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1 Introduction

1.1 Aim

The aim of this lab was to investigate the mechanical properties of 4 commonly used engineering materials: a mild steel alloy, an aluminium alloy, and two plastics. These basic properties — Young's modulus, elastic limit, yield strength, ultimate tensile strength, and total elongation until failure — were investigated through subjecting each material to a mechanical tensile test.

1.2 Background

When a load is placed on a material, the material is expected to deform. This deformation is proportional to the magnitude of the load. In order to exclude the specimen size effect on the mechanical properties of the material, we introduce the concepts of stress and strain. Stress is defined by

$$\sigma = \frac{F}{A_0} \qquad \left(\mathrm{Nm}^{-2} \text{ or Pa}\right) \tag{1}$$

where F is the instantaneous load applied perpendicular to the original cross-section and A_0 is the original cross-sectional area. Strain is defined by

$$\varepsilon = \frac{\Delta l}{l_0} \qquad \text{(dimensionless)} \tag{2}$$

where Δl is the deformation elongation and l_0 is the original length. Furthermore, the degree to which a structure *strains* depends on the magnitude of the imposed *stress*. In other words, stress and strain are proportional to one another. We denote the proportionality constant as E, known as the modulus of elasticity or Young's modulus.

$$\sigma = E\varepsilon \tag{3}$$

Conducting a tensile test and plotting the stress vs strain curve yields insight into many fundamental mechanical properties of a metal, such as the Young's modulus. The tensile testing machine is designed to elongate the specimen at a constant rate and to continuously measure the instantaneous applied load (using a load cell) required to maintain this rate. It is this instantaneous applied load that we refer to as the *load*. The specimen is usually in the shape of a "dogbone" so as to allow the machine to grip onto the specimen at the ends and to limit deformation to the narrow center region. The length of this center region, the part which is actually undergoing the test, is known as the "gauge length."

2 Methodology

2.1 Testing Apparatus

The testing apparatus used for this investigation was the Instron 5567. This machine is a "low-force universal testing system" meaning it can be used for tensile, compression, bend, peel, and tear tests while delivering up to 30 kN of force. As labelled in Figure 1 (for all figures, see Appendix 5), there are 5 key parts to this equipment.

1. Load cell: responsible for applying and measuring the instantaneous force to the material during the test.
2. Cross head: a stiff beam responsible for the vertical movement of the specimen while test is running.
3. Grips: used to physically mount the specimen. Also, the force required to drive the crosshead is transferred to the specimen through the grips.
4. Manual control: a set of controls used to move the grips manually if desired, with separate buttons for gross or refined movements.
5. Computer control: contains software which allows the user to set up the test itself and modify all test parameters such as the strain rate.

2.2 Materials

4 materials were tested in this lab:

1. mild steel (a low carbon steel, known for its ductility and formability) [12]
2. aluminium 5050 (a specific grade of aluminium allow, formed with high amounts of magnesium) [1]
3. PMMA (also known as acrylic, a rigid material known to be quite brittle) [11] and
4. nylon (an incredibly ductile and strong plastic material) [9]

As mentioned earlier in section 1.2, ATSM standards usually call for specimens to be cut in the shape of a "dogbone" (see Figure 2 for a specimen sketch). This ensures that deformation is confined to the center region, which has a width w, gauge length l_0 and a thickness t. Therefore, this entire section has a uniform cross sectional area $A_0 = wt$.

To ensure reliability and reproducibility, the tensile test for each material was repeated 3 times. Hence, a total of 12 specimen (3 for each material) were cut, with efforts made to ensure the dimensions were in-line with ATSM standards; that is, all specimen had a dogbone shape with a gauge length of 50 mm and a width of approximately 12.8 mm. The exact width and thickness of each specimen was then measured using Vernier callipers. See Table 1 (for all tables, see Appendix A) for the exact dimensions and the cross-sectional area A_0 for each specimen.

