Module 2

Processing, Construction Methods and Testing of Steel Products Used in Shipbuilding

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Contents

1. Introduction

The building of a ship is an extremely complex task involving a multitude of activities across a wide range of disciplines including commercial and administration activities, design (CAD/CAM), shipyard management and, the logistics associated with application of numerous specialised technical skills such as cutting, forming, welding etc. Most important are procurement of fit-for-purpose materials, material storage, movement and process flow, the latter facilitated by a logical shipyard layout. Central to the process flow aspects are the location and provision of facilities for cleaning, priming, painting, cutting, forming and welding and, at the relevant flow points, assembly of structural units from small frames and subassemblies to large blocks - completed ship sections, the precursor to final assembly of a whole ship.

This module is intended to give a detailed insight into some of the more important technical processes involved in shipbuilding with an emphasis on operations such as cutting, welding and forming. As in previous modules these areas are complemented by a substantial slide set.

At the heart of any shipbuilding project is the shipyard and the module begins with a consideration of the modern shipyard from its humbler beginnings in the form of small riverside boat/ship building operations to larger scale, modern layouts.

2. Ship Building

2.1 Shipyard Layouts

Until the advent of steel ships, a shipbuilding operation could be set up almost anywhere close to the sea or a river and to trees for the main construction materials. Iron, rapidly followed by steel for construction resulted in shipbuilding moving to areas where raw materials, primarily coal and iron ore, were available. These were also often areas where the basic metalworking skills were to be found as the basis for the labor force, or in some cases a labor force was moved into the area. Shipyards were usually found along river banks, or in protected harbors, giving sheltered water and their basic arrangement did not vary. Figure 1 shows the typical arrangement of a shipyard up until around 1960. The slipways on which the ships are constructed piece by piece are supported by small and simple workshops. There was a relatively small initial investment and the output could be varied by opening or closing building slipways and taking on or laying off labor.

The layout of a shipyard did not vary significantly until the mid-1950s. A relatively small number of shipyards engaged in capital warship construction or passenger ships, where the product is significantly larger and more complex than average commercial ships. These had extensive outfitting workshops and quays, as well as larger slipways. Large cranes, almost always fixed in position, were available to lift heavy items, perhaps 200 tonnes for large, complex ships. However, for the lifting of hull parts and most outfitting the available lifting capacity was usually below 10 tonnes.

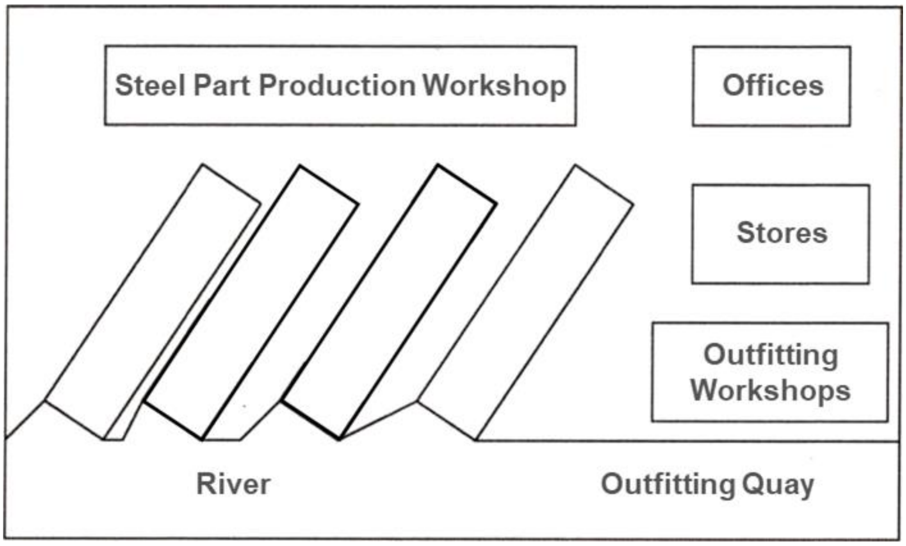


Figure 1 Traditional Riverside Shipyard Layout

The major change in the shipyards came about initially because of rapid increases in commercial ship size after 1950. At that time a typical cargo ship was of below 10,000 deadweight tonnes, and a tanker of 20,000 deadweight tonnes was considered large. By 1958, the first tanker over 100,000 deadweight tonnes was in operation and the first over 200,000 tonnes deadweight by 1966. By 1970, 250,000-tonne and larger ships were being built. An important aspect of these newer ships was a tenfold increase in steel weight, from a typical 3000 tonnes to 30,000 tonnes. Also, the largest ships were in excess of 300 meters in length. As such, they were too large for most existing shipyards' slipways and the lifting capacities of the small cranes usually available would have meant an excessive construction time.

The result was first that existing shipyards reduced the number of slipways and increased the size of their cranes as the ship size increased. This allowed them to construct the ships in a shorter time, so keeping the construction time acceptable. A very few European shipyards increased the slipway sizes and cranes to be able to build very large crude carriers (VLCC). However, the 1960s saw the emergence of a substantial number of new shipyards, primarily in Asia but also in Europe, which were purpose designed for the new, large ships. The basic arrangement was established by the mid-1960s in Japan, and many shipyards built subsequently, including in Eastern Europe, and more recently in South Korea, China and now Vietnam, have been specifically planned to construct the larger ships. The contemporary shipbuilding practices and production methods have improved but the basic technology and main equipment has been consistent for the last half century.

A number of traditional shipbuilders, which were often based on river banks, also established new yards where they could build larger ships and/or exploit the new technology and production methods. In general, the smaller shipbuilders have been able to reconfigure their site in order to utilize new technology and improve production, whilst continuing to build smaller and medium-sized ships. In many cases the shipyards are constrained as to the size and type of ship that can be built. Many smaller shipyards have adopted total undercover construction, providing a dry, warm (or cool) environment. Undercover ship construction has been extended to some larger ships, including many military ships and also passenger ships, especially in Northern Europe. As in the early days of such large ships, where the shipyards differed from the routine, the complexity and cost of the ship can justify the massive capital expenditure on covered facilities.

An ideal layout for a modern shipyard is based on a production flow basis, as in Figure 2, with the shipyard built on a greenfield site and no longer, as with existing shipyards, having to follow the river bank.

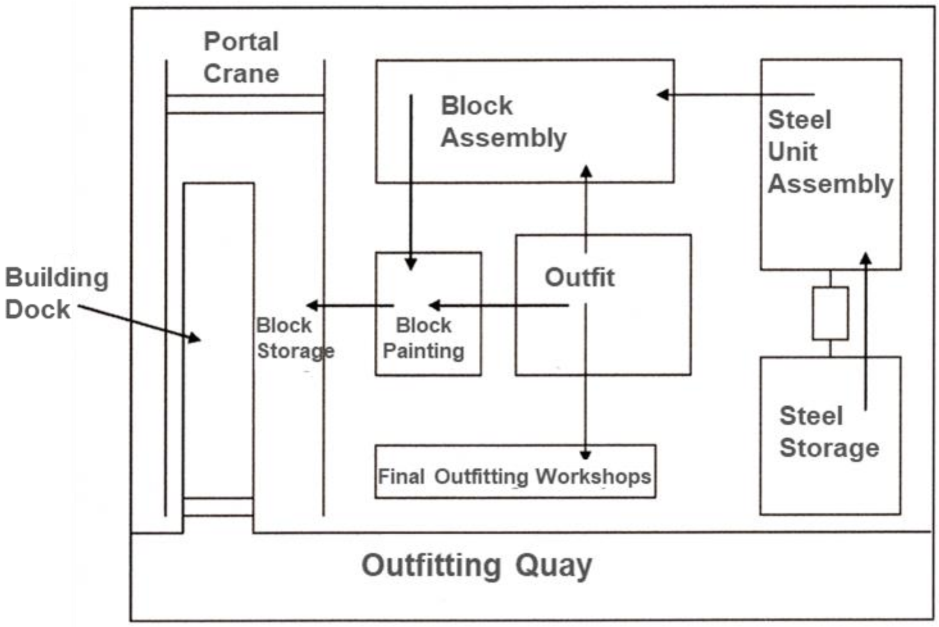


Figure 2. Modern Shipyard Layout

This removes typical restrictions on old sites, restricted by their location in a built-up area or the physical river bank slope from extending back from the river, so that modified production flow lines are required.

The sequence of layout development is outlined below. It should be noted that p articular locations and circumstances can dictate significantly different arrangements that may not be ideal but that do work.

Planning a new shipyard, or re-planning an existing one, will involve decisions to be made on many important factors, including:

- Size and type of ship to be built
- Number of ships per year to be achieved
- Breakdown of the ships into structural blocks and outfit modules (interim products)
- Material handling equipment required for the interim products
- Pan production and assembly processes to be installed
- Amount of outfit and engine installation to be undertaken
- Control services to be supplied
- Administration facilities required.

Shipyards usually have a fitting out basin or berth where the virtually completed ship is tied up after launching and the finishing off work and static trails may be carried out.

Some of the facilities identified may be omitted from the shipyard and a subcontractor used instead. This will depend on the location, availability of subcontractors, and the economics of the alternatives.

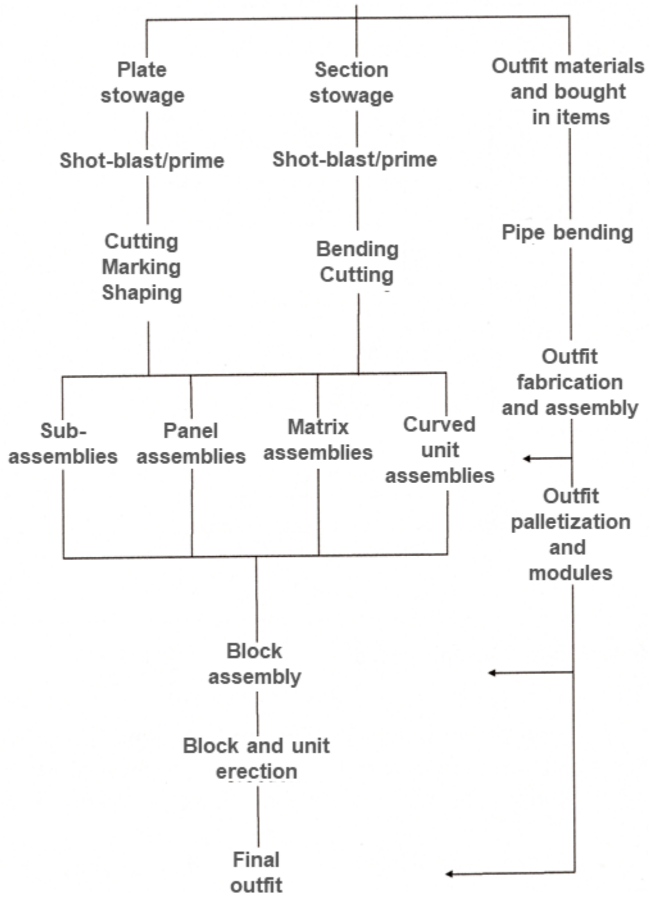


Figure 3. Elements of a Shipbuilding Process

Before considering the actual layout of the shipyard, it is as well to consider the relationship of the work processes involved in building a ship, as illustrated in Figure 3.

An idealized layout of a new shipyard is indicated in Figure 4, which might be appropriate for a smaller yard specializing in one or two standard type ships with a fairly high throughput so that one covered building dock or berth is sufficient.

At this point it may be convenient to mention the advantages and disadvantages of building docks as opposed to building berths. Building docks can be of advantage in the building of large vessels where launching costs are high, and there is a possibility of structural damage owing to the large stresses imposed by a conventional launch. They also give good crane clearance for positioning units. The greatest disadvantage of the building dock is its high initial cost. However, the dock is the usual choice for new shipyards, especially for larger ships. The level base simplifies the construction process, for example alignment of structural blocks. Also, the dock is more flexible in operation, for example in some cases ships are built in two stages with the outfit and labour-intensive stern, containing machinery and accommodation, built as a single structure, then moved along the dock for the cargo-carrying part to be constructed. This doubles the available time for outfitting the ship.

