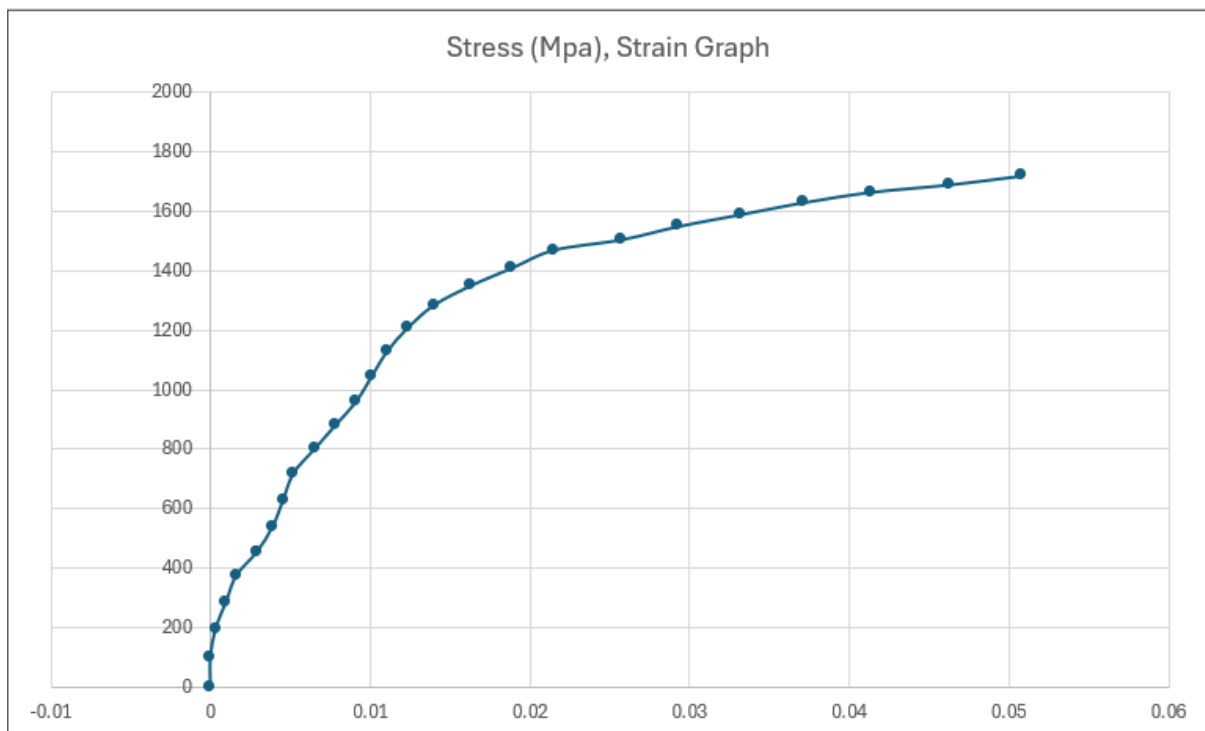


Figure 5 Stress, Strain Graph of specimen

From the graph:

- **Elastic region:**

From $\varepsilon = 0$ up to about $\varepsilon \approx 0.007$, the graph is almost a straight line. This is the elastic region, where stress is proportional to strain and the material follows Hooke's Law.

- **Onset of plastic deformation:**

Around $\varepsilon \approx 0.006 - 0.008$ and $\sigma = 800$, the curve starts to bend and becomes less steep. This shows that plastic deformation is beginning and the material is no longer purely elastic.

- **Approach to maximum stress:**

As strain increases beyond about 0.01, the stress continues to rise but more slowly, giving a rounded curve towards the top. The maximum recorded stress just before fracture is about 1720 at a strain of approximately 0.051.