2.3 Testing procedure

In order to properly mount the specimen into the Instron 5567, the bottom shoulder of the material was loaded into the lower grip first, keeping the screws slightly loose, before mounting the top shoulder into the top grip. The grip screws were only fully tightened once the direction of the specimen was confirmed to be in line with the testing axis.

The test itself was set up on the computer control. The test to be conducted was a simple tensile test with a fixed displacement rate. For the steel, aluminium, and PMMA, the displacement rate was set to 5 mm/ min. Due to nylon's incredibly ductile behaviour, in order to save time, the displacement rate was set to 50 mm/ min.

Finally, in the last step before the test was actually run, the values of displacement and force were calibrated to zero using the "balance force" and "zero displacement" functions provided in the computer control software. Note that the magnitude of the force value after calibrating the machine may register a small value such as 0.0001 kN. This is normal and is known as the "prelude". It is the magnitude of the force required to create some friction between the test sample and the grip of the machine, keeping the material fixed during the test.

3 Results

Each stress-strain curve was plotted and labelled with the mechanical properties of interest, namely: Young's modulus (E), yield stress (σ_y), elastic limit (EL), ultimate tensile strength (UTS), and the strain at failure ($\varepsilon_{\text{fail}}$). Please refer to Appendix 5 to view Figures 3, 4, 5 and 6.

The results from these graphs were then tabulated, and can be seen in Appendix A in Table 2.

3.1 Describe necking and stretching

Necking is a form of plastic deformation, which in turn occurs through dislocation motion. To illustrate this further, consider a generic edge dislocation. When an external shear stress is applied, the edge dislocation (along with all neighbouring planes) moves in the direction of the stress. If the applied stress is of great enough magnitude, the interatomic bonds of the plane adjacent to the extra half-plane are severed. The upper half of this adjacent plane then becomes the extra half-plane, with the bottom half linking up with the original dislocation. This process is repeated such that the extra half-plane, by the repeated and successive breaking and reforming of bonds, moves towards the surface of the crystal, ultimately emerging and forming an edge that is one atomic distance wide. It is this edge which, in a process termed as *slip*, forms a permanent (plastic) deformation.

The 'strain hardening' which is exhibited between the yield point and UTS is also related to dislocations. When plastic deformation occurs, the dislocation density increases because of dislocation multiplication, decreasing the average separation distance between dislocations. This brings dislocations closer to one another, allowing them to experience dislocation-dislocation strain field interactions. A large majority of these interactions are repulsive, hindering the motion of a dislocation as it is trying to traverse through the crystal lattice. If an interaction happens to be attractive, dislocation annihilation will occur, leading to the formation of a perfect crystalline lattice in place of the dislocations. Either way, the motion of a particular dislocation is impeded by the very presence of other dislocations. This increases the strength of the metal, thus the term 'strain hardening.'

Recall that microscopic flaws always exist at the surface and within the interior of a material. These flaws are able to concentrate the magnitude of an applied stress according to the equation

$$\sigma_m = 2 \cdot \sigma_0 \left(\frac{a}{\rho_t} \right)^{1/2} \tag{4}$$

It is these 'stress concentrators' which act as a catalyst for necking, occurring due to small cavities or microvoids forming in the interior of the cross section of the metal. As deformation continues, these microvoids enlarge and coalesce to form a crack perpendicular to the applied stress. The point of this crack formation is known as the 'neck' which here on in, all applied force is concentrated at. This causes a rapid decrease in the material's cross-sectional area.

4 Discussion

The experimentally obtained values are compared to literature values in Table 3. Literary values were taken from multiple sources; see the footnotes for the respective references. Some key similarities and differences are worth noting here.

Firstly, **all** values for the modulus of elasticity E substantially deviate from the literary values. Recalling that Young's modulus is a constant for a particular material at a particular temperature, differences of up to 250-fold between a measured value and a theoretical one (see Table 3/Nylon) is clearly erroneous. Of course, every material has a small range of possible E values, however such large differences suggests that rather than the error being caused by the apparatus or lab technician, the error lies in the analysis of the data. Perhaps errors arose while using analysis software Microsoft Excel or the graphing software LaTeX. This is

the only sensible explanation of these errors. Interestingly, these errors must have been quite reproducible, as from Table 2 it is evident that there is very little deviation between results for each sample.