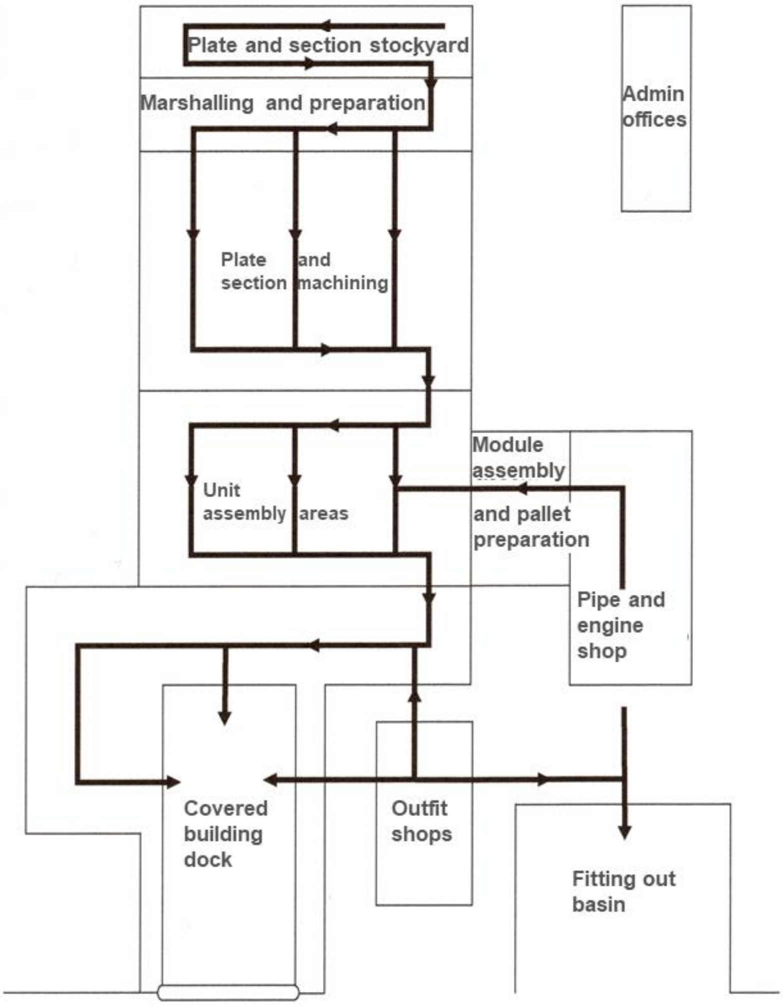


Figure 4. Shipyard Layout

3. Production of Steel

The production of all steels used for shipbuilding purposes starts with the smelting of iron ore and the making of pig-iron. Normally the iron ore is smelted in a blast furnace, which is a large, slightly conical structure lined with a refractory material. To provide the heat for smelting, coke is used and limestone is also added. This makes the slag formed by the incombustible impurities in the iron ore fluid, so that it can be drawn off. Air necessary for combustion is blown in through a ring of holes near the bottom, and the coke, ore, and limestone are charged into the top of the furnace in rotation. Molten metal may be drawn off at intervals from a hole or spout at the bottom of the furnace and run into molds formed in a bed of sand or into metal molds.

The resultant pig-iron contains 92-91% iron, the remainder being carbon, silicon, manganese, sulfur, and phosphorus. In the subsequent manufacture of steels, the pig- iron is refined; in other words, the impurities are reduced.

Steels may be broadly considered as alloys of iron and carbon, the carbon percentage varying from about 0.1% in mild steels to about 1.8% in some hardened steels. These may be produced by one of four different processes: the open-hearth process, the Bessemer converter process, the electric furnace process, or an oxygen process. Processes may be either an acid or basic process according to the chemical nature of the slag produced. Acid processes are used to refine pig-iron low in phosphorus and sulfur that are rich in silicon and therefore produce an acid slag. The furnace lining is constructed of an acid material so that it will prevent a reaction with the slag. A basic process is used to refine pig-iron that is rich in phosphorus and low in silicon. Phosphorus can be removed only by introducing a large amount of lime, which produces a basic slag. The furnace lining must then be of a basic refractory to prevent a reaction with the slag. About 85% of all steel produced in Britain is of the basic type, and with modem techniques is almost as good as the acid steels produced with superior ores.

Only the open hearth, electric furnace, and oxygen processes are described here as the Bessemer converter process is obsolete and not used for shipbuilding steels.

3.1 Open hearth process

The open-hearth furnace is capable of producing large quantities of steel, handling 150-300 tonnes in a single melt. It consists of a shallow bath, roofed in, and set above two brick-lined heating chambers. At the ends are openings for heated air and fuel (gas or oil) to be introduced into the furnace. Also, these permit the escape of the burned gas, which is used for heating the air and fuel. Every 20 minutes or so the flow of air and fuel is reversed.

In this process a mixture of pig-iron and steel scrap is melted in the furnace, carbon and the impurities being oxidized. Oxidization is produced by the oxygen present in the iron oxide of the pig-iron. Subsequently carbon, manganese, and other elements are added to eliminate iron oxides and give the required chemical composition.

3.2 Electric Arc Furnaces

Electric furnaces are generally of two types: the arc furnace and the high-frequency induction furnace. The former is used for refining a charge to give the required composition, whereas the latter may only be used for melting down a charge whose composition is similar to that finally required. For this reason only the arc furnace is considered in any detail. In an arc furnace melting is produced by striking an arc between electrodes suspended from the roof of the furnace and the charge itself in the hearth of the furnace. A charge consists of pig-iron and steel scrap, and the process enables consistent results to be obtained and the final composition of the steel can be accurately controlled.

Electric furnace processes are often used for the production of high-grade alloy steels.

3.3 Basic Oxygen Steelmaking (BOS)

This is a modem steelmaking process by which a molten charge of pig-iron and steel scrap with alloying elements is contained in a basic lined converter. A jet of high- purity gaseous oxygen is then directed onto the surface of the liquid metal in order to refine it.

Steel from the open hearth or electric furnace is tapped into large ladles and poured into ingot molds. It is allowed to cool in these molds until it becomes reasonably solidified, permitting it to be transferred to ‘soaking pits’ where the ingot is reheated to the required temperature for rolling.

3.4 Chemical Additions

Additions of chemical elements to steels during the above processes serve several purposes. They may be used to deoxidize the metal, to remove impurities and bring them out into the slag, and finally to bring about the desired composition.

The amount of deoxidizing elements added determines whether the steels are 'rimmed steels' or 'killed steels'. Rimmed steels are produced when only small additions of deoxidizing material are added to the molten metal. Only those steels having less than 0.2% carbon and less than 0.6% manganese can be rimmed. Owing to the absence of deoxidizing material, the oxygen in the steel combines with the carbon and other gases present and a large volume of gas is liberated. So long as the metal is molten, the gas passes upwards through the molten metal. When solidification takes place in ingot form, initially from the sides and bottom and then across the top, the gases can no longer leave the metal. In the central portion of the ingot a large quantity of gas is trapped, with the result that the core of the rimmed ingot is a mass of blow holes. Normally the hot rolling of the ingot into thin sheet is sufficient to weld the surfaces of the blow holes together, but this material is unsuitable for thicker plate.

The term 'killed' steel indicates that the metal has solidified in the ingot mold with little or no evolution of gas. This has been prevented by the addition of sufficient quantities of deoxidizing material, normally silicon or aluminum. Steel of this type has a high degree of chemical homogeneity, and killed steels are superior to rimmed steels. Where the process of deoxidation is only partially carried out by restricting the amount of deoxidizing material, a 'semi-killed' steel is produced.

In the ingot mold the steel gradually solidifies from the sides and base, as mentioned previously. The melting points of impurities like sulfides and phosphides in the steel are lower than that of the pure metal and these will tend to separate out and collect towards the center and top of the ingot, which is the last to solidify. This forms what is known as the 'segregate' in the way of the noticeable contraction at the top of the ingot. Owing to the high concentration of impurities at this point, this portion of the ingot is often discarded prior to rolling plate and sections.

3.5 Heat Treatment of Steels

The properties of steels may be altered greatly by the heat treatment to which the steel is subsequently subjected. These heat treatments bring about a change in the mechanical properties principally by modifying the steel's structure. Those heat treatments that concern shipbuilding materials are briefly described below.

3.5.1 Annealing

This consists of heating the steel at a slow rate to a temperature of say 850-950 °C, and then cooling it in the furnace at a very slow rate. The objects of annealing are to relieve any internal stresses, to soften the steel, or to bring the steel to a condition suitable for a subsequent heat treatment.

3.5.2 Normalizing

This is carried out by heating the steel slowly to a temperature similar to that for annealing and allowing it to cool in air. The resulting faster cooling rate produces a harder, stronger steel than annealing, and also refines the grain size.

3.5.3 Quenching (for hardening)

Steel is heated to temperatures similar to that for annealing and normalizing, and then quenched in water or oil. The fast-cooling rate produces a very hard structure with a higher tensile strength.

3.5.4 Tempering

Quenched steels may be further heated to a temperature somewhat between 200oC to 540 °C, the exact conditions very much dependent on the combination of strength versus ductility and toughness required. The object of this treatment is to relieve the severe internal stresses produced by the original hardening process and to make the material less brittle and optimize strength and toughness (resistance to cracking).

3.5.5 Stress Relieving

To relieve internal stresses the temperature of the steel may be raised so that no structural change of the material occurs and then it may be slowly cooled.

3.6 Steel Sections

A range of steel sections are rolled hot from ingots. The more common types associated with shipbuilding are shown in Figure 5. It is preferable to limit the sections required for shipbuilding to those readily available, i.e. the standard types; otherwise a steel mill is required to set up rolls for a small amount of material, which is not very economic.

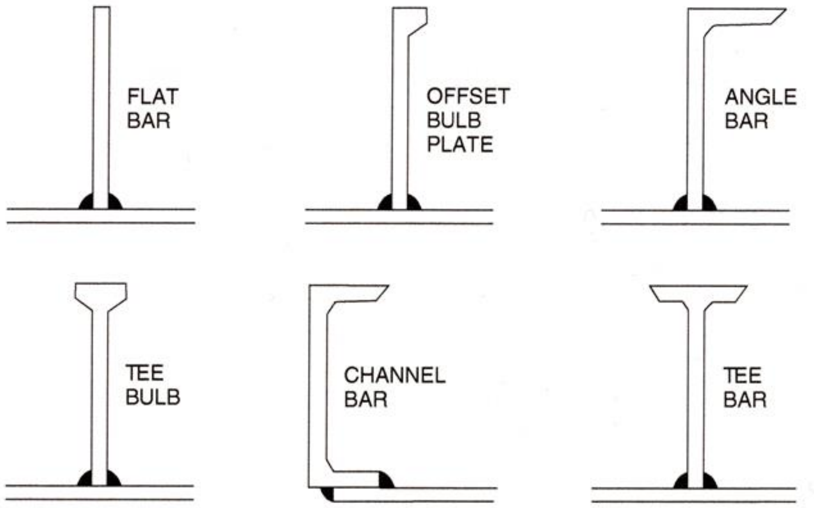


Figure 5. Common Steel Sections used in Shipbuilding

3.7 Ship Building Steels

Steel for hull construction purposes is usually mild steel containing 0.15-0.23% carbon and a reasonably high manganese content. Both sulfur and phosphorus in the mild steel are kept to a minimum (less than 0.05%). Higher concentrations of both are detrimental to the welding properties of the steel, and cracks can develop during the rolling process if the sulfur content is high.

Steel for a ship classed with Lloyd’s Register is produced by an approved manufacturer, and inspection and prescribed tests are carried out at the steel mill before dispatch. All certified materials are marked with the society’s brand and other particulars as required by the rules.

Ship classification societies originally had varying specifications for steel. However, in 1959, the major societies agreed to standardize their requirements in order to reduce the required grades of steel to a minimum. There are now five different qualities of steel employed in merchant ship construction and now often referred to as IACS steels. These are graded A, B, C, D, and E, Grade A being an ordinary mild steel to Lloyd's Register requirements and generally used in shipbuilding. Grade B is a better quality mild steel than Grade A and specified where thicker plates are required in the more critical regions. Grades C, D, and E possess increasing notch-tough characteristics, Grade C being to American Bureau of Shipping requirements. Lloyd's Register requirements for Grades A, B, D, and E steels may be found in Lloyd's Rules for the Manufacture, Testing and Certification of Materials[REF].

4. Processes Used in Shipbuilding

4.1 Welding and Cutting

Initially welding was used in ships as a means of repairing various metal parts. During the First World War various authorities connected with shipbuilding, including Lloyd's Register, undertook research into welding and in some cases prototype welded structures were built. However, riveting remained the predominant method employed for joining ship plates and sections until the time of the Second World War. During and after this war the use and development of welding for shipbuilding purposes was widespread, and welding totally replaced riveting in the latter part of the twentieth century.

There are many advantages to be gained from employing welding in ships as opposed to a riveted construction. The advantages concern both building and operating the ship.

For the shipbuilder the advantages are:

- Welding lends itself to the adoption of prefabrication techniques
- Ease of obtaining watertightness and oil tightness
- Joints are produced more quickly.
- Less skilled labor is required.

For the shipowner the advantages are:

- Reduced hull steel weight, therefore more deadweight.
- Less maintenance from slack rivets, etc.
- Elimination of overlapping plate joints leads to a smoother hull, reduced skin friction resistance and reduced fuel costs.

