Unit 25: Mechanical Behaviour of Metallic Materials

Level: **3**

Unit type: **Internal**

Guided learning hours: **60**

Unit in brief

Learners investigate and conduct tests on the mechanical properties of metals, consider suitable applications and explore failure modes to improve component design.

Unit introduction

Selecting the most appropriate material and processing method for an engineered product or system is critical to ensure that it is fit for purpose. The materials used in the airframe of an aeroplane, car body pressings, cast components in domestic appliances and the 'T'-shaped electricity pylons (in the UK) all require careful selection and testing of appropriate metallic materials.

In this unit, you will investigate and research the microstructures of ferrous and non-ferrous metallic materials, some of which will have been processed, for example heat treated. You will use a metallurgical microscope to inspect the microstructures of the materials you are investigating. You will also undertake destructive and non-destructive tests on the materials and use the results of the experimentation and research to determine the mechanical properties of, and suitable applications for, the materials. Finally, you will examine the reasons why components have failed in service and consider possible design improvements that could prevent failure.

As an engineer it is important to know about and understand the capabilities of a range of metallic materials to create products and systems that are suitable for application. This unit will help to prepare you for an apprenticeship or a technician-level role in industry. It will also help to prepare you for a range of higher education courses, such as a Higher National Diploma (HND) or a degree in any engineering discipline.

Learning aims

In this unit you will:

A Investigate the microstructures of metallic materials, the effects of processing on them and how these effects influence their mechanical properties

B Explore safely the mechanical properties of metallic materials and the impact on their in-service requirements

C Explore the in-service failure of metallic components and consider improvements to their design.

Summary of unit

Learning aim	Key content areas	Recommended assessment approach
A Investigate the microstructures of metallic materials, the effects of processing on them and how these effects influence their mechanical properties	**A1** Types of ferrous metals and alloys **A2** Types of non-ferrous metals and alloys **A3** Mechanical properties of metallic materials **A4** Grain structure of metallic materials **A5** Effects of processing on the mechanical properties of metallic materials **A6** Microstructure investigation of metallic materials	A report containing investigative research and library images of the microstructures of metallic materials, some of which will have been processed.
B Explore safely the mechanical properties of metallic materials and the impact on their in-service requirements	**B1** In-service requirements of metallic materials **B2** Destructive test procedures **B3** Non-destructive test procedures	A portfolio of results gathered from tests on samples of given metallic materials and an investigation of the materials, supported by a logbook and images. Observation records are essential.
C Explore the in-service failure of metallic components and consider improvements to their design	**C1** Ductile and brittle fracture **C2** Creep failure **C3** Fatigue failure **C4** Corrosion mechanisms **C5** Design considerations to help prevent component failure	A report containing investigative research into the failure mode of given engineered products or components and possible design solutions. Observation records are essential.

Content

Learning aim A: Investigate the microstructures of metallic materials, the effects of processing on them and how these effects influence their mechanical properties

A1 Types of ferrous metals and alloys

- Plain carbon steel: low, medium, high carbon.
- Alloy steels: constructional, tool, stainless, heat-resistant.
- Cast iron: grey, white, malleable.
- Wrought iron.
- Identification methods, e.g. BS, EN, DIN and ISO coding, MIL-Spec, American UNS.

A2 Types of non-ferrous metals and alloys

- Types: aluminium, copper, gold, lead, magnesium, silver, tin, titanium, zinc.
- Alloys: aluminium (wrought and cast), copper (brass and bronze), magnesium and titanium.
- Shape memory alloys (SMA), e.g. nickel-titanium, copper-aluminium-nickel.
- Identification methods, e.g. ISO, SAE, MIL-Spec, American UNS, EN 485.

A3 Mechanical properties of metallic materials

- Elastic and plastic behaviour of a metal when subjected to stress.
- Strength: yield, proof, tensile, compressive, shear.
- Specific strength: strength per unit density.
- Surface hardness.
- Fracture toughness.
- Plasticity: ductility, malleability.
- Elastic modulus: Young's (E), shear (G).
- Specific stiffness, resistance to bending: elastic modulus per unit density.
- Fatigue limit.