Secondly, **all** values for the Nylon tensile test are well outside of the range of literary quoted values. This has one major possible reason, and that is that the method of determination of yield strength and ultimate tensile strength is incorrect for this type of material. Indeed, rather than the 0.2% strain offset value, the yield strength for ductile polymers is more accurately determined from the initial peak in the curve before the yield drop. Similarly, the UTS is actually the stress value at the final peak. Analysis was completed as requested, however, leading to vastly incorrect values. Indeed, the experimental values extracted by using incorrect methods will obviously be incorrect.

Futhermore, note that there will always be limitations to an experiment when using any equipment. In this case, if the load required to sustain a certain strain rate exceeds 30 kN, the test will simply remain incomplete and data will be inaccurate. A similar result ensues if the cross head needs to move higher than it is physically capable of (due to the size limitation of the machine). Also, tensile testing systems use extensometers to measure the deformation elongation Δl and load cells to measure the applied force F. These are both just simple sensors, prone to miscalibration and deterioration over time. Any analysis conducted from the results of these sensors will only be as good as the sensors themselves (garbage in, garbage out).

In order to run any tensile test accurately, each specimen must first be loaded into the grips of the tensile testing apparatus properly, completely perpendicular to both the grip arms. This is to ensure that when performing the test, the loading remains completely uniaxial. Otherwise, the instantaneous force could be contributing to some unwanted phenomena such as bending moments, shear forces, torsional forces etc, rendering our results inaccurate and definitely unreproducible.

Finally, it is worth briefly mentioning the effect of strain rate on the mechanical properties of a material. It has been shown in many papers (see [13]) that the strain rate at which a tensile test is conducted at has a large effect on the measured ductility of the material, further influencing factors such as strain at failure. Nylon is the only material which the strain rate was modified for. Perhaps this had some weighting on the largely erroneous data at hand

References

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5 Figures

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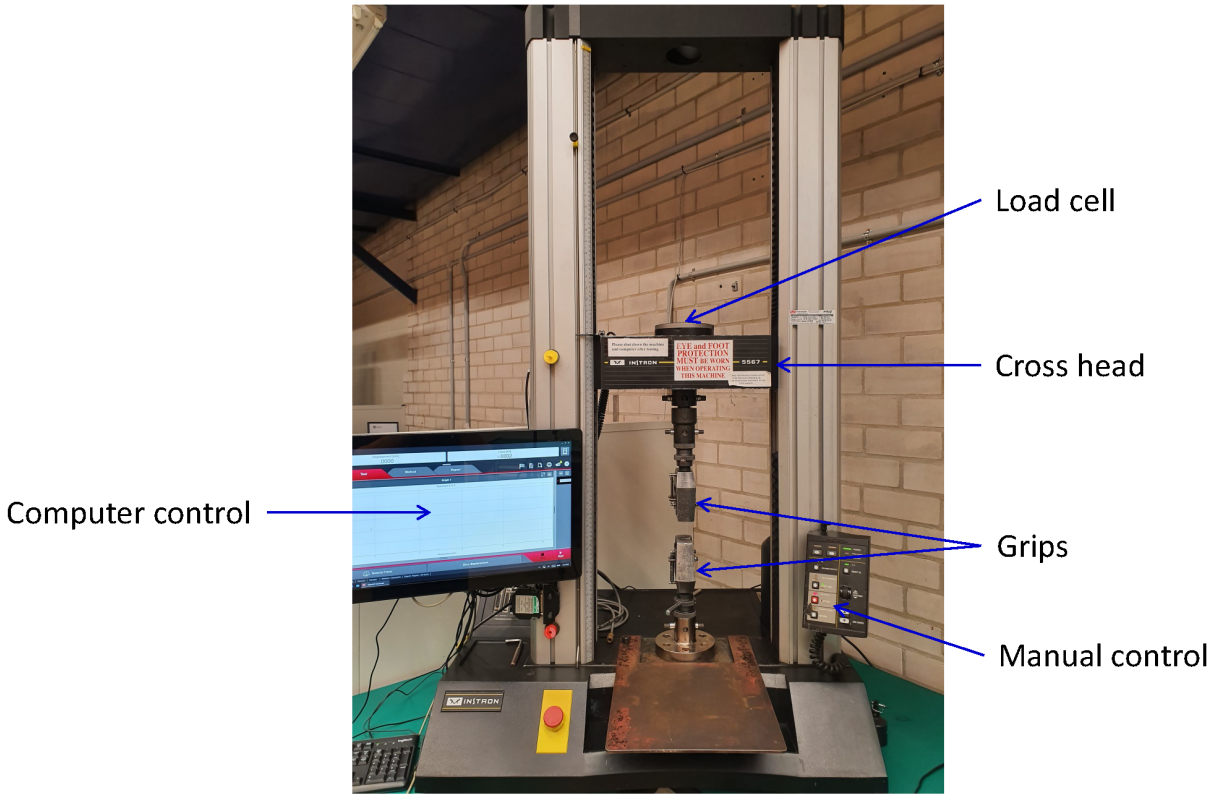