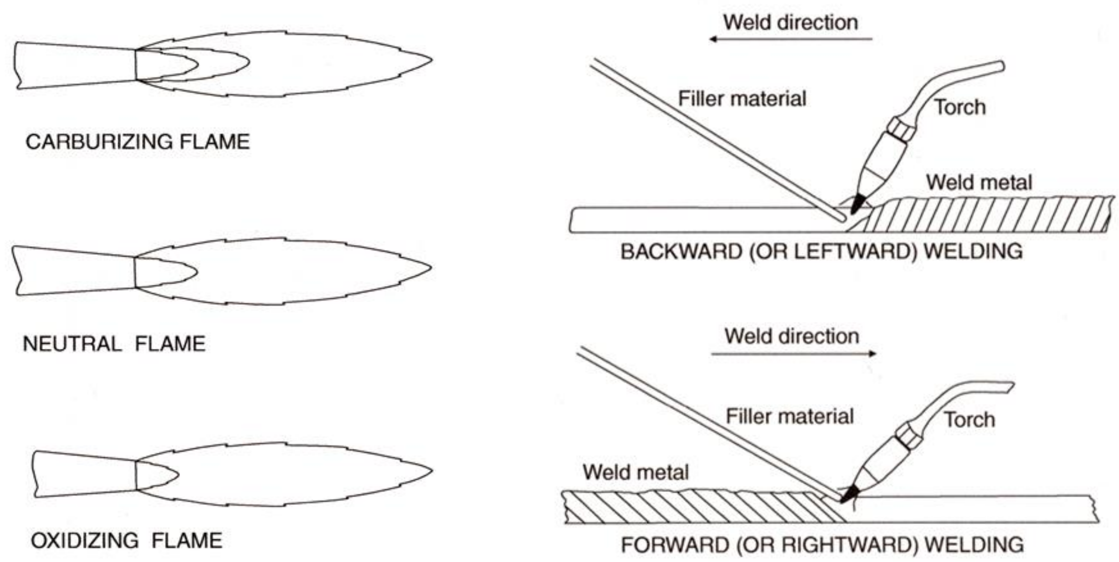
Other than some blacksmith work involving solid-phase welding, the welding processes employed in shipbuilding are of the fusion welding type. Fusion welding is achieved by means of a heat source that is intense enough to melt the edges of the material to be joined as it is traversed along the joint. Gas welding, arc welding, laser welding, and resistance welding all provide heat sources of sufficient intensity to achieve fusion welds.

4.2 Gas Welding

A gas flame was probably the first form of heat source to be used for fusion welding, and a variety of fuel gases with oxygen have been used to produce a high-temperature flame. The most commonly used gas in use is acetylene, which gives an intense concentrated flame (average temperature 3000 °C) when burnt in oxygen.

An oxyacetylene flame has two distinct regions: an inner cone, in which the oxygen for combustion is supplied via the torch; and a surrounding envelope, in which some or all the oxygen for combustion is drawn from the surrounding air. By varying the ratio of oxygen to acetylene in the gas mixture supplied by the torch, it is possible to vary the efficiency of the combustion and alter the nature of the flame, see Figure 6a. If the oxygen supply is slightly greater than the supply of acetylene by volume, what is known as an 'oxidizing' flame is obtained. This type of flame may be used for welding materials of high thermal conductivity, e.g. copper, but not steels, as the steel may be decarburized and the weld pool depleted of silicon. With equal amounts of acetylene and oxygen a 'neutral' flame is obtained, and this would normally be used for welding steels and most other metals. Where the acetylene supply exceeds the oxygen by volume a 'carburizing' flame is obtained, the excess acetylene decomposing and producing submicroscopic particles of carbon. These readily go into solution in the molten steel, and can produce metallurgical problems in service.

The outer envelope of the oxyacetylene flame by consuming the surrounding oxygen to some extent protects the molten weld metal pool from the surrounding air. If unprotected the oxygen may diffuse into the molten metal and produce porosity



(a) Flame Types **(b) Basic Method**

Figure 6. Gas Welding Characteristics

steels and aluminum, it is necessary to use an active flux to remove the oxides during the welding process.

Both oxygen and acetylene are supplied in cylinders, the oxygen under pressure and the acetylene dissolved in acetone since it cannot be compressed. Each cylinder, which is distinctly colored (red—acetylene, black—oxygen), has a regulator for controlling the working gas pressures. The welding torch consists of a long thick copper nozzle, a gas mixer body, and valves for adjusting the oxygen and acetylene flow rates. Usually, a welding rod is used to provide filler metal for the joint, but in some cases the parts to be joined may be fused together without any filler metal. Gas welding techniques are shown in Figure 6b.

Oxyacetylene welding tends to be slower than other fusion welding processes because the process temperature is low in comparison with the melting temperature of the metal, and because the heat must be transferred from the flame to the plate. The process is therefore only really applicable to thinner mild steel plate, thicknesses up to 7 mm being welded using this process with a speed of 3-4 meters per hour. In shipbuilding oxyacetylene welding has almost disappeared but can be employed in the fabrication of ventilation and air-conditioning trunking, cable trays, and light steel furniture; some plumbing and similar work may also make use of gas welding. These trades may also employ the gas flame for brazing purposes, where joints are obtained without reaching the fusion temperature of the material being joined.

4.3 Electric Arc Welding

The basic principle of electric arc welding is that a wire or electrode is connected to a source of electrical supply with a return lead to the plates to be welded. If the electrode is brought into contact with the plates an electric current flows in the circuit. By removing the electrode a short distance from the plate, so that the electric current is able to jump the gap, a high-temperature electrical arc is created. This will melt the plate edges and the end of the electrode if this is of the consumable type.

Electrical power sources vary, DC generators or rectifiers with variable or constant voltage characteristics being available, as well as AC transformers with variable voltage characteristics for single or multiple operation. The latter are most commonly used in shipbuilding.

A range of manual, semi-automatic, and automatic electric arc welding processes that might be employed in shipbuilding are shown in Figure 7. Each of these electric arc welding processes is discussed below with its application.

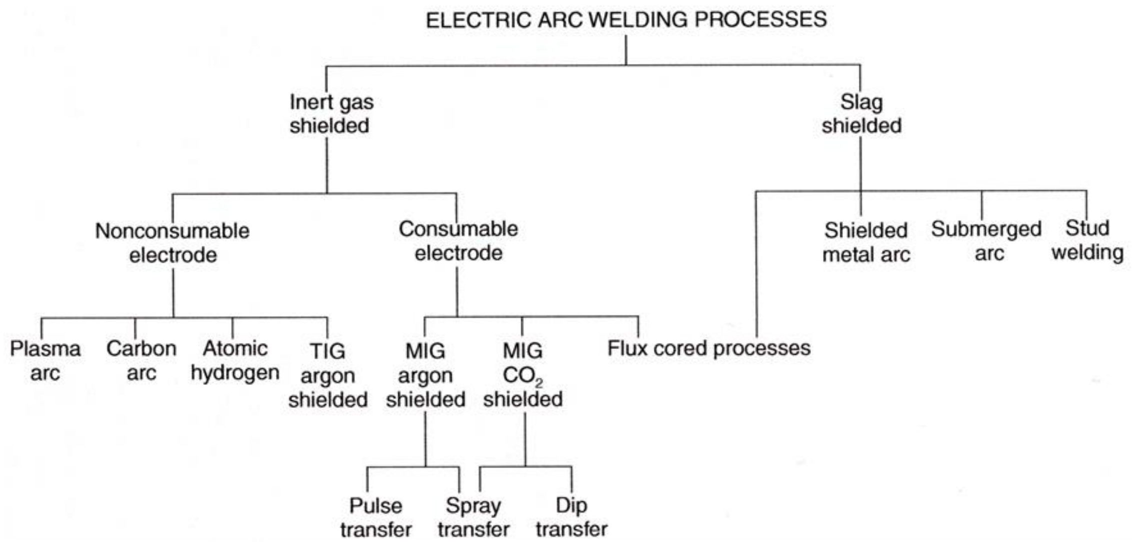


Figure 7. Electric Arc Welding Processes

4.3.1 Slag-Shielded Processes

Metal arc welding started as bare wire welding; the wire being attached to normal power lines. This gave unsatisfactory welds, and subsequently it was discovered that by dipping the wire in lime a more stable arc was obtained. As a result of further developments many forms of flux are now available for coating the wire or for deposition on the joint prior to welding. Other developments include a hollow wire for continuous welding with the flux within the hollow core. The flux melts, then solidifies during the welding process, forming a solid slag that protects the weld from atmospheric oxygen and nitrogen.

4.3.2 Manual Welding Electrodes

The cored wire normally used for mild steel electrodes is rimming steel. This is ideal for wire-drawing purposes, and elements used to 'kill' steel such as silicon or aluminum tend to destabilize the arc, making 'killed' steels unsuitable. Coatings for the electrodes normally consist of a mixture of mineral silicates, oxides, fluorides, carbonates, hydro-carbons, and powdered metal alloys plus a liquid binder. After mixing, the coating is then extruded onto the core wire and the finished electrodes are dried in batches in ovens.

Electrode coatings should provide gas shielding for the arc, easy striking and arc stability, a protective slag, good weld shape, and most important of all a gas shield consuming the surrounding oxygen and protecting the molten weld metal. Various electrode types are available, the type often being defined by the nature of the coating. The more important types are the rutile and basic (or low-hydrogen) electrodes. Rutile electrodes have coatings containing a high percentage of titania, and are general- purpose electrodes that are easily controlled and give a good weld finish with sound properties. Basic or low-hydrogen electrodes, the coating of which has a high lime content, are manufactured with the moisture content of the coating reduced to a minimum to ensure low-hydrogen properties. The mechanical properties of weld metal deposited with this type of electrode are superior to those of other types, and basic electrodes are generally specified for welding the higher tensile strength steels. Where high restraint occurs, for example at the final erection seam weld between two athwartships rings of unit structure, low-hydrogen electrodes may also be employed. An experienced welder is required where this type of electrode is used since it is less easily controlled. Welding with manual electrodes may be accomplished in the downhand position, for example welding at the deck from above, also in the horizontal vertical, or vertical positions, for example across or up a bulkhead, and in the overhead position, for example welding at the deck from below, see Figure 8. Welding in any of these positions requires selection of the correct electrode (positional suitability stipulated by the manufacturer), correct current, correct technique, and inevitably experience, particularly for the vertical and overhead positions.

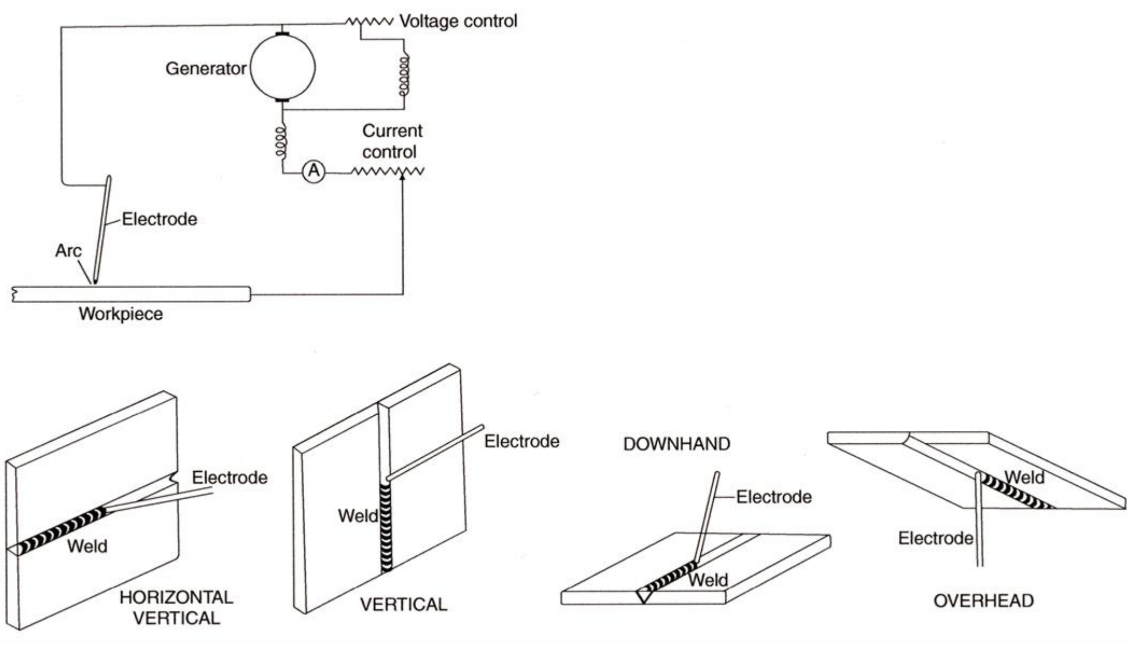


Figure 8. Manual Arc Welding Techniques

4.3.3 Automatic Welding with Cored Wires

Flux-cored wires (FCAW) are often used in mechanized welding, allowing higher deposition rates and improved quality of weld. Basic or rutile flux-cored wires are commonly used for one-sided welding with a ceramic backing.

