PART IB EXPERIMENTAL ENGINEERING

SUBJECT: MATERIALS | **EXPERIMENT M3**

LOCATION: INGLIS MEZZANINE | **(LONG)**

TORSION TESTING: PLASTICITY AND FRACTURE

1. OBJECTIVES

1.1 Experiment I: torsion of a cast iron bar

(i) To make an estimate of the fracture stress in shear τ_f for cast iron, and hence the fracture toughness K_C .

(ii) To observe the mode of failure of the cast iron bar.

1.2 Experiment II: torsion of a mild steel bar

(i) To determine the yield stress in shear τ_y and the angle of twist at failure ϕ_f for mild steel.

(ii) To observe the mode of failure of the mild steel bar.

1.3 Experiment III: torsion of a brass bar

(i) To determine the yield stress in shear τ_y , and the angle of twist at failure ϕ_f for brass in the annealed and work hardened states.

(ii) To observe the mode of failure of the brass bar.

- In each case, the aim is to understand the relationship between the properties of the material, its microstructure and its deformation history.

2. INTRODUCTION

This is a **long** experiment.

The whole class will investigate the torsion of a brittle cast iron bar (**Experiment I**). Half the class will also investigate the plasticity and fracture in torsion of a solid mild steel circular bar (**Experiment II**). The other half will test a solid brass circular bar (**Experiment III**).

3. APPARATUS

All experiments make use of a test machine which enables a torque to be applied to one end of a specimen by hanging dead weights onto the end of a lever arm. This torque is reacted at the other end where the specimen may be twisted by means of a gear train connected to a hand wheel.

In addition to the test machine the apparatus includes:

(i) a solid circular torsion specimen with square ends and gauge length $L = 150$ mm .

(ii) a pair of bar carrier plates which locate onto circular pins on the test machine.

(iii) a micrometer and a piece of chalk are also provided.

4. PROCEDURE

4.1 Fitting the torsion specimen

The procedure for fitting each torsion specimen into the test machine is as follows:

(i) Measure the diameter, D, of the bar with the micrometer at three different positions along the length. Record the data in the appropriate table at the end of the handout. Note the length of the lever arm, A, of the load hanger as marked on the machine.

(ii) Note the direction of rotation of the hand wheel required to produce positive rotation as measured by the protractor or gearwheel. Ensure the hand wheel is rotated to the starting position.

(iii) Slide the bar carrier plates fully onto the square ends and locate the holes in the ends of the bar onto the centres of the test machine. The mechanism for moving the centring pins is located at the end opposite to that of the protractor; on the older rigs there is a small hand wheel, on the newer test rigs, the end fitting can be pushed in and out. Make sure there is some freedom for small longitudinal movements. Rotating the hand wheel as necessary, locate the bar carrier plates onto the two circular locating pins. The ends of the bar must be fully into the end fittings and on the centres, otherwise failure may occur locally at one of the square ends.

Safety note: For cast iron specimens a plastic tube must be placed around the bar before mounting it in the test machine as sharp fragments of cast iron may fly out on fracture.

(iv) Initially ensure a 1 kg weight is on the hanger to create a small initial torque. (The play in the system makes it impossible to define the position of the specimen until it is under load). Rotate the hand wheel until the lever arm is horizontal as indicated by the bubble on the lever arm. Read the scale on the protractor or gearwheel and enter this reading in the appropriate table at the end of the handout as the angle θ_0.

Three materials are to be tested to failure in torsion: cast iron, mild steel and brass. Each group will test cast iron and either mild steel or brass.

4.2 Experiment I: cast iron

(i) Once the bar is mounted in the torsion machine (following the procedure described in Section 4.1) proceed to increase the load by increments of 8 kg up to 65 kg and then by 4 kg until failure occurs. For each load increment, turn the hand wheel until the lever-arm bubble is brought back to the horizontal. The protractor reveals the approximate overall angle of twist of the specimen. Record the protractor or gearwheel reading at each load increment in the table provided at the end of the handout.

(ii) At failure record the load P_f and protractor reading θ_f in the space provided in the table. Calculate the torque at failure T_f and the corresponding angle of twist per unit length ϕ_f and add these values to the table.

(vii) Remove the weights from the lever arm and then remove the specimen from the rig. Examine and sketch the fracture surface. Also estimate the size of any surface imperfections on the cast bar. Why do these occur and what effect might they have?

4.3 Experiment II: mild steel

(i) Once the bar is mounted in the torsion machine (following the procedure described in Section 4.1) draw a straight chalk line along the full length of the top of the bar so that the twist can be observed.