Figure 1: The Instron 5567 used for the tensile test.

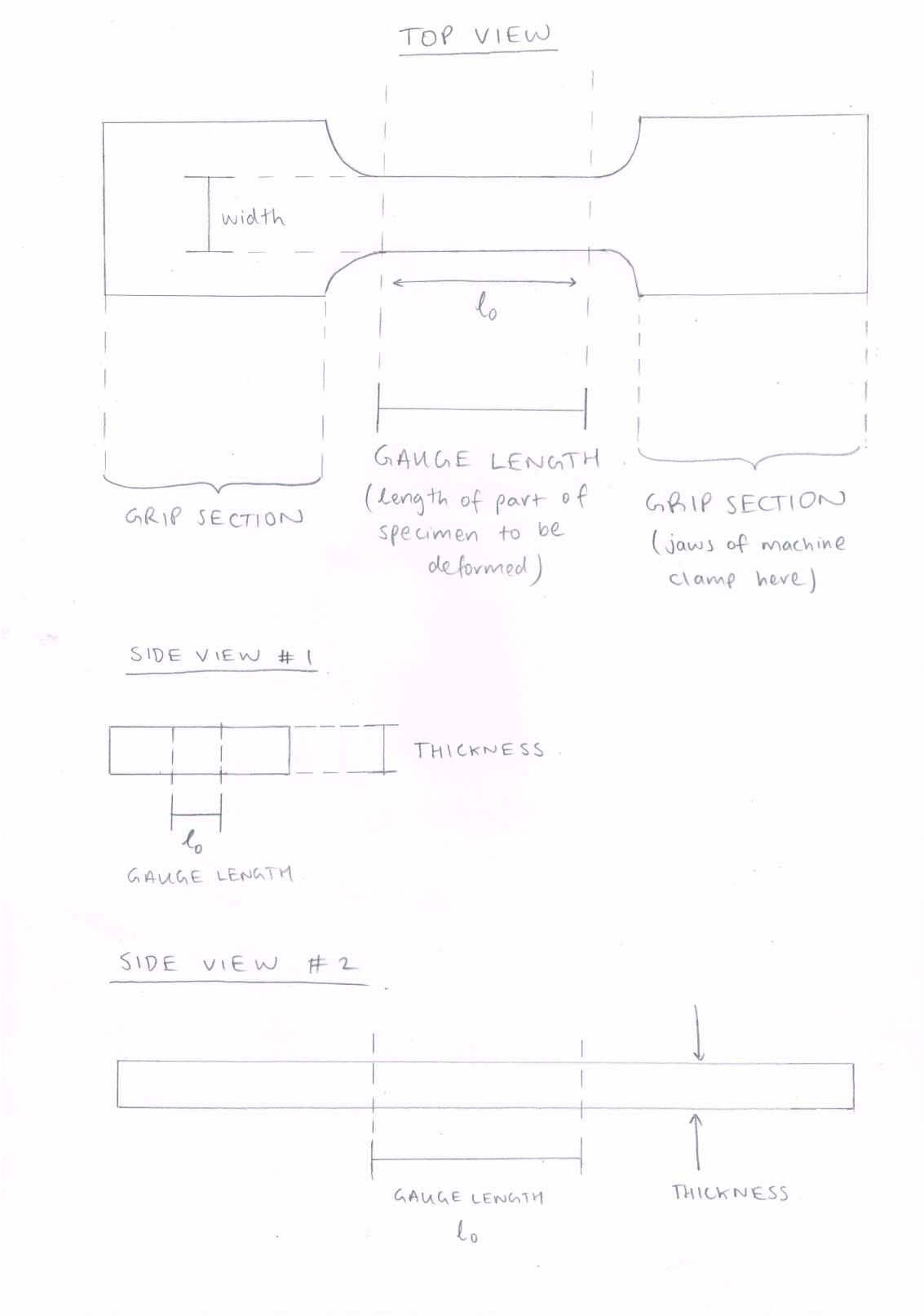

Figure 2: The "dogbone" specimen used for the tensile test.