4.3.4 Submerged Arc Welding

This is an arc welding process in which the arc is maintained within a blanket of granulated flux, see Figure 9. A consumable filler wire is employed and the arc is maintained between this wire and the parent plate. Around the arc the granulated flux breaks down and provides some gases, and a highly protective thermally insulating molten container for the arc. This allows a high concentration of heat, making the process very efficient and suitable for heavy deposits at fast speeds. After welding the molten metal is protected by a layer of fused flux, which together with the unfused flux may be recovered before cooling.

This is the most commonly used process for downhand mechanical welding in the shipbuilding industry, in particular for joining plates for ship shell, decks, and bulkheads. Metal powder additions that result in a 30-50% increase in metal deposition rate without incurring an increase in arc energy input may be used for the welding of joint thicknesses of 25 mm or more. Submerged arc multi-wire and twin- arc systems are also used to give high productivity.

With shipyards worldwide adopting one-side welding in their ship panel lines for improved productivity, the submerged arc process is commonly used with a fusible backing, using either flux or glass fiber materials to contain and control the weld penetration bead.

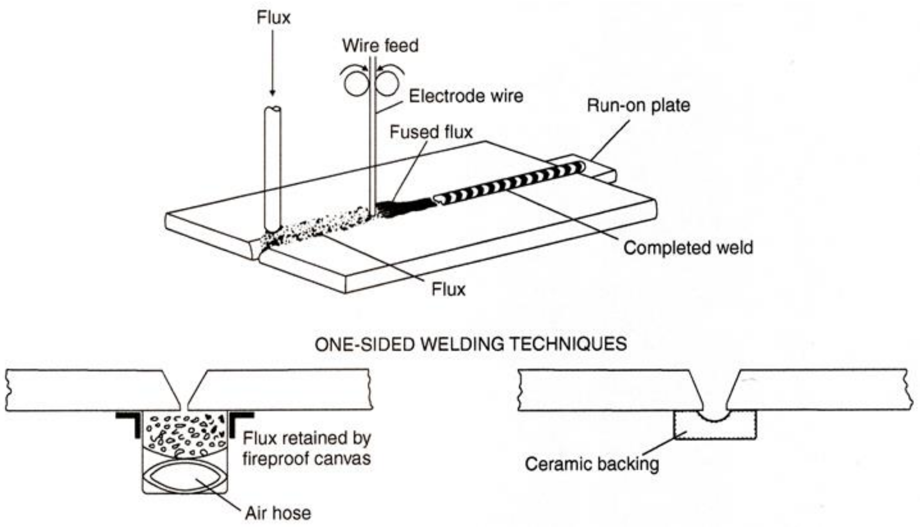


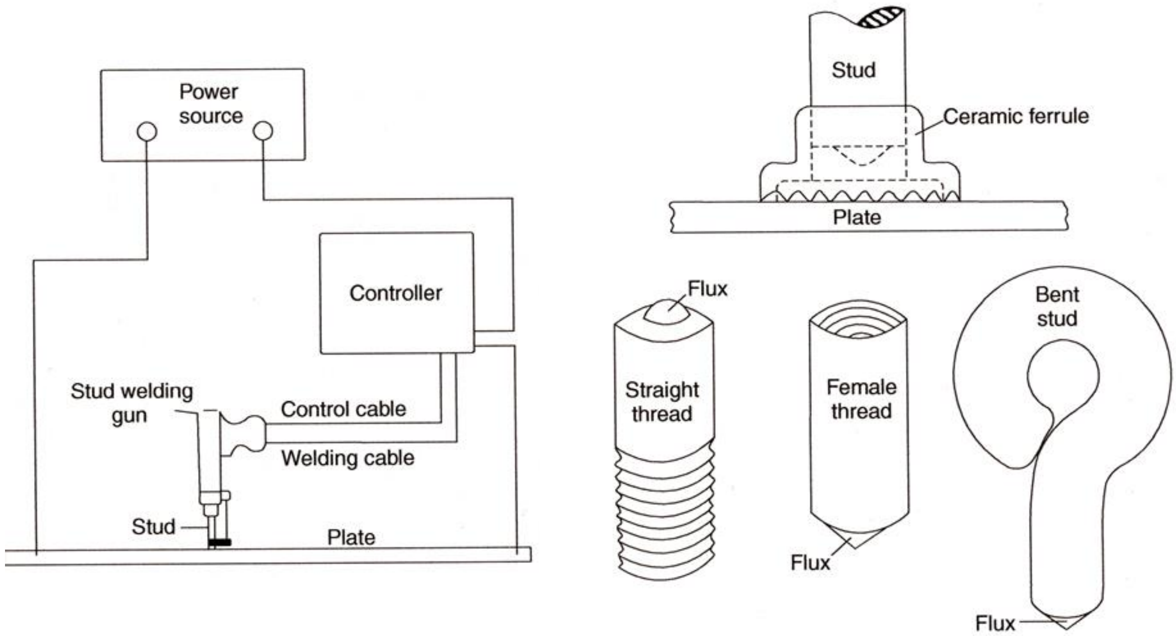
Figure 9. Automatic – Submerged Arc Welding

4.3.5 Stud Welding

Stud welding may be classed as a shielded arc process, the arc being drawn between the stud (electrode) and the plate to which the stud is to be attached. Each stud is inserted into a stud welding gun chuck, and a ceramic ferrule is slipped over it before the stud is placed against the plate surface. On depressing the gun trigger the stud is automatically retracted from the plate and the arc established, melting the end of the stud and the local plate surface. When the arcing period is complete, the current is automatically shut off and the stud driven into a molten pool of weld metal, so attaching stud to plate.

Apart from the stud welding gun the equipment includes a control unit for timing the period of current flow. Granular flux is contained within the end of each stud to create a protective atmosphere during arcing. The ceramic ferrule that surrounds the weld area restricts the access of air to the weld zone; it also concentrates the heat of the arc and confines the molten metal to the weld area, see Figure 10.

Stud welding is often used in shipbuilding, generally for the fastening of stud bolts to secure supports for pipe hangars, electric cable trays and other fittings, also insulation to bulkheads and wood sheathing to decks, etc. Apart from various forms of stud bolts, items like stud hooks and rings are also available.



(a) Welding Circuit (b) Stud Types

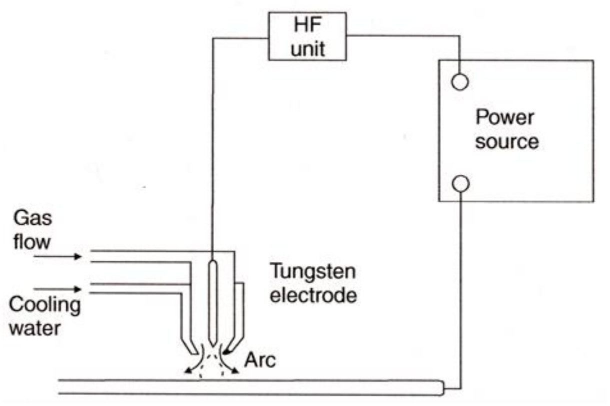
Figure 10. Stud Welding

4.3.6 Gas Shielded Arc Welding Processes

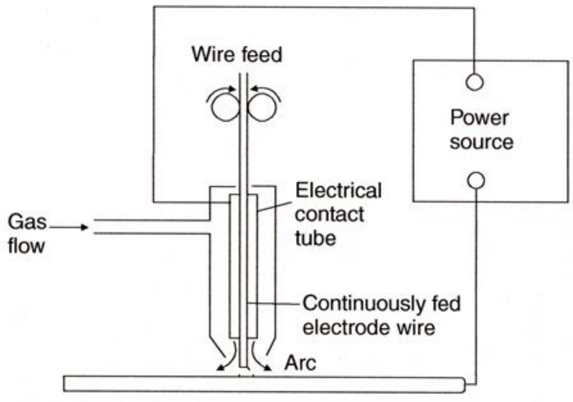
The application of bare wire welding with gas shielding was developed in the 1960s, and was quickly adopted for the welding of lighter steel structures in shipyards, as well as for welding aluminum alloys. Gas-shielded processes are principally of an automatic or semi-automatic nature.

4.3.6.1 Tungsten inert gas (TIG) welding

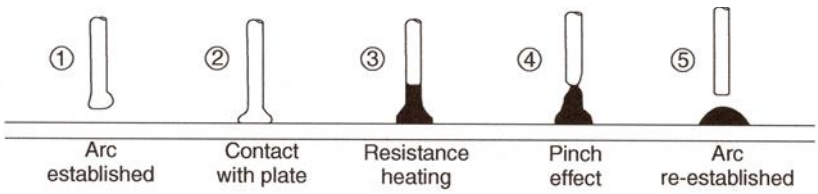
In the TIG welding process the arc is drawn between a water-cooled nonconsumable tungsten electrode and the plate, see Figure 11. An inert gas shield is provided to protect the weld metal from the atmosphere, and filler metal may be added to the weld pool as required. Ignition of the arc is obtained by means of a high-frequency discharge across the gap, since it is not advisable to strike an arc on the plate with the tungsten electrode. Normally in Britain the inert gas shield used for welding aluminum and steel is argon. Only plate thicknesses of less than 6 mm would normally be welded by this process, and in particular aluminum sheet, a skilled operator being required for manual work. This may also be referred to as TAGS welding, i.e. tungsten arc gas- shielded welding.



(a) Tungsten Inert Gas (TIG) Process



(b) Metal Inert Gas (MIG) Process



(c) Dip Transfer Principle

Figure 11. Metal Inert Gas Welding

4.3.6.2 Metal inert gas (MIG) welding

This is in effect an extension of TIG welding, the electrode in this process becoming a consumable metal wire.

Basically the process is as illustrated in Figure 11, a wire feed motor supplying wire via guide rollers through a contact tube in the torch to the arc. An inert gas is supplied to the torch to shield the arc, and electrical connections are made to the contact tube and workpiece. Welding is almost always done with a DC source and electrode positive for regular metal transfer, and when welding aluminum to remove the oxide film by the action of the arc cathode. Although the process may be fully automatic, semi-automatic processes as illustrated with hand gun are now in greater use, and are particularly suitable in many cases for application to shipyard work.

Initially aluminum accounted for most of the MIG welding, with argon being used as the inert shielding gas. Much of the welding undertaken on aluminum deckhouses, and liquid methane gas tanks of specialized carriers, has made use of this process. Generally larger wire sizes and heavier currents have been employed in this work, metal transfer in the arc being by means of a spray transfer, i.e. metal droplets being projected at high speed across the arc. At low currents metal transfer in the arc is rather difficult and very little fusion of the plate results, which has made the welding of light aluminum plate rather difficult with the MIG/argon process. The introduction of the 'pulsed arc' process has to some extent overcome this problem and made positional welding easier. Here a low-level current is used with high-level pulses of current that detach the metal from the electrode and accelerate it across the arc to give good penetration.

Early work on the welding of mild steel with the metal inert gas process made use of argon as a shielding gas, but as this gas is rather expensive, and satisfactory welding could only be accomplished in the downhand position, an alternative shielding gas was sought.

Research in this direction was concentrated on the use of CO_2 as the shielding gas, and the MIG/CO_2 process is now widely used for welding mild steel. Using higher current values with thicker steel plate a fine spray transfer of the metal from the electrode across the arc is achieved, with a deep penetration. Wire diameters in excess of 1.6 mm are used, and currents above about 350 amps are required to obtain this form of transfer. Much of the higher current work is undertaken with automatic machines, but some semi-automatic torches are available to operate in this range in the hands of skilled welders. Welding is downhand only.

On thinner plating where lower currents would be employed, a different mode of transfer of metal in the arc is achieved with the MIG/CO_2 process. This form of welding is referred to as the dip transfer (or short-circuiting) process. The sequence of metal transfer is (see Figure 11):

1. Establish the arc
2. Wire fed into arc until it makes contact with plate
3. Resistance heating of wire in contact with plate
4. Pinch effect, detaching heated portion of wire as droplet of molten metal
5. Re-establish the arc

To prevent a rapid rise of current and 'blast off' of the end of the wire when it short- circuits on the plate, variable inductance is introduced in the electrical circuit. Smaller wire diameters, 0.8 and 1.2 mm, are used where the dip transfer method is employed on lighter plate at low currents. The process is suitable for welding light mild steel plate in all positions. It may be used in shipbuilding as a semi-automatic process, particularly for welding deckhouses and other light steel assemblies.

The pulsed MIG/argon process, developed for positional welding of light aluminum plate, may be used for positional welding of light steel plate but is likely to prove more expensive.

Use of the MIG semi-automatic processes can considerably increase weld output and lower costs.

This form of welding may also be collectively referred to as MAGS welding, i.e. metal arc gas-shielded welding.