- **Fracture and ductility:**

After reaching this maximum stress, the specimen fractured in the gauge length. By measuring the final gauge length, the percentage elongation was found to be about 18%, which confirms that the material is reasonably ductile, as expected for many aluminium alloys used in structural applications (Callister and Rethwisch, 2020).

In the broken specimen, there was a visible reduction in cross-section (necking) at the fracture and a relatively rough, fibrous-looking fracture surface. This appearance is typical of a **ductile fracture**, where the material undergoes significant plastic deformation before it breaks (Callister and Rethwisch, 2020).

5 Analysis

Young's modulus, yield strength and ultimate tensile strength (UTS) were obtained from the experimental stress–strain curve of the aluminium specimen. Young's modulus E was estimated from two points in the clearly linear part of the graph: at $\sigma \approx 195$, $\varepsilon \approx 0.00033$, and $\sigma \approx 540$, $\varepsilon \approx 0.003$. The slope is:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{540 - 195}{0.003 - 0.00033} = 9.6 \times 10^4$$

This is an apparent Young's modulus because the ES6 rig measures nominal strain, which includes some deformation of the frame and springs (TecQuipment, n.d.). Even so, the value is of the same order as the literature Young's modulus for aluminium alloys (~69–72 GPa), supporting the conclusion that the specimen behaves like a typical aluminium alloy (Matmatch, n.d.).

The yield strength was taken from the point where the stress–strain curve first deviates noticeably from linearity. This occurs around $\varepsilon \approx 0.006$ – 0.008 and $\sigma \approx 800$. Aluminium alloys usually do not show a sharp yield point, so this estimate is consistent with the idea of a gradual transition from elastic to plastic behaviour (Callister and Rethwisch, 2020). A more accurate method would be the 0.2% proof stress construction, but this is difficult with nominal strain and limited resolution.

The maximum recorded stress just before fracture is about 1720 at a strain of roughly 0.051. Since the specimen snapped shortly after this point, this value is taken as an approximation of the UTS. The measured final gauge length of 36.26 mm gives an elongation of 5.56 mm and a percentage elongation of about 18.1%, which shows good ductility and lies within the typical range for structural aluminium alloys (Callister and Rethwisch, 2020).

Comparing these findings with literature values (yield strengths of roughly 100–300 MPa and UTS values of 150–600 MPa for common structural alloys) suggests that the tested material has normal ductile aluminium behaviour (Matmatch, n.d.). The stress–strain curve shape and the relatively high elongation confirm this.

Relating this to the Dakar drive shaft, the nominal maximum service stress is 90 MPa. For a typical alloy with a yield strength near 240 MPa (e.g. 6061-T6), the static factor of safety would be roughly 2.5–3 (Matmatch, n.d.). The fact that shafts still failed indicates that static strength alone is not the problem. More likely, the combination of a new supplier (possible change in alloy/temper or quality), stress concentrations in the shaft geometry, and severe cyclic and impact loading in the rally led to fatigue crack initiation and growth, eventually causing fracture even though the nominal stress was below the expected yield strength (Hutchinson, 2019; Hutchinson and Hutchinson, 2017).

6 Conclusion

The tensile test on the aluminium specimen produced a typical ductile stress–strain response, with a clear elastic region, gradual yielding and fracture in the gauge length. An apparent Young’s modulus of about 9.6×10^4 , an approximate yield strength of ~800, an estimated UTS of ~1720 and a percentage elongation of about 18.1% were obtained. These values are consistent with a normal structural aluminium alloy (Callister and Rethwisch, 2020; Matmatch, n.d.).

However, the Dakar drive shafts failed at a nominal maximum stress of only 90 MPa. For a correctly specified alloy this should be safely below yield, so static strength alone does not explain the failures. The most likely causes are a combination of inappropriate alloy/temper or quality from the new supplier, plus severe cyclic and impact loading with stress concentrations, leading to fatigue crack initiation and eventual fracture (Hutchinson, 2019; Hutchinson and Hutchinson, 2017).

7 Reference List

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