(ii) Proceed to increase the load by increments of 4 kg up to 9 kg. For each load increment, turn the hand wheel until the lever-arm bubble is brought back to the horizontal. The protractor reveals the approximate overall angle of twist of the specimen. Record the protractor or gearwheel reading at each load increment in the table provided at the end of the handout.

(iii) Continue by increments of 1 kg until the increasing increments in the angle of twist indicate that the bar has become fully plastic. Record the protractor reading at each load.

(iv) Continue to add loads in increments of 4 kg, levelling the lever arm after each and then reading the protractor or gearwheel. Note whether the specimen temperature changes during testing. If failure has not already occurred when the load reaches 35 kg, reduce the load increments to 1 kg until failure occurs. In the final stages the chalk line will keep a tally of the number of revolutions.

(v) At failure record the load P_f and protractor reading θ_f in the space provided in the table. Calculate the torque at failure T_f and the corresponding angle of twist per unit length ϕ_f and add these values to the table.

(vi) Remove the weights from the lever arm and then remove the specimen from the rig. Examine and sketch the fracture surface.

4.4 Experiment III: brass

(i-iii) Follow steps (i)-(iii) of Experiment II, Section 4.3 above.

(iv) Continue to add loads in increments of 4 kg, levelling the lever arm after each and then reading the protractor or gearwheel. Note whether the specimen temperature changes during testing. Stop after taking a reading at 33 kg, by which stage the specimen will have undergone approximately 3 complete revolutions.

(v) Unload to 1 kg, taking at least 3 intermediate protractor readings. Then reload, again taking at least 3 intermediate readings of the angle of twist.

(vi) Continue to add loads in increments of 1 kg up to failure, levelling the lever arm after each increment and then reading the protractor or gearwheel. At failure record the load P_f and protractor reading θ_f in the space provided in the table. Calculate the torque at failure T_f and the corresponding angle of twist per unit length ϕ_f and add these values to the table.

(vii) Remove the weights from the lever arm and then remove the specimen from the rig. Examine and sketch the fracture surface.

5. THE LABORATORY REPORT

(a) **Summary** – see the sheet handed out at the start of the year for details.

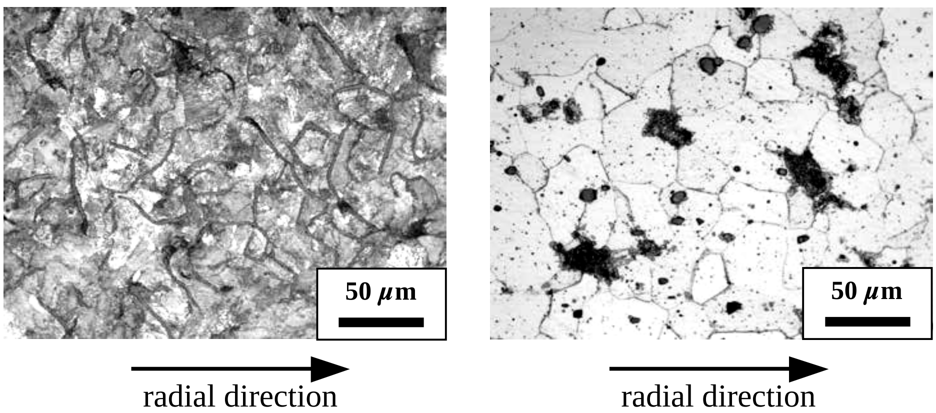
(b) **Readings and Results**. These should be put into the tables provided. Then using a photocopier or by detaching the page, it should be glued into your report. Every group will need a complete set of results for all three experiments (I, II and III). At the end of the lab you can collect a completed table of results for experiment II or III as appropriate.

(c) **Discussion**. Every group should include the following discussion for all three experiments. The required torsion theory is described in the Appendix.

<u>**Steel and cast iron**</u>

(i) <u>Graph 1</u>: On the same axes, plot torque T against angle of twist per unit length ϕ for the mild steel bar and the cast iron bar. Figure 1 shows the microstructures of the cast iron and mild steel used in these experiments. With reference to these microstructures, comment on the differences between these two curves.

Figure 1



(a) Microstructure of the cast iron bar: graphite flakes in a pearlitic matrix.

(b) Microstructure of the mild steel bar: ferrite (lighter regions) and pearlite.

(ii) Assuming the cast iron bar to remain elastic up to failure, estimate the shear stress at the surface of the bar at failure τ_f.

(iii) Draw a Mohr's circle for the stresses at a point on the surface of a bar subjected to pure torque. Hence find the maximum tensile stress σ_f in the surface of the cast iron bar at failure and its orientation to the longitudinal axis of the bar.