4.3.6.3 Plasma welding

This is very similar to TIG welding as the arc is formed between a pointed tungsten electrode and the plate. But, with the tungsten electrode positioned within the body of the torch, the plasma arc is separated from the shielding gas envelope, see Figure 12. Plasma is forced through a fine-bore copper nozzle that constricts the arc. By varying the bore diameter and plasma gas flow rate, three different operating modes can be achieved:

1. Microplasma - the arc is operated at very low welding currents (0.1-15 amps) and used for welding thin sheets (down to 0.1 mm thickness.
2. Medium current—the arc is operated at currents from 15 to 200 amps. Plasma welding is an alternative to conventional TIG welding, but with the advantage of achieving deeper penetration and having greater tolerance to surface contamination. Because of the bulkiness of the torch, it is more suited to mechanized welding than hand welding

3. Keyhole plasma—the arc is operated at currents above 100 amps and by increasing the plasma flow a very powerful plasma beam is created. This can penetrate thicknesses up to 10 mm, but when using a single-pass technique is normally limited to a thickness of 6 mm. This operating mode is normally used for welding sheet metal (over 3 mm) in the downhand position

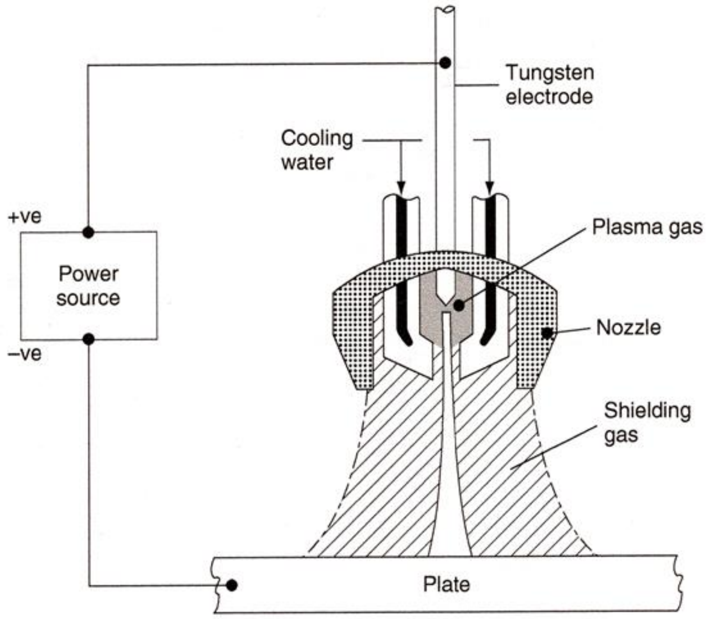


Figure 12. Plasma Welding

4.4 Cutting Processes

Steel plates and sections were mostly cut to shape in shipyards using a gas cutting technique, but the introduction of competitive plasma-arc cutting machines has led to their widespread use in shipyards today.

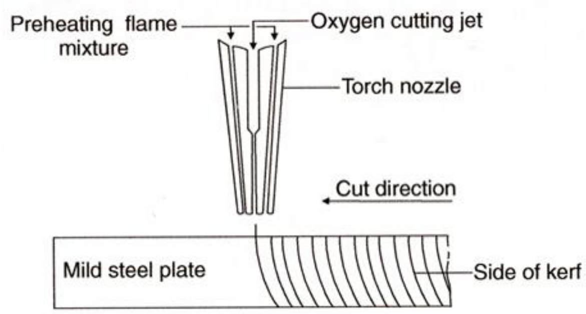
4.4.1 Gas Cutting

Gas cutting is achieved by what is basically a chemical/thermal reaction occurring with iron and iron alloys only. Iron or its alloys may be heated to a temperature at which the iron will rapidly oxidize in an atmosphere of high purity oxygen.

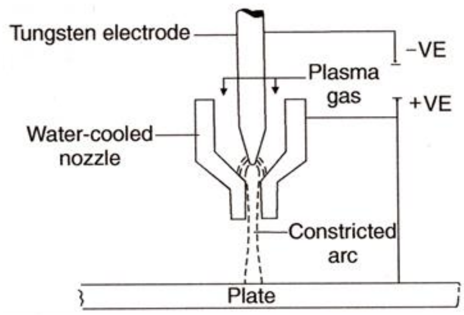
The principle of the process as applied to the cutting of steel plates and sections in shipbuilding is as follows. Over a small area the metal is preheated to a given temperature, and a confined stream of oxygen is then blown onto this area. The iron is then oxidized in a narrow band, and the molten oxide and metal are removed by the kinetic energy of the oxygen stream. A narrow parallel sided gap is then left between the cut edges. Throughout the cutting operation the preheat flame is left on to heat the top of the cut since most of the heat produced by the reaction at the cutting front is not instantaneous, and tends to be liberated at the lower level of the cut only. Alloying elements in small amounts are dissolved in the slag and removed when cutting steel. However, if they are present in large quantities, alloying elements, especially chromium, will retard and even prevent cutting. The reason for this is that they either decrease the fluidity of the slag or produce a tenacious oxide film over the surface which prevents further oxidation of the iron. This may be overcome by introducing an iron rich powder into the cutting area, a process often referred to as ‘powder cutting'. When cutting stainless steels which have a high chromium content 'powder cutting' would be employed.

Generally, acetylene is used with oxygen to provide the preheat flame but other gases can be used: propane for example or hydrogen which is used for underwater work because of its compressibility. Apart from the torch, the equipment is similar to that for gas welding. The torch has valves for controlling the volume of acetylene and oxygen provided for the preheat flame, and it has a separate valve for controlling the oxygen jet, see Figure 13a.

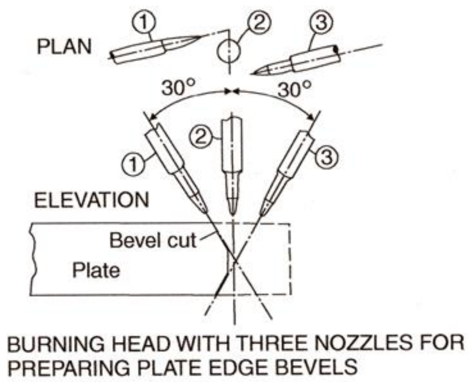
The oxyacetylene cutting process has been highly automated for use in shipyards. Hand burning with an oxyacetylene flame is used extensively for small jobbing work, and during the fabrication and erection of units.



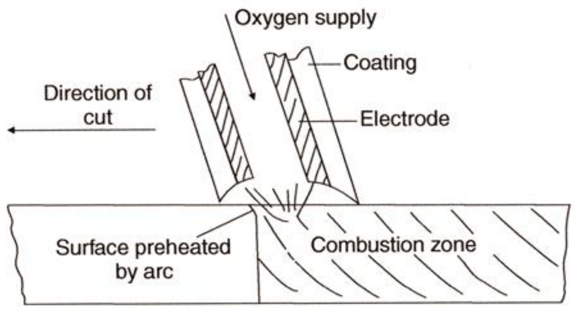
(a) Oxyacetylene Cutting



(b) Plasma Torch Cutting



(c) Bevel Cutting



(d) Arc-Air Gouging

Figure 13. Metal Cutting Processes

4.4.2 Plasma-Arc Cutting

Plasma in this sense is a mass of ionized gas which will conduct electricity. An electrode is connected to the negative terminal of a DC supply and a gas shield is supplied for the arc from a nozzle which has a bore less than the natural diameter of the arc. As a result, a constricted arc is obtained which has a temperature considerably higher than that of an open arc. The arc is established between the electrode and workpiece when the ionized conducting gas comes into contact with the work. This gas is ionized in the first place by a subsidiary electrical discharge between the electrode and the nozzle. Plates are cut by the high-temperature concentrated arc melting the material locally, see Figure 13b.

The plasma-arc process may be used for cutting all electrically conductive materials. Cutting units are available with cutting currents of 20-1000 amps to cut plates with thicknesses of

0.6-150 mm. The plasma carrier gas may be compressed air, nitrogen, oxygen, or argon/hydrogen to cut mild or high alloy steels, and aluminum alloys, the more expensive argon/hydrogen mixture being required to cut the greater thickness sections. A water-injection plasma-arc cutting system is available for cutting materials up to 75 mm thick using nitrogen as the carrier gas. A higher cutting speed is possible and pollution minimized with the use of water and an exhaust system around the torch.

Water cutting tables were often used with plasma-arc cutting, but more recent systems have dispensed with underwater cutting. Cutting in water absorbed the dust and particulate matter and reduced the plasma noise and ultraviolet radiation of earlier plasma cutters.

4.4.3 Gouging

Both gas and arc welding processes may be modified to produce means of gouging out shallow depressions in plates to form edge preparations for welding purposes where precision is not important. Gouging is particularly useful in shipbuilding for cleaning out the backs of welds to expose clean metal prior to depositing a weld back run. The alternative to gouging for this task is mechanical chipping, which is slow and arduous. Usually, where gouging is applied for this purpose, what is known as 'arc-air' gouging is used. A tubular electrode is employed, the electrode metal conducting the current and maintaining an arc of sufficient intensity to heat the workpiece to incandescence. Whilst the arc is maintained, a stream of oxygen is discharged from the bore of the electrode that ignites the incandescent electrode metal and the combustible elements of the workpiece. At the same time the kinetic energy of the excess oxygen removes the products of combustion, and produces a cut. Held at an angle to the plate, the electrode will gouge out the unwanted material, see Figure 13d.

A gas cutting torch may be provided with special nozzles that allow gouging to be accomplished when the torch is held at an acute angle to the plate.

4.4.4 Laser Cutting

Profile cutting and planing at high speeds can be achieved with a concentrated laser beam and has increasingly been employed in a mechanized or robotic form in the shipbuilding industry in recent years. In a laser beam the light is of one wavelength, travels in the same direction, and is coherent, i.e. all the waves are in phase. Such a beam can be focused to give high energy densities. For welding and cutting the beam is generated in a CO_2 laser. This consists of a tube filled with a mixture of CO_2, nitrogen, and helium that is made to fluoresce by a high-voltage discharge. The tube emits infrared radiation with a wavelength of about 1.6 pm and is capable of delivering outputs up to 20 kW. Laser cutting relies on keyholing to penetrate the thickness, and the molten metal is blown out of the hole by a gas jet. A nozzle is fitted concentric with the output from a CO2 laser so that a gas jet can be directed at the work coaxial with the laser beam. The jet can be an inert gas, nitrogen, or in the case of steel, oxygen. With oxygen there is an exothermic reaction with the steel, giving additional heat as in oxy-fuel cutting. The thermal keyholing gives a narrow straight-sided cut compared with the normal cut obtained by other processes relying on a chemical reaction.

4.4.5 Water Jet Cutting

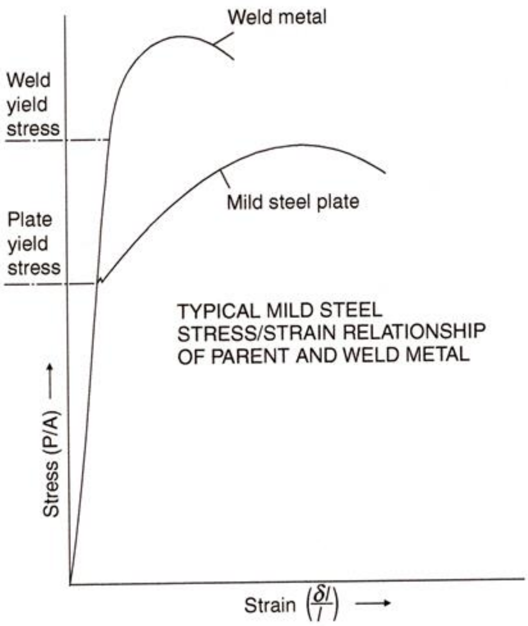
The cutting tool employed in this process is a concentrated water jet, with or without abrasive, which is released from a nozzle at 2.5 times the speed of sound and at a pressure level of several thousand bar. Water jet cutting can be used on a range of materials such as timber, plastics, rubber, etc., as well as steels and aluminum alloys. Mild steel from 0.25 to

150 mm in thickness and aluminum alloys from 0.5 to 250 mm in thickness can be cut. Being a cold cutting process, the heat-affected zone, mechanical stresses, and distortion are left at the cut surface.

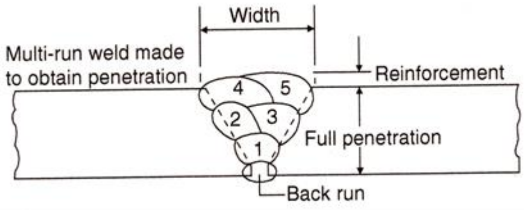
Water jet cutting is slower than most thermal cutting processes and is not a portable machine tool.