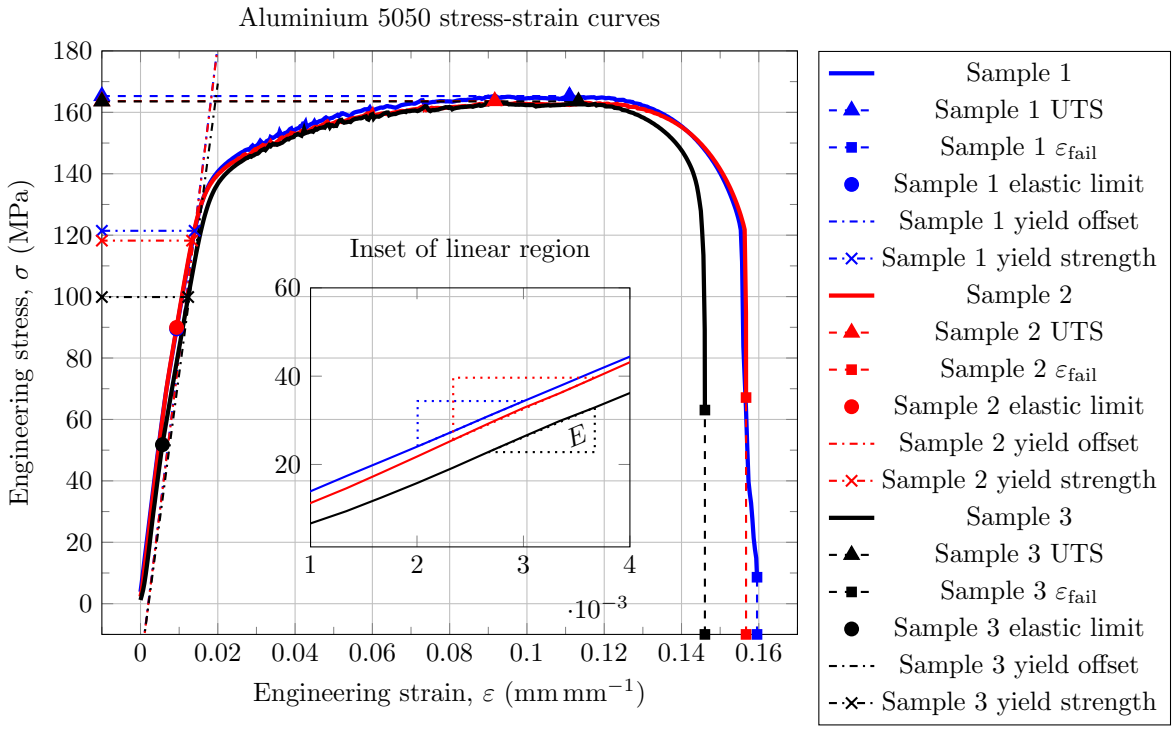

Figure 3: Experimental aluminium 5050 stress-strain curve

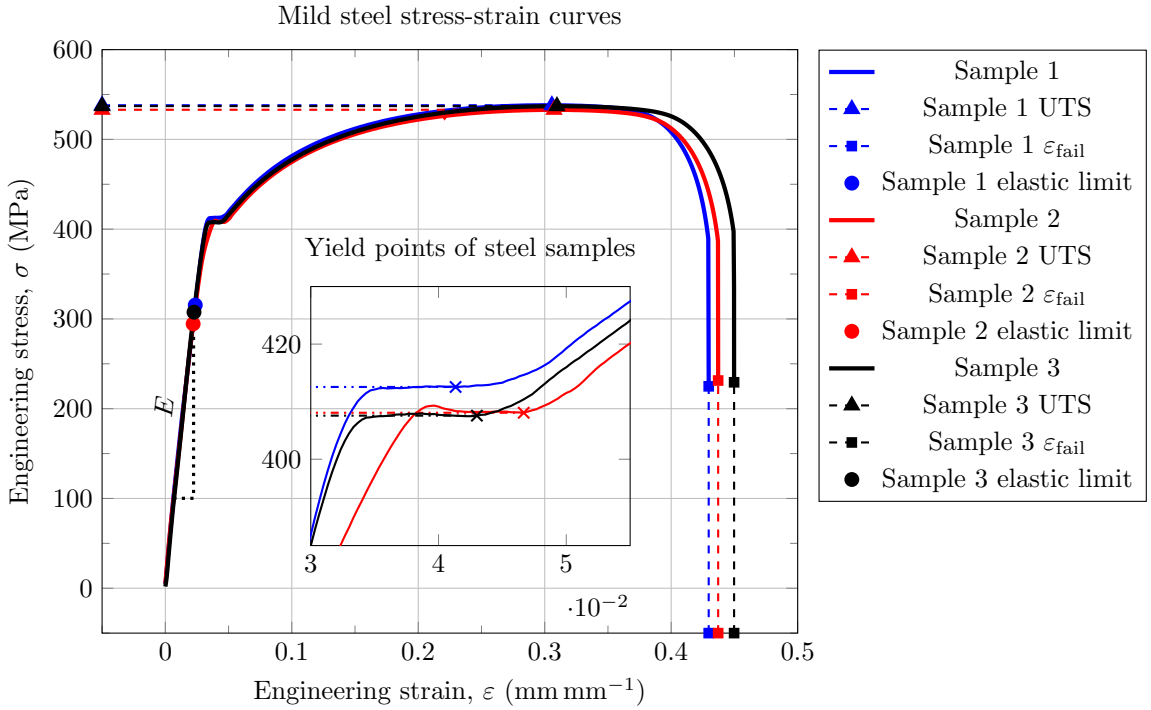

Figure 4: Experimental mild steel stress-strain curve

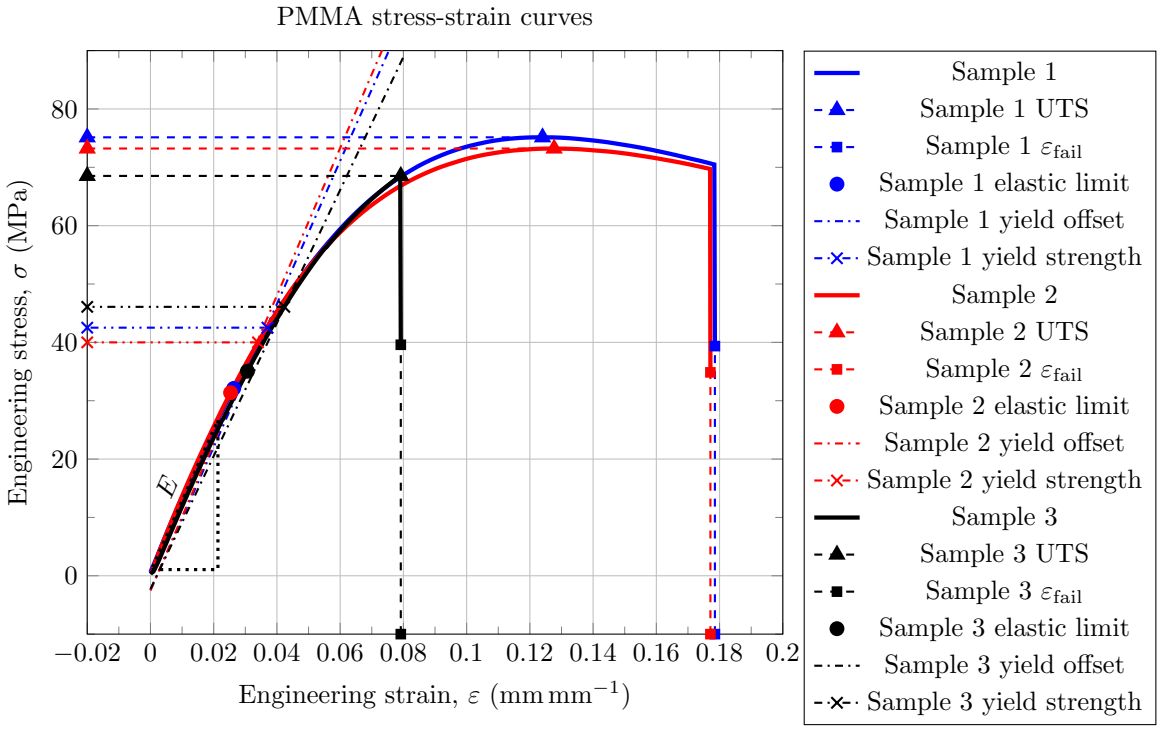

Figure 5: Experimental PMMA stress-strain curve

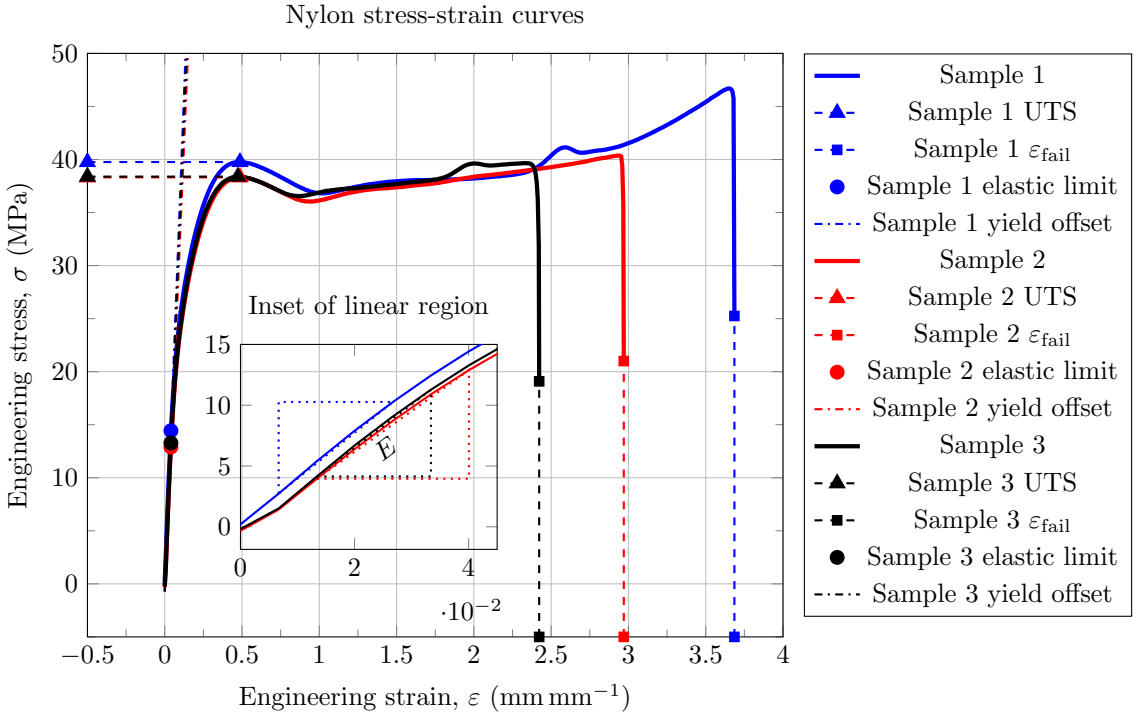

Figure 6: Experimental Nylon stress-strain curve

A Tables

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Table 1: Exact dimensions of all specimens used in tensile testing.

	Width (mm)	Thickness (mm)	Area (mm^2)
Mild steel			
Trial 1	12.88	2.95	38.0
Trial 2	12.92	2.97	38.4