A4 Grain structure of metallic materials

- Atomic lattice packing: body-centred cubic (BCC), face-centred cubic (FCC), close-packed hexagonal (CPH).
- Features of grain structure: formation, growth, boundary, size.
- Crystal defects: point, line/dislocation, planar.
- Slip planes: elastic and plastic deformation, surface slip bands.
- Metallurgical phase: single substance in an alloy system, e.g. pure metal, solid solution, uniform liquid.
- Alloys: eutectics, interstitial and substitutional solid solutions, intermetallic compounds.
- Iron/carbon thermal equilibrium diagram: ferrite, pearlite, cementite, austenite.
- Aluminium/copper thermal equilibrium diagram: solubility curve for the aluminium-rich end of the diagram, unsaturated and saturated solid solutions of copper in aluminium.
- Effect of grain structure, lattice packing and alloying on a parent metal's mechanical properties, e.g. ductility, brittleness, hardness, tensile and compressive strength.

A5 Effects of processing on the mechanical properties of metallic materials

- A non-processed material is one that has not undergone any subsequent processing from the point of being made as a raw material, e.g. bar stock or billet.
- Recrystallisation: grain growth, structure.
- Hot working: forging, pressing, rolling, extrusion.
- Cold working, e.g. rolling, drawing, pressing, deep drawing, coining, embossing, impact extrusion, spinning, stretch forming.
- Heat treatment of steels through hardening, case hardening, annealing, normalising.
- Heat treatment of aluminium alloys: solution treatment, precipitation hardening, over-ageing.

- Heat treatment of titanium alloys: precipitation hardening.
- Alloying elements in steel, e.g. chromium, manganese, molybdenum, nickel, tungsten, vanadium.
- Alloying elements in aluminium, e.g. copper, silicon, magnesium, manganese, titanium, chromium, lithium.
- Alloying elements in titanium: aluminium, vanadium.

A6 Microstructure investigation of metallic materials

- Macro-investigation and micro-investigation of metals and alloys, including identification of grain structures and boundaries, phases within grains and segregation of impurities at grain boundaries.
- Surface examination equipment, including a hand magnifier, optical microscope and, if available, a digital imaging system.
- Reference sources, including micrographs.

Learning aim B: Explore safely the mechanical properties of metallic materials and the impact on their in-service requirements

B1 In-service requirements of metallic materials

- High strength requirement, e.g. vehicle suspension components, pressure vessel.
- High strength to weight ratio, e.g. aircraft undercarriage components, high-performance motor vehicles.
- High resistance to impact loading, e.g. impact tool bits.
- Hardness, e.g. drill bit.
- Toughness, resistance to fracture under impact loads, e.g. car body.
- Ductility, e.g. drawn wire.

B2 Destructive test procedures

- Tensile strength testing:
  - British Standard (BS EN ISO 6892-1:2009) or other relevant international equivalents, selection and preparation of test specimens, tensile test machine, extensometer, data recording, pull to destruction, force–extension graph, examination of fractured surface
  - analysis of results: elastic limit/limit of proportionality, yield point, tensile strength, Young's modulus, percentage elongation and reduction in cross-sectional area.
- Hardness testing:
  - hardness standards relevant to test being performed, including British Standards BS EN ISO 6506-1:1999, BS EN ISO 6508-1:2015 or other relevant international equivalents
  - surface preparation, e.g. cleaning using light abrasion and removal of surface film
  - use of equipment to determine hardness, e.g. Brinell hardness number, Vickers pyramid number (HV), Rockwell (A, B, C) value, Shore scleroscope hardness index.
- Impact testing:
  - British Standard BS EN ISO 148-3:2008 or other relevant international equivalents, selection and preparation of test specimens
  - test specimens: selection, notch preparation
  - use of equipment to measure impact values, e.g. Izod test, Charpy test, Hounsfield balanced impact machine
  - visual inspection of the fractured surface to estimate the crystalline area percentage
  - test reporting, e.g. presentation of results and comparison with reference values taken from accredited data sources.

B3 Non-destructive test procedures

- Surface and sub-surface defect detection, e.g. visual inspection, dye penetrant, magnetic particle, ultrasonic, radiographic, eddy current.
- Test reporting and presentation of results.

Learning aim C: Explore the in-service failure of metallic components and consider improvements to their design

C1 Ductile and brittle fracture

- Effects of gradual and impact loading and grain size.
- Surface appearance: crystalline, torn, cup and cone configuration.

C2 Creep failure

- Primary, secondary, tertiary creep.
- The effect on creep rate of temperature, grain size, applied stress.
- Strain–time graphs and limiting creep stress.