5. Welding Practice and Assessment

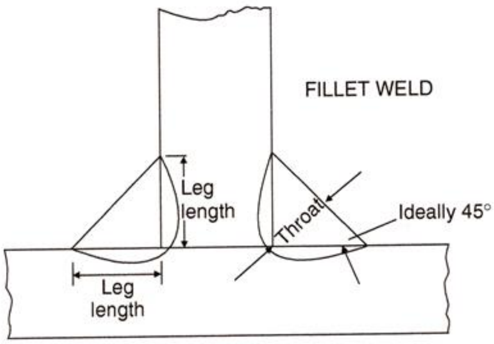
The strongest welded joint that may be produced in two plates subsequently subjected to a tensile pull is the butt joint. A butt joint is one where the two joined plates are in the same plane, and in any welded structure it is desirable that butt joints should be used wherever possible.



Stress vs Strain Curves



Butt Weld



Fillet Weld

Figure 14. Stress versus Strain for Parent/Weld Metals and Butt/Fillet Weld Detail

In mild steel the weld metal tends to have a higher yield strength than the plate material, see Figure 14. Under tension it is found that initial yielding usually occurs adjacent to a butt weld in the plate when the yield strength of the plate material is reached locally. Since a good butt weld in tension has a strength equivalent to that of the mild steel plate, it is not considered as a line of structural weakness.

Lapped joints, where fillet welds are used to connect the plates, should be avoided in strength members of a welded structure. As the fillet welds are in shear when the plates are in tension, the strength of the joint is very much less than that of the plate material or butt joint. Fillet welds are unavoidable where sections or plates are connected at an angle to an adjacent plate, but often there is not the same problem as the loading is different. The fatigue strength of fillet welds is also inferior to that of a butt weld.

5.1 Welding Practice

In making a butt weld with manual arc welding, where the plate thickness exceeds, say, 5-6 mm it will become necessary to make more than one welding pass to deposit sufficient weld metal to close the joint. With the higher current automatic welding processes thicker plates may be welded with a single pass, but at greater thicknesses multi-pass welds become necessary.

In ship work unless a permanent backing bar is used, or a ‘one-sided’ welding technique or process is used, a back run of weld is required to ensure complete weld penetration. This is made on the reverse side of the joint after cleaning out the slag, etc., by chipping or gouging. Permanent backing bars may conveniently be introduced where it is desired to weld from one side only during erection at the berth. A good example is the use of a cut-down channel bar used as a deck beam, the upper flange providing the backing bar for a deck panel butt weld, made by machine above.

Tack welds are used throughout the construction to hold plates and sections in place after alignment and prior to completion of the full butt or fillet weld. These are short light runs of weld metal, which may be welded over, or cut out in more critical joints during the final welding of the joint.

Fillet welds may be continuous or intermittent depending on the structural effectiveness of the member to be welded. Where fillets are intermittent, they may be either staggered or chain welded, see Figure 15, the member may also be scalloped to give the same result when continuously welded.

On thicker plates it becomes necessary to bevel the edges of plates that are to be butted together in order to achieve complete penetration of the weld metal (Figure 10.2). This operation may be carried out whilst profiling or trimming the plate edges, which must be aligned correctly. Most edge preparations are made by gas or plasma heads having three nozzles out of phase that can be set at different angles to give the required bevels. Alternatively, the edge preparation may be obtained by mechanical machining methods using either a planing or milling tool. For very high-quality welds in thick plate, particularly of the higher tensile types of steel, mechanical machining may well be specified. It is worth noting that there is little to choose between the two as far as metallurgical damage goes, but mechanical methods provide a better finish.

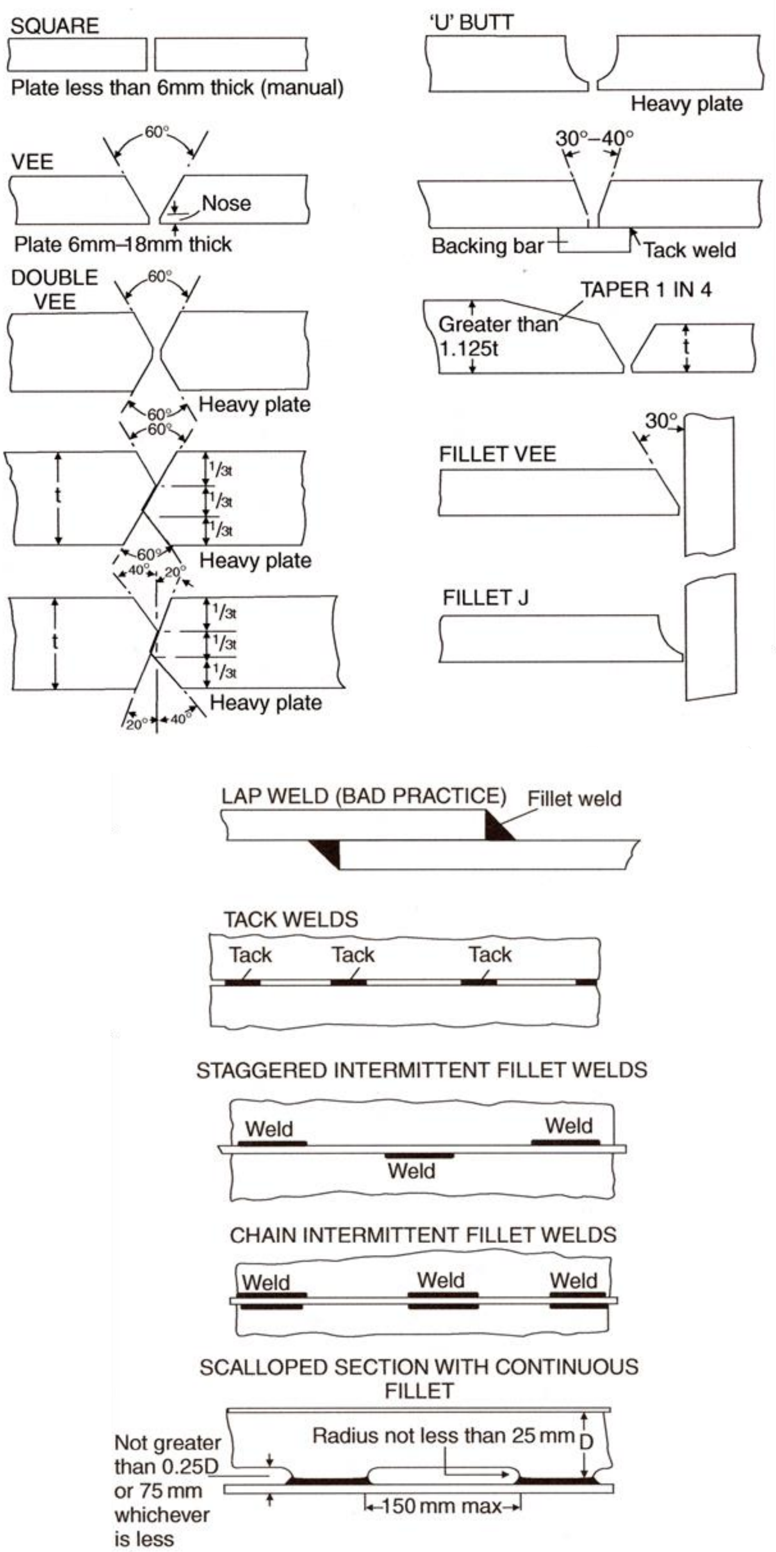


Figure 15. Plate Edge Preparation

Plates of varying thickness may be butt welded together at different locations, a good example being where heavy insert plates are fitted. Insert plates are preferred to doubling plates in welded construction, and the heavy plate is chamfered to the thickness of the adjacent thinner plate before the butt edge preparation is made.

To ease the assembly of welded units it is common practice to make use of what is known as an 'egg box' construction. Within the double-bottom unit the floors and side girders may be slotted at their intersections so that they fit neatly together prior to construction.

5.1.1 Automatic Welding

Larger shipyards with a large production line throughput of welded panels use automated welding systems to produce the stiffened panels. To join the plates, high-speed one-sided submerged arc welding is used, see Figure 9 above. The required welding parameters are set in advance in the operation box and linked to a computer. The operator selects the plate thickness and starts the machine. The machine automatically controls the welding parameters for the weld crater and stops when the run-off tab is reached at the end of the plates. The welded plate panel is then moved over floor-mounted rollers to the next stage where the stiffening members are to be attached. Each stiffener is lowered onto the plate panel and tack welded using metal arc gas-shielded welding. The plate panel with tacked stiffeners is then rolled within reach of a fillet welding gantry with double-fillet welding machines. The gantry moves parallel to the stiffeners at the same speed as the welding heads and carries packs containing the welding wires and power sources for the double-fillet welding heads. Welding is carried out using flux-cored wires with CO_2 gas shielding.

5.1.2 Weld Distortion

During the welding process the metal is heated, which causes expansion and the metal then contracts on cooling. The initial rapid heating causes the welded area to expand locally. The slower cooling of the weld causes the plate to move as the weld contracts. The result is a distortion of the part, and this is a major cause of extra work during assembly of units and construction of the ship. The need to adjust distorted parts so that they fit correctly can take considerable time and effort. In-plane distortion is basically shrinkage of the plate. For repeatable processes, which are usual in ship-building, the shrinkage can be measured and sufficient data built up to allow the shrinkage to be predicted. Computer-aided design systems can now include an allowance for shrinkage, so that the part as modeled in the system can then be adjusted during the generation of cutting information. The plates are cut oversized and the shrinkage after welding brings it to the correct size. More recently, work has been carried out to model shrinkage of more complex parts, for example structural webs with face flats. Again, these parts can then have their dimensions adjusted prior to cutting so that the effect of shrinkage is to bring them to the correct shape. Out-of-plane distortion is much more difficult to predict and manage. The cause is the same as in-plane shrinkage, but the distortion is often associated with fillet welds used to attach stiffeners to plates. The fillet welds, as they shrink, pull the plate out of plane, resulting in the typical appearance of a welded hull with indentations between the frames. The effect is much more noticeable for thin plate structures, for smaller ships, and for superstructures. Restraining the plate during assembly and welding is one commonly used solution.

The causes of distortion are complex and also include any residual stresses in the steel plate as a result of the steel mill rolling and cooling. Some of the stress may be relieved by rolling the plate prior to production, but distortion remains a significant problem for many shipbuilders.

5.1.3 Weld Sequences

In order to minimize distortion in manual welding the ‘backstep’ and ‘wandering’ methods of welding are often used, the length of each step being the amount of weld metal laid down by an electrode to suit the required cross-section of weld, see Figure 17.