Trial 3	12.86	2.96	38.1
Aluminium			
Trial 1	12.91	2.95	38.1
Trial 2	12.90	2.97	38.3
Trial 3	12.94	2.98	38.6
PMMA			
Trial 1	12.73	2.95	37.6
Trial 2	12.71	2.94	37.4
Trial 3	12.70	2.94	37.3
Nylon			
Trial 1	12.70	2.18	27.7
Trial 2	12.72	2.19	27.9
Trial 3	12.72	2.18	27.7

Table 2: Experimentally determined mechanical properties of select materials.

	E (GPa)	UTS (MPa)	$\varepsilon_{\text{fail}}$ (mm/mm)	EL (MPa)	σ_y (MPa)
Mild steel					
Sample 1	12.44	538.04	0.43	315.43	412.55
Sample 2	12.44	532.99	0.44	294.50	408.07
Sample 3	12.44	537.06	0.45	307.50	407.57
Average	12.44	536.03	0.44	305.81	409.40
Aluminium					
Sample 1	10.30	165.30	0.16	89.48	121.42
Sample 2	10.11	163.67	0.16	89.97	118.23
Sample 3	9.47	163.55	0.15	51.78	99.86
Average	9.96	164.17	0.15	77.08	113.17
PMMA					
Sample 1	1.23	75.14	0.18	32.11	42.52
Sample 2	1.26	73.22	0.18	31.37	40.00
Sample 3	1.14	68.53	0.08	35.05	46.09
Average	1.21	72.30	0.18[1]	32.84	42.87
Nylon					
Sample 1	376.42	39.76	3.69	14.44	*
Sample 2	335.16	38.32	2.97	12.89	*
Sample 3	356.79	38.39	2.42	13.28	*
Average	356.12	38.82	3.03	13.54	*

[1] Excluding the sample 3 outlier.

Table 3: Mechanical properties: experiment vs literature

	E (GPa)	UTS (MPa)	$\varepsilon_{\text{fail}}$ (mm/mm)	σ_y (MPa)
Mild steel				
Average	12.44	536.03	0.44	409.40
Literature[2]	202 - 205	440 - 716	0.15 - 0.20	370 - 519
Aluminium				
Average	9.96	164.17	0.15	113.17
Literature[3]	68.9 - 80	145 - 170	0.09 - 0.24	55 - 145
PMMA				
Average	1.21	72.30	0.18	42.87
Literature[4]	2.85 - 3.3	62.0 - 83.0	0.03 - 0.065	64.8 - 83.4
Nylon				
Average	356.12	38.82	3.03	13.54[5]
Literature[6]	1.30 - 4.20	50.0 - 79	0.50 - 1.20	40 - 100

[2]See [7], [4]
[3]See [5], [2]
[4]See [3], [6]
[5]As no yield strength points were able to be determined using the 0.2% offset method, here the elastic limit average is used.
[6]See [10], [8]