C3 Fatigue failure

- Crack propagation and growth.
- Internal stress concentrations: granular defects, porosity.
- External stress concentration: surface defects, sharp changes of section.
- Stress variation: reversal due to cyclic loading, random loading, vibration.
- Stress and endurance (S/N) curves: fatigue and endurance limits for ferrous and non-ferrous alloys.
- Final, catastrophic failure: reduction in load carrying area, tensile strength exceeded.
- Characteristic appearance of fracture surface: smooth burnished area (crack growth), crystalline area (final tear), ripple-like marks showing crack progression.

C4 Corrosion mechanisms

- Chemical fundamentals, e.g. the corrosion cell, rust reactions, dry corrosion, galvanic action, active and passive materials, electro-chemical series for metals.
- Types of corrosion and their recognition and cause, e.g. hydrogen embrittlement, surface, crevice, exfoliation, inter-granular, bimetallic, pitting, fretting, stress.

C5 Design considerations to help prevent component failure

- Knowledge of the component's operating environment, e.g. static loading, dynamic loading, cyclic stressing, temperatures, wet or dry conditions.
- Correct choice of material based on mechanical properties, consequences of sudden failure, corrosion resistance.
- Design features, e.g. reducing the impact of stress raisers, e.g. sharp corners, sudden changes in cross-sectional areas, poor surface finish.
- Higher quality material, e.g. free from inclusions or porosity.
- Surface treatment and finishes, e.g. painting, polymer coating, plating.

Assessment criteria

Pass	Merit	Distinction
Learning aim A: Investigate the microstructures of metallic materials, the effects of processing on them and how these effects influence their mechanical properties		**A.D1** Evaluate, using an accredited data source, the microstructures of non-processed and processed metallic materials to correctly identify the material, including how the processing history, impurities and grain boundaries affect the mechanical properties of the materials.
A.P1 Explain how the microstructures of non-processed metallic materials affects the mechanical properties of the materials. **A.P2** Explain how the microstructures of processed metallic materials affects the mechanical properties of the materials.	**A.M1** Analyse, using an accredited data source, the microstructures of non-processed and processed metallic materials to correctly identify the material, including how the processing history affects the mechanical properties of the materials.	
Learning aim B: Explore safely the mechanical properties of metallic materials and the impact on their in-service requirements		**B.D2** Evaluate, using the results from safely conducted tests and an accredited data source, how the mechanical properties of processed and non-processed metallic materials affect their behaviour and suitability for different realistic applications, justifying the validity of the test methods used.
B.P3 Conduct destructive tests safely on different non-processed and processed metallic samples. **B.P4** Conduct non-destructive tests safely on at least two non-processed and processed metallic samples. **B.P5** Explain, using the test results, how the mechanical properties of metallic materials affect their behaviour and suggest an application.	**B.M2** Conduct destructive and non-destructive tests accurately on different non-processed and processed metallic samples. **B.M3** Analyse, using the test results and an accredited data source, how the mechanical properties of metallic materials affect their behaviour and suggest a realistic application.	
Learning aim C: Explore the in-service failure of metallic components and consider improvements to their design		**C.D3** Evaluate, using language that is technically correct and of a high standard, the results from safely conducted and accurate checks and tests to establish how components failed in service, recommending a design solution from a range of alternatives.
C.P6 Conduct a visual inspection check and at least one test safely on components that have failed in service. **C.P7** Explain, using the results, how each component failed and how each component's design could be improved.	**C.M4** Conduct a visual inspection check and at least one test safely and accurately on components that have failed in service. **C.M5** Analyse, using the results, how each component failed and justify how each component's design could be improved.	

Essential information for assignments

The recommended structure of assessment is shown in the unit summary along with suitable forms of evidence. *Section 6* gives information on setting assignments and there is further information on our website.

There is a maximum number of three summative assignments for this unit. The relationship of the learning aims and criteria is:

Learning aim: A (A.P1, A.P2, A.M1, A.D1)

Learning aim: B (B.P3, B.P4, B.P5, B.M2, B.M3, B.D2)

Learning aim: C (C.P6, C.P7, C.M4, C.M5, C.D3)

Further information for teachers and assessors

Resource requirements

For this unit, learners must have access to:

- access to data sources, e.g. MatWeb, an online materials information resource, www.matweb.com
- metallic material samples of known composition and processing history from, for example, the Institute of Materials, Minerals and Mining (IOM3), www.iom3.org
- hardware equipment, including:
  - hand magnifiers and a metallurgical microscope
  - tensile test, hardness and impact testing equipment (essential)
  - non-destructive test equipment
  - creep and fatigue test equipment – preferred, but it can be replicated using simulation software.