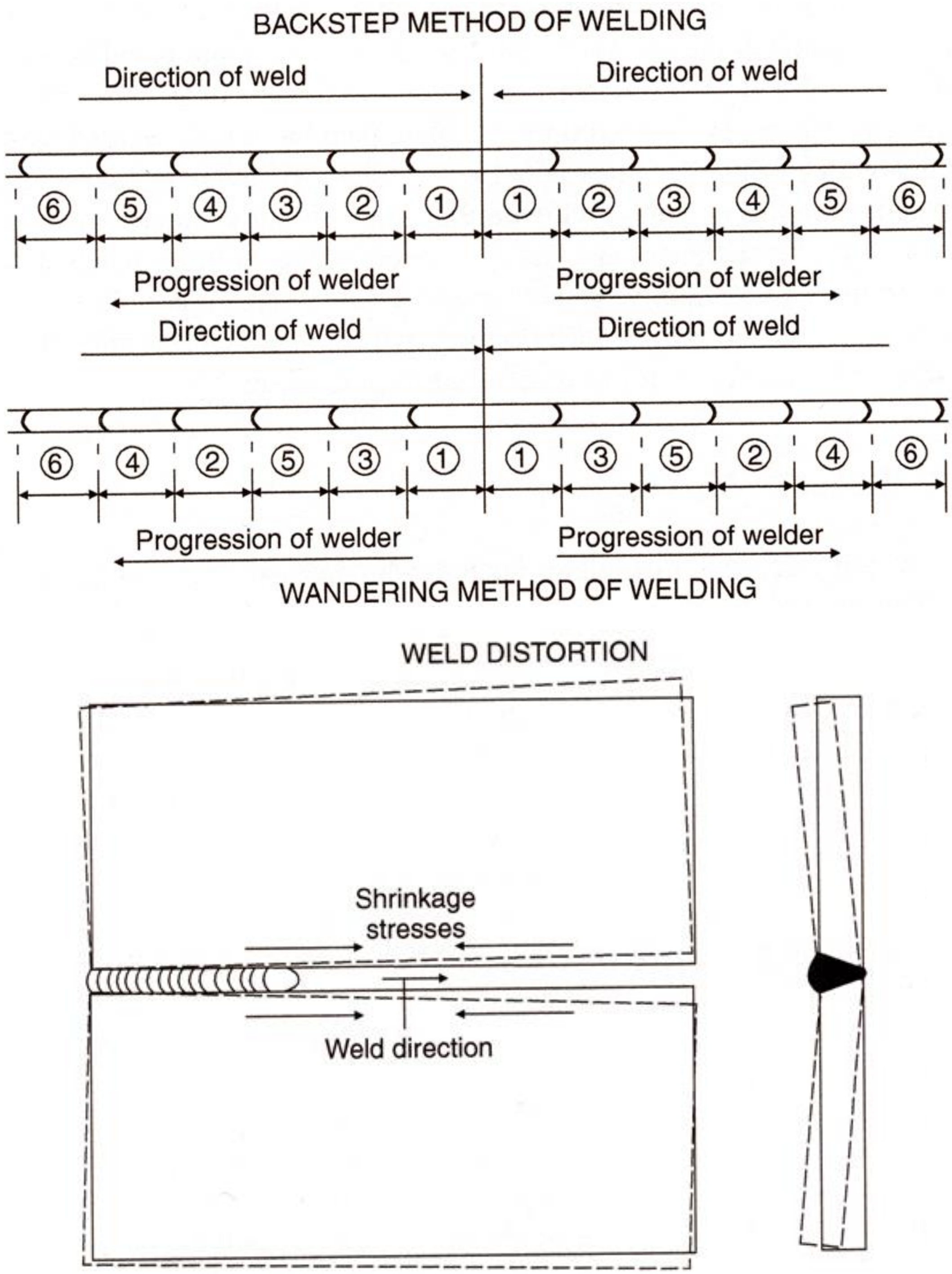
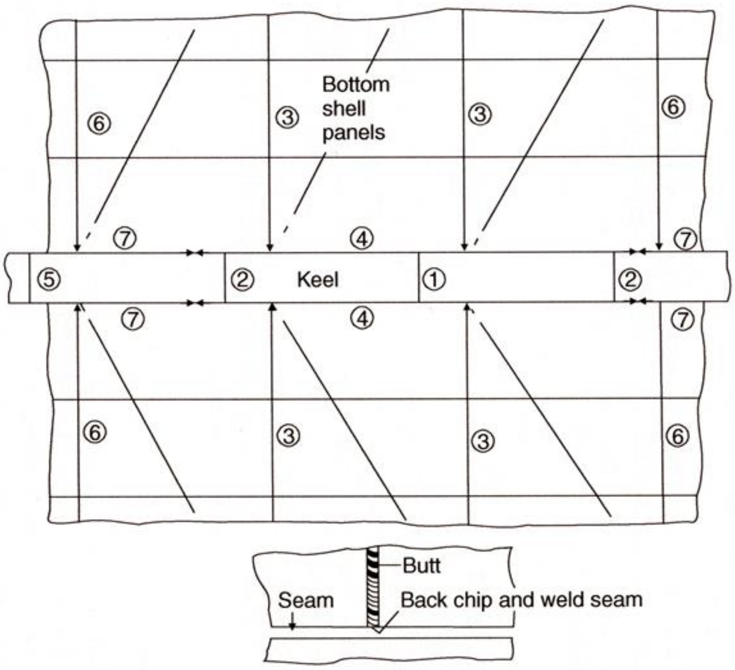
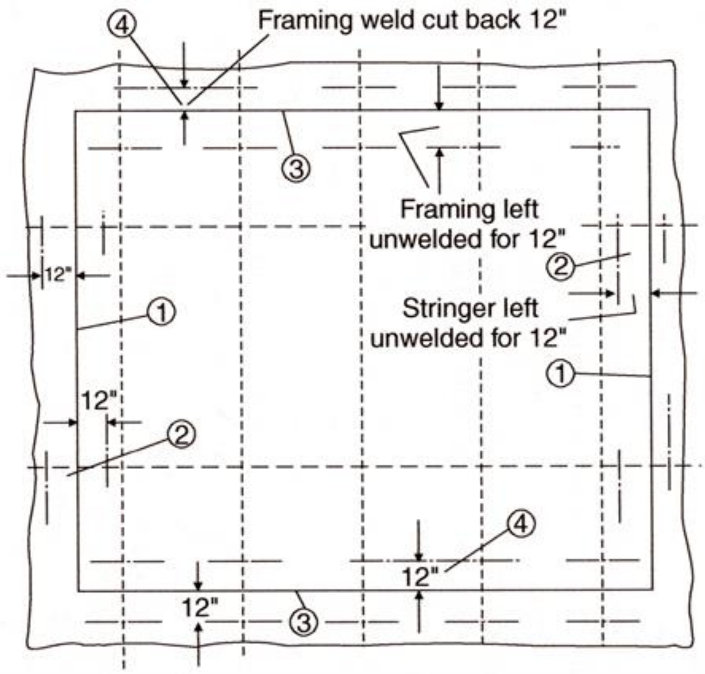


Figure 16. Backstep and Wandering Welding Methods

To reduce distortion and limit the residual stresses in the structure it is important that a correct welding sequence should be utilized throughout the construction. This applies both during the fabrication of units and at erection and joining on the berth.



(a) Welding Sequence – Bottom Shell



(b) Welding Sequence – Bottom Shell

Figure 17. Welding Sequences

Of the more important welds in the construction of the ship the sequences involving welding of butts and seams in plating panels may be considered (see Figure 10.4). At T intersections it is necessary to weld the butt first fully, then gouge out the ends to renew the seam edge preparation before welding the seam. Welding the seam first would cause high restraint across the plate strake and when the butt was finished a crack might occur. General practice when welding shell panels is to start by welding the central butts and then adjacent seams, working outwards both transversely and longitudinally. Ships' structural panels have various forms of stiffener attached to the plate panels; these generally being welded to the panel after completing the welding of the panel plates. These stiffening members are left unwelded across the butts and seams of the plates until these are completed, if they are attached at some intermediate stage.

Erection welding sequences generally follow the principles laid down for plating panels. In welded ships the lower side plating seams should not be welded before the upper seams, particularly the deck and gunwale seams. If this sequence of welding the side shell were adopted the upper portion of the hull structure would tend to be shortened, causing the hull to rise from the blocks at the ends. Where in modem construction the side shell and deck plating are erected in blocks and a suitable welding sequence is employed, this problem does not arise.

In repair work correct welding sequences are also important, particularly where new material is fitted into the existing relatively rigid structure. Again, the procedure follows the general pattern for butts and seams in plate panels. If a new shell plate is to be welded in place the seams and butts in the surrounding structure are cut back 300-375 mm from the opening, likewise the connection of the stiffening in way of the opening.

The inserted plate panel is then welded to within 300-375 mm of the free edges, the butts are completed, and then the seams after welding any longitudinal stiffening across the butts. Finally, the vertical framing is welded in way of the seams, see Figure 17.

5.2 Testing Welds

For economic reasons much of the weld testing carried out in shipbuilding is done visually by trained inspectors. Spot checks at convenient intervals are made on the more important welds in merchant ship construction, generally using radiographic or ultrasonic equipment. Welding materials are subjected to comprehensive tests before they are approved by Lloyd's Register or the other classification societies for use in ship work. Operatives are required to undergo periodical welder approval tests to ascertain their standard of workmanship.

5.2.1 Weld Defects

Various faults may be observed in butt and fillet welds. These may be due to a number of factors: bad design, incorrect welding procedure, use of wrong materials, and bad workmanship. Different faults are illustrated in Figure 19. The judgment of the seriousness of the fault rests with the weld inspector and surveyor, and where the weld is considered to be unacceptable it will be cut out and re welded.

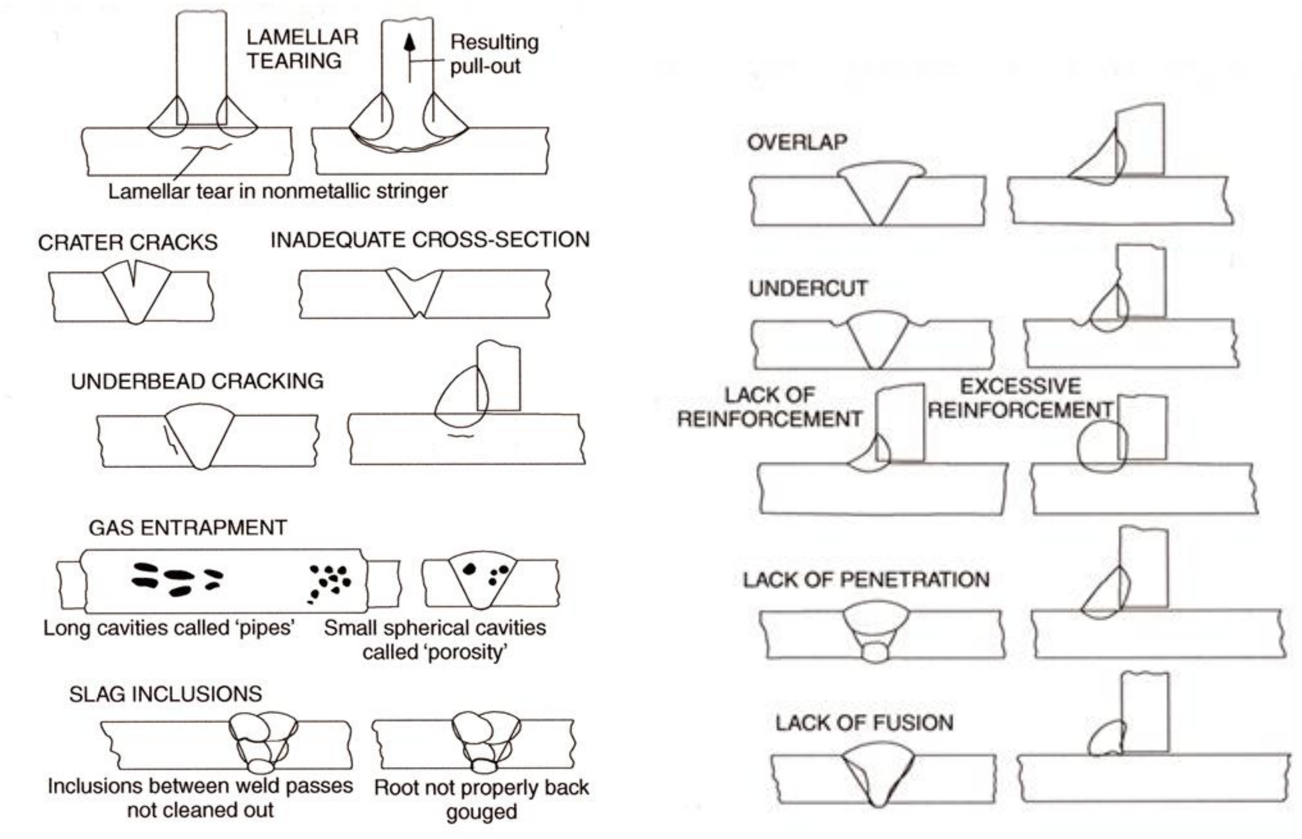


Figure 18. Weld Faults

6. Nondestructive Testing (NDT)

For obvious reasons some form of nondestructive test is required to enable the soundness of ship welds to be assessed. The various available nondestructive testing methods may be summarized as follows:

- Visual examination
- Dye penetrant
- Magnetic particle
- Radiographic
- Ultrasonic.

Of these five methods, the dye penetrant and magnetic particle tests have few applications in ship hull construction, being used for examining surface cracks in stem frames and other castings. Visual, radiographic, and ultrasonic examinations are considered in more detail, as they are in common use.

Magnetic particle testing is carried out by magnetizing the casting and spreading a fluid of magnetic particles (e.g. iron fillings suspended in paraffin) on the surface. Any discontinuity such as a surface crack will show up as the particles will concentrate at this point where there is an alteration in the magnetic field. A dye penetrant will also show up a surface flaw if it remains after the casting has been washed following the application of the dye. To aid the detection of a surface crack the dye penetrant used is often luminous and is revealed under an ultraviolet light.

Visual inspection of welds is routine procedure, and surface defects are soon noticed by the experienced inspector and surveyor. Incorrect bead shape, high spatter, undercutting, bad stop and start points, incorrect alignment, and surface cracks are all faults that may be observed at the surface. Subsurface and internal defects are not observed, but the cost of visual inspection is low, and it can be very effective where examination is made before, during, and after welding.

The principle of radiographic inspection is simply to subject a material to radiation from one side, and record the radiation emitted from the opposite side. Any obstacle in the path of the radiation will affect the radiation density emitted and may be recorded. As radiation will expose photographic plate, for all practical weld test purposes this is used to record the consistency of the weld metal. The photographic plate records changes in radiation density emitted; for example, a void will show up as a darker shadow on the radiograph.

Either X-ray or gamma-ray devices may be used to provide the source of radiation. X-ray equipment consists of a high-voltage power source (50-400 kV), which is used to provide potential between a cathode and target anode in a glass vacuum tube. Only a small percentage of this energy is converted to X-rays, so that large amounts of heat have to be conducted away from the target. From the target the X-rays are projected out of the tube onto the weld surface, see Figure 19.