(iv) Using the calculated value of σ_f and assuming an appropriate flaw size a estimate the fracture toughness K_C of cast iron. Compare with the values in the Materials Data Book and suggest reasons for any discrepancy.

(v) Compare the orientation and appearances of the fracture surfaces of the mild steel specimen and the cast iron specimen. Comment briefly on the different modes of failure and the stress systems responsible for them.

(vi) Estimate the torque T_y required to induce yielding at the surface of the mild steel bar. Hence estimate the yield stress in shear τ_y for mild steel. Calculate the yield stress of mild steel in uniaxial tension σ_Y using (a) the Tresca yield criterion and (b) the Von Mises yield criterion. Compare these with values in the Materials Data Book and suggest reasons for any discrepancy. Why might it be more difficult to identify the onset of plasticity for a torsion test compared to a uniaxial tensile test?

(vii) Summarise briefly the advantages and disadvantages of torsion testing compared to uniaxial tension testing for measuring the plastic behaviour of materials.

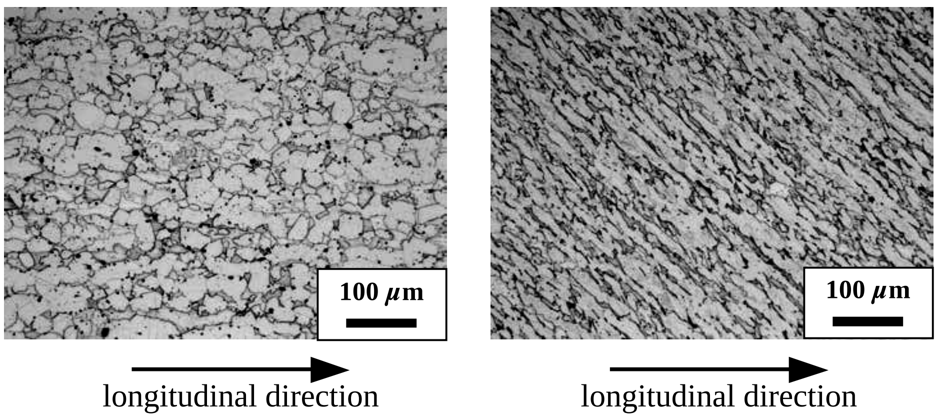
<u>Annealed and work hardened brass</u>

(i) <u>Graph 2</u>: Plot torque T against angle of twist per unit length ϕ up to failure for the brass bar including the unloading portion. On the same axes re-plot the final portion of the data (from the start of reloading up to failure) translated to the origin of the ϕ axis (i.e. as if the torsion test had begun with a bar in the twisted state). We now have effectively two material curves: one for brass in the 'as-received' annealed condition and one for brass initially 'work hardened' by 3 revolutions in torsion.

(ii) From Graph 2, estimate the torque T_y at the onset of plasticity, the shear yield stress τ_y and the twist per unit length at failure ϕ_f for both material curves. Comment on the effect of work hardening on the torsional response of a brass bar.

(iii) Figure 2 shows the microstructure at the surface of the brass bar used in this experiment in two conditions: 'as-received', prior to torsion (Figure 2a) and after twisting through 3 complete revolutions (Figure 2b). Briefly outline how you would expect both the microstructure and hardness (or yield stress) of the brass to vary radially in the bar (a) for the 'as-received' annealed brass bar prior to torsion and (b) for a brass bar work hardened in torsion by twisting through 3 complete revolutions.

Figure 2



(a) Surface microstructure of a brass bar prior to torsion: the grains are equiaxed.

(b) Surface microstructure of the same brass bar after twisting through 3 complete revolutions.

APPENDIX: TORSION THEORY FOR SOLID CIRCULAR BARS

A1 Ductile materials

Consider a circular bar of outer radius $R = D/2$ deforming subject to pure torsion. If the material is initially linear elastic with shear modulus G, the applied torque T is proportional to the angle of twist per unit length ϕ:

$$T = GJ\phi = G\left(\frac{\pi R^4}{2}\right)\phi$$

where J is the polar second moment of area. When elastic, the shear stress increases linearly with the radial distance from the centre, r. For a ductile material, as the torque is increased yield will occur first at the outer radius R where the shear stress is a maximum. The torque at which this occurs T_y is related to the shear yield stress of the material τ_y as follows:

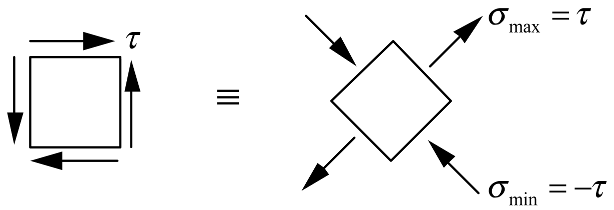
$$\tau_{\max} = \tau_y = GR\phi = \frac{T_y R}{J}$$