Essential information for assessment decisions

Learning aim A

For distinction standard, learners will investigate the microstructures of at least six unlabelled material samples, which will comprise a mix of ferrous, non-ferrous and processed metallic materials. Learners' evaluation will involve comparing evidence of the microstructure in each sample with examples from an accredited data source and will include the impact that impurities and grain boundaries have on the mechanical properties. For example, for a steel sample learners may have identified impurities at grain boundaries, phases such as pearlite and cementite, equiaxed grains or elongated grains for a sample that has been cold worked. Learners' observations will also be linked to the mechanical properties of the material, for example the elongated grain structure of wrought iron and the distribution of impurities, making for a laminated structure that improves the impact resistance. For each of the examined samples learners' evidence will contain an equilibrium diagram marked up with images of the phases, for example eutectic.

Overall the evidence, such as a logbook and report, will be presented clearly and in a way that would be understood by a third party who may or may not be an engineer.

For merit standard, learners will compare in their evidence the observed grain structure images of material samples with those from accredited data sources, to correctly identify the materials of at least six unlabelled samples. The samples will comprise a mix of ferrous, non-ferrous and processed metallic materials. Learners will analyse how the microstructures affect the mechanical properties of the materials. For example, they may analyse the differences between materials with fine and coarse grains.

Overall, the evidence should be logically structured, technically accurate and easy to understand.

For pass standard, learners will investigate the microstructures of at least six prepared and unlabelled samples of metallic materials, using a suitable hand magnifier and metallurgical microscope. Samples will contain ferrous and non-ferrous metallic materials and at least three will have been processed, for example one heat treated, one alloy and one mechanically worked. Learners will use the samples to explain how the microstructures of the metallic materials affect their mechanical properties. For example, fine-grained castings generally have higher toughness and strength properties than those with coarse grains.

Overall, the evidence will be logically structured, although it may be basic in parts, and it may contain minor technical inaccuracies relating to engineering terminology.

Learning aim B

For distinction standard, learners will safely set up and correctly use mechanical tensile, impact and hardness test equipment and gather accurate results when completing destructive tests independently. They will test at least six prepared samples comprising unlabelled ferrous and non-ferrous materials, some of which will have been processed, for example work hardened. Learners will justify why they have selected the correct test for the mechanical property that they are measuring. For example, if they are testing a thin piece of metal it would invalidate the results to use a hardness test that has a high-impact force, because it will distort the metal and the indentation measurements will not be a true indication of surface hardness.

Learners will also complete at least two non-destructive tests safely and accurately on metallic material samples.

Learners will use a combination of the mechanical test results and accredited data sources to evaluate their results. The evaluation for the:

- tensile tests will include plot load–extension plot (stress–strain graphs) and provide key data, for example yield strength, tensile strength, Young's modulus, percentage elongation and reduction in area
- tensile and impact tests will include the condition of the fracture surface in terms of how crystalline it is
- hardness tests will make comparisons between measured hardness values and what is expected for the material
- non-destructive tests will include a report on the surface or internal condition of the given metallic materials.

Learners will present suitable realistic applications of where the tested materials might be used in service, for example appreciating that while high-strength alloy steel might be good for the passenger shell of a car, lower-strength, more malleable steel would be a better option for the front and rear crumple zones. Learners will also determine that there is often a trade-off between tensile strength, hardness and impact strength of materials.

Overall the evidence, such as a logbook and report, will have been presented clearly and in a way that would be understood by a third party who may or may not be an engineer.

For merit standard, learners will complete accurate and safe mechanical tests using at least six pre-prepared given and unlabelled samples. Limited help may be given in setting up the equipment and learners will independently gather and process their test results, for example finding the yield and tensile strengths and seeing how they compare with published values.

Learners' analysis will compare the results of destructive testing with accredited data sources and identify the materials that were tested. For example, learners will be able to determine, from the density, colour and surface finish of two samples, that the type of material they are testing is a form of steel. The mechanical tests and data from the accredited source will allow learners to determine what types of steel they are testing and whether these have been processed.