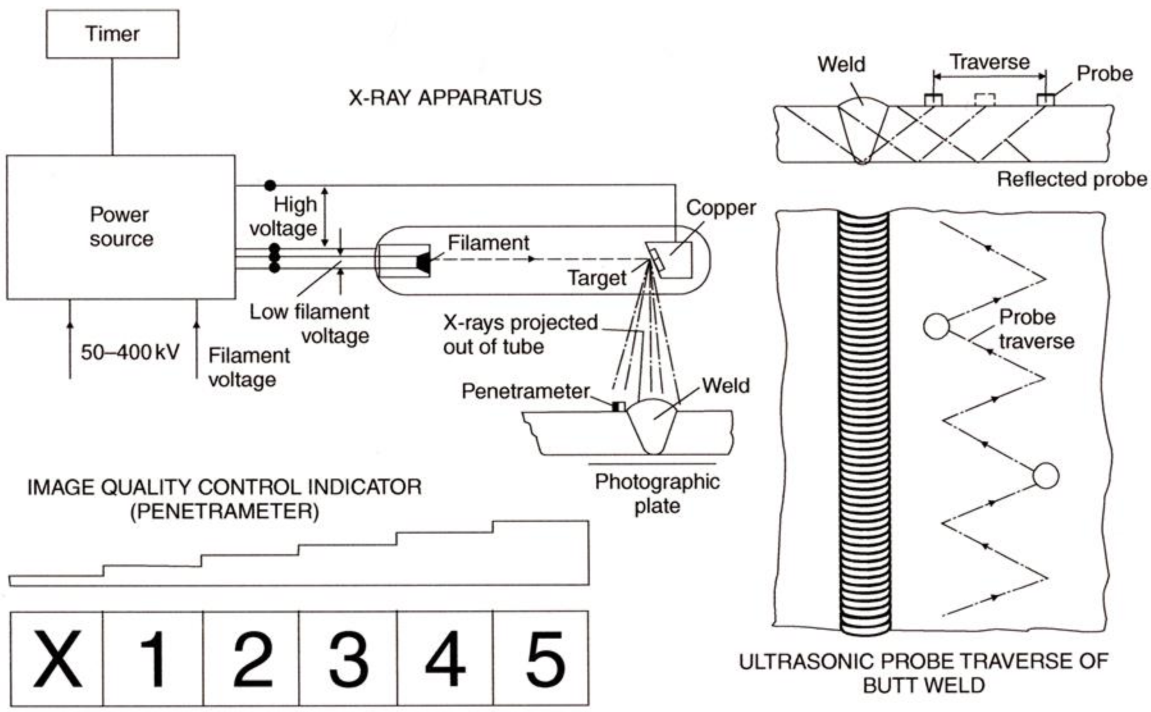


Figure 19. Inspection of Welds

Where gamma-ray devices are used ray emission is produced by decay of a radioactive nucleus, the rate of emission being reduced with time. The radiation given off may be magnetically separated into three parts, a-rays, (3-rays and y-rays, the y-rays being similar to X-rays and of most importance since they are very penetrating, but this also means that heavy shielding is required. Since natural radioactive sources are in short supply, great use is made of artificial radioactive sources, namely isotopes.

To interpret the weld radiograph a large amount of experience is required, and a sound knowledge of the welding process. Radiographs usually carry the image of an 'image quality indicator', which shows the minimum change of thickness revealed by the technique. This image quality indicator may have graded steps of metal, each step being identified on the radiograph so that the minimum step thickness discernible is noted and the sensitivity of the radiograph assessed. This indicator is placed adjacent to the weld prior to taking the radiograph.

Ultrasonic energy is commonly used as a tool for locating defects in welds, and has several advantages over radiography, particularly as no health hazard is involved. The technique is particularly useful for locating fine cracks that are often missed by radiography, particularly where they lie perpendicular to the emission source.

The principle of ultrasonic inspection depends on the fact that pulses of ultrasonic energy are reflected from any surface that they encounter. Ultrasonic waves traveling through a plate may be reflected from the surface of the metal and also from the surfaces of any flaws that exist in the metal. Virtually total reflection occurs at an air-metal interface, and therefore to get the ultrasonic wave into the metal a liquid is placed between the source and metal. The pattern of reflection is revealed on a cathode ray tube, which may be calibrated using a standard reference block. An experienced operator is able to recognize flaws from the cathode ray tube display, and to some extent recognition of defect types is possible. Apart from weld inspection, ultrasonic techniques are valuable for assessing the thickness of structural members.

6.1 Classification Society Weld Tests

Classification societies specify a number of destructive tests that are intended to be used for initial electrode and weld material approval. These tests are carried out to ascertain whether the electrode or wire-flux combination submitted is suitable for shipbuilding purposes in the category specified by the manufacturer.

Tests are made for conventional electrodes, deep penetration electrodes, wire-gas and wire-flux combinations, consumables for electro-slag and electro-gas welding, and consumables for one-sided welding with temporary backing. Tensile, bend, and impact tests are carried out on the deposited weld metal and welded plate specimens. Other tests are made for the composition of the weld metal deposited and possible cracking.

All works where electrodes, wire-flux and wire-gas combinations, consumables for electro-slag and electro-gas welding, and consumables for one-sided welding with temporary backing are produced, and have been initially approved, are subject to annual inspection.

7. Mechanical Testing of Ship Steels

Metals are tested to ensure that their strength, ductility, and toughness are suitable for the function they are required to perform.

Material properties are important to the capability of the structure. The properties outlined below are appropriate in determining the suitability of a material for ship construction.

The strength of the material is its ability to resist deformation. Yield stress and ultimate tensile strength measure the ability to resist forces on the structure and resist plastic deformation.

Hardness of a material describes its ability to resist abrasion. Hardness is important, for example, in bulk carriers where the cargo handling produces abrasive action on the cargo hold structures. Hardness is usually measured on a scale (Rockwell or Brinell), based on test results.

Ductility is the ability of a material to be deformed before it fails.

Brittleness is the opposite of ductility and describes a material that fails under stress because it cannot deform. Softer metals, such as aluminum, are ductile. Hard materials such as cast iron are strong but brittle.

Toughness is the ability of a material to absorb energy.

In comparing the strengths of various metals, stresses and strains are often referred to and require to be defined. Stress is a measure of the ability of a material to transmit a load, and the intensity of stress in the material, which is the load per unit area, is often stated. The load per unit area is simply obtained by dividing the applied load by the cross-sectional area of the material, e.g. if a tensile load of *P* kg is applied to a rod having a cross-sectional area of *A* mm^2, then the tensile stress in the material of the rod is P/A kg/mm^2, see Figure 20.

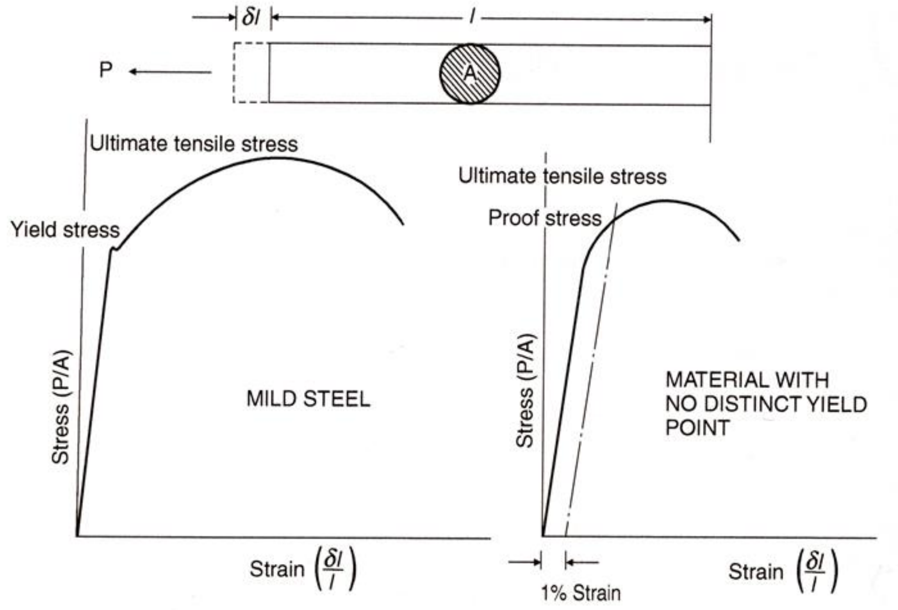


Figure 20. Stress versus Strain Plot for Shipbuilding Materials

Total strain is defined as the total deformation that a body undergoes when subjected to an applied load. The strain is the deformation per unit length or unit volume, e.g. if the tensile load *P* applied to the rod of original length / produces an elongation, or extension, of the rod of amount d/, then the tensile strain to which the material of the rod is subjected is given by the extension per unit length, i.e.

$$\frac{extension}{original\ length} \quad or \quad \frac{dl}{l}$$

It can be shown that the load on the rod may be increased uniformly and the resulting extension will also increase uniformly until a certain load is reached. This indicates that the load is proportional to extension, and hence stress and strain are proportional since the cross-sectional area and original length of the rod remain constant. For most metals this direct proportionality holds until what is known as the 'elastic limit' is reached. The metal behaves elastically to this point, the rod for example returning to its original length if the load is removed before the 'elastic limit' is reached.

If a mild steel bar is placed in a testing machine and the extensions are recorded for uniformly increasing loads, a graph of load against extension, or stress against strain, may be plotted as in Figure 20. This shows the straight-line relationship (i.e. direct proportionality) between stress and strain up to the elastic limit.

Since stress is directly proportional to strain, the stress is equal to a constant, which is in fact the slope of the straight-line part of the graph, and is given by:

A constant = stress ÷ strain

This constant is referred to as the modulus of elasticity for the metal (Young's modulus) and is denoted E (for mild steel its value is approximately 21,100 kg/mm^2 or 21.1 tonnes/mm^2).

The yield stress for a metal corresponds to the stress at the 'yield point'; that is, the point at which the metal no longer behaves elastically. Ultimate tensile stress is the maximum load to which the metal is subjected, divided by the original cross-sectional area. Beyond the yield point the metal behaves plastically, which means that the metal deforms at a greater, unproportional, rate when the yield stress is exceeded, and will not return to its original dimensions on removal of the load. It becomes deformed or is often said to be permanently 'set'.

Many metals do not have a clearly defined yield point, for example aluminum, having a stress-strain curve over its lower range that is a straight line becoming gradually curved without any sharp transformation on yielding, as shown by mild steel (see Figure 7.1). A 'proof stress' is quoted for the material and this may be obtained by setting off on the base some percentage of the strain, say 0.2%, and drawing a line parallel to the straight portion of the curve. The intersection of this line with the actual stress-strain curve marks the proof stress.

It is worth noting at this stage that the ship's structure is designed for working stresses that are within the elastic range and much lower than the ultimate tensile strength of the material to allow a reasonable factor of safety.

7.1 Classification Society Tests for Hull Materials

Both mild steel and higher tensile steel plates and sections built into a ship are to be produced at works approved by the appropriate classification society. During production an analysis of the material is required and so are prescribed tests of the rolled metal. Similar analyses and tests are required by the classification societies for steel forgings and steel castings, in order to maintain an approved quality.

Destructive tests are made on specimens obtained from the same product as the finished material in accordance with the societies' requirements, which may be found in the appropriate rules. These tests usually take the form of a tensile test and impact test.

7.2 Tensile Test

The basic principle of this test has already been above, a specimen of given dimensions being subject to an axial pull and a minimum specified yield stress, ultimate tensile stress, and elongation must be obtained. In order to make comparisons between the elongation of tensile test pieces of the same material the test pieces must have the same proportions of sectional area and gage length. Therefore, a standard gauge length equal to 5.65 times the square root of the cross-sectional area, which is equivalent to a gauge length of five times the diameter, is adopted by the major classification societies.

7.3 Impact Test

There are several forms of impact test, but the Charpy V-notch test or Charpy U-notch test is commonly specified and therefore described in this text. The object of the impact test is to determine the toughness of the material; that is, its ability to resists crack development and withstand fracture under shock loading. In Figure 21 the principle of the Charpy test machine is illustrated, along with the standard test specimen for a Charpy V-notch test. This specimen is placed on an anvil and the pendulum is allowed to swing so that the striker hits the specimen opposite the notch and fractures it. Energy absorbed in fracturing the specimen is automatically recorded by the machine. Basically, making allowances for friction, the energy absorbed in fracturing the specimen is the difference between the potential energy the pendulum possesses before being released, and that which it attains in swinging past the vertical after fracturing the specimen. A specified average impact energy for the specimens tested must be obtained at the specified test temperature, fracture energy being dependent on temperature.