The relationship between the yield stress in shear τ_y and the yield stress in uniaxial tension σ_y depends on the assumed yield criterion. According to the Tresca criterion $\sigma_y = 2\tau_y$. According to the Von Mises criterion $\sigma_y = \sqrt{3}\tau_y$. Any further increase in torque will cause an increasing yielded zone at the outer radii, with the core remaining elastic. If strain hardening of the material is neglected (i.e. if the material is assumed to be perfectly plastic) in the limit when the shearing stress at every radius has reached τ_y, the fully plastic torque T_p is

$$T_p = \int_0^R \tau_y 2\pi r^2 dr = \frac{2\pi R^3 \tau_y}{3} = \frac{4}{3}T_y$$

A2 Brittle materials

Failure of a brittle material, such as cast iron, will depend on the maximum tensile stress at failure σ_f. Fast fracture occurs when $\sigma_f\sqrt{\pi a} = K_c$ where a is the depth of a surface imperfection and K_c is the fracture toughness. According to Mohr's circle of stress, the pure shearing stress τ produced by applying a torque about the axis of the bar results in equal and opposite direct stresses $\sigma_{max} = \tau$ and $\sigma_{min} = -\tau$ on planes at 45°:



Therefore, putting $\sigma_f = \sigma_{max} = \tau_f$, gives the torque at failure T_f:

$$\tau_f\sqrt{\pi a} = \frac{2T_f}{\pi R^3}\sqrt{\pi a} = K_c$$

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<u>Experiment I: cast iron</u>

Bar diameter readings (1) ______ mm (2) ______ mm (3) ______ mm

Average diameter $D =$ mm

Gauge length $L = 150$ mm

Lever arm $A =$ mm

Table 1

(i) Experimental data (completed during the lab.):				(ii) Calculated values for the report:	
P (kg)	θ (°)	$\theta - \theta_0$ (°)		T (Nm)	ϕ (rad m^{-1})
Fit the specimen as described in Section 4.1, page 2.					
$P_0 = 1$	$\theta_0 =$	0		0	0
Proceed as described in Section 4.2, page 2.					
9					
17					
25					
33					
41					
49					
57					
65					
Further increments as described in Section 4.2, page 2.					
69					
73					
$P_f =$	$\theta_f =$	$\theta_f - \theta_0 =$		$T_f =$	$\phi_f =$

Load on the hanger: P

Reading on the protractor: θ

Torque: $T = A(P - P_0)g$

Angle of twist per unit length: $\phi = \dfrac{\theta - \theta_0}{L}$

Experiment II: mild steel

	1		2		3	
Bar diameter readings		mm		mm		mm

Average diameter $D =$ mm
Gauge length $L = 150$ mm
Lever arm $A =$ mm

Table 2

(i) Experimental data (completed during the lab.):				(ii) Calculated values for the report:	
P (kg)	θ (°)	$\theta - \theta_0$ (°)		T (Nm)	ϕ (rad m^{-1})
Fit the specimen as described in Section 4.1, page 2.					
$P_0 = 1$	$\theta_0 =$	0		0	0
Proceed as described in Section 4.3, page 3.					
5					
9					
10					
At 33 kg, reduce the increments as described on page 3.					
33					
35					
$P_f =$	$\theta_f =$	$\theta_f - \theta_0 =$		$T_f =$	$\phi_f =$

Load on the hanger: P
Reading on the protractor: θ
Torque: $T = A(P - P_0)g$
Angle of twist per unit length: $\phi = \dfrac{\theta - \theta_0}{L}$

<u>Experiment III: brass</u>

Bar diameter readings (1) [ ] mm (2) [ ] mm (3) [ ] mm

Average diameter $D =$ mm

Gauge length $L = 150$ mm

Lever arm $A =$ mm

Table 3

(i) Experimental data (completed during the lab.):				(ii) Calculated values for the report:	
P (kg)	θ (˚)	$\theta - \theta_0$ (˚)		T (Nm)	ϕ (rad m^{-1})
Fit the specimen as described in Section 4.1, page 2.					
$P_0 = 1$	$\theta_0 =$	0		0	0
Proceed as described in Section 4.4, page 3.					
5					
9					
10					
After 33 kg, begin unloading as described on page 3.					
33					
$P_f =$	$\theta_f =$	$\theta_f - \theta_0 =$		$T_f =$	$\phi_f =$

Load on the hanger: P

Reading on the protractor: θ

Torque: $T = A(P - P_0)g$

Angle of twist per unit length: $\phi = \dfrac{\theta - \theta_0}{L}$