Learners will also complete at least two non-destructive tests safely and accurately on metallic material samples and will draw conclusions from the results, for example a dye penetrant test that reveals surface cracks, with the learner explaining why the cracks have occurred.

Overall, the evidence should be logically structured, technically accurate and easy to understand. Learners' evidence will include a realistic application for each material sample, for example stainless steel can be used for a high-temperature pressure vessel.

For pass standard, learners will complete mechanical tensile tests (to destruction), impact tests and hardness tests using pre-prepared given ferrous and non-ferrous metal samples, some of which will be processed. In total learners will test at least six samples. For each sample they will carry out a mechanical test and record their results. Throughout the delivery of the tests they will demonstrate safe working practices, for example by completing a risk assessment and checking with the assessor before conducting an impact test. Although help may be given to set up the equipment, learners will gather their test results independently.

Learners' evidence will explain, using the test results, how the mechanical properties of different metallic materials affect their behaviour. For example, a material with good impact resistance (determined, for example, from an Izod test) is better able to withstand shock loading.

Learners will also complete at least one non-destructive test safely and explain the results, for example identifying that there is porosity in a casting by completing an ultrasonic test.

Overall, the evidence, such as a logbook and report, will be logically structured and will include the results and an application for each metallic material sample. The evidence may be basic in parts and may contain minor technical inaccuracies relating to engineering terminology.

Learning aim C

For distinction standard, learners will explore a range of given components that have failed in service after having been in use for significant periods of time. At least two components will have failed due to a mechanical fault and at least one other due to corrosion. Learners will undertake a visual inspection check of the corrosion and complete at least one mechanical test safely. The type of mechanical test(s) undertaken will depend on the components selected. It is expected that most learners will complete a hardness test, although some may also or instead complete a creep test.

Having investigated the various failure modes, learners will evaluate how to eliminate or mitigate the problem by thinking how to redesign the component, for example by specifying a larger fillet radius where there is a change of cross-section and by using a material that has a better operating performance at high temperature and stress levels, such as a titanium alloy.

Overall the evidence, such as a logbook and report, will be presented clearly and in a way that would be understood by a third party who may or may not be an engineer. This means that learners must clearly demonstrate a good understanding of mechanical design principles when evaluating the failure modes of the selected components and suggesting improvements.

For merit standard, learners will examine at least three components that have collectively suffered creep and fatigue failure and surface degradation due to corrosion. This will involve visual inspection checks, a hardness test and/or a creep test and comparison with reference sources, for example images.

Having investigated the various failure modes, learners will justify design modifications to the components so as to eliminate or reduce the impact of the failures, for example changing the design of a product to reduce the impact of electrolytic corrosion by choosing materials that are closer together in the electromagnetic (galvanic) series.

Overall, the evidence should be logically structured, technically accurate and easy to understand.

For pass standard, learners will carry out a visual inspection check and a mechanical hardness and/or creep test on at least three sample components that have failed in service for different reasons. At least two components will have failed due to mechanical faults (fatigue and creep) and at least one other due to corrosion. Throughout the delivery of the tests they will demonstrate safe working practice, for example by completing a risk assessment and checking with the assessor before conducting a test. Although help may be given to set up some of the equipment, learners will gather their test results independently.

Using the visual inspection check and mechanical test results, learners' evidence will explain how the components failed in service. Learners will also give at least one explanation for how the design of the component could be improved, for example by increasing the size of a fillet radius on a stepped shaft.

Overall, the evidence, such as a logbook and report, will be logically structured and will include the results. The evidence may be basic in parts.

Links to other units

This unit links to:

- Unit 3: Engineering Product Design and Manufacture
- Unit 26: Mechanical Behaviour of Non-metallic Materials
- Unit 39: Modern Manufacturing Systems
- Unit 41: Manufacturing Secondary Machining Processes
- Unit 42: Manufacturing Primary Forming Processes
- Unit 43: Manufacturing Computer Numerical Control Machining Processes
- Unit 44: Fabrication Manufacturing Processes
- Unit 45: Additive Manufacturing Processes
- Unit 46: Manufacturing Joining, Finishing and Assembly Processes.

Employer involvement

This unit would benefit from employer involvement in the form of:

- guest speakers
- technical workshops involving staff from local engineering organisations with expertise in metallic materials
- contribution of ideas to unit assignment/project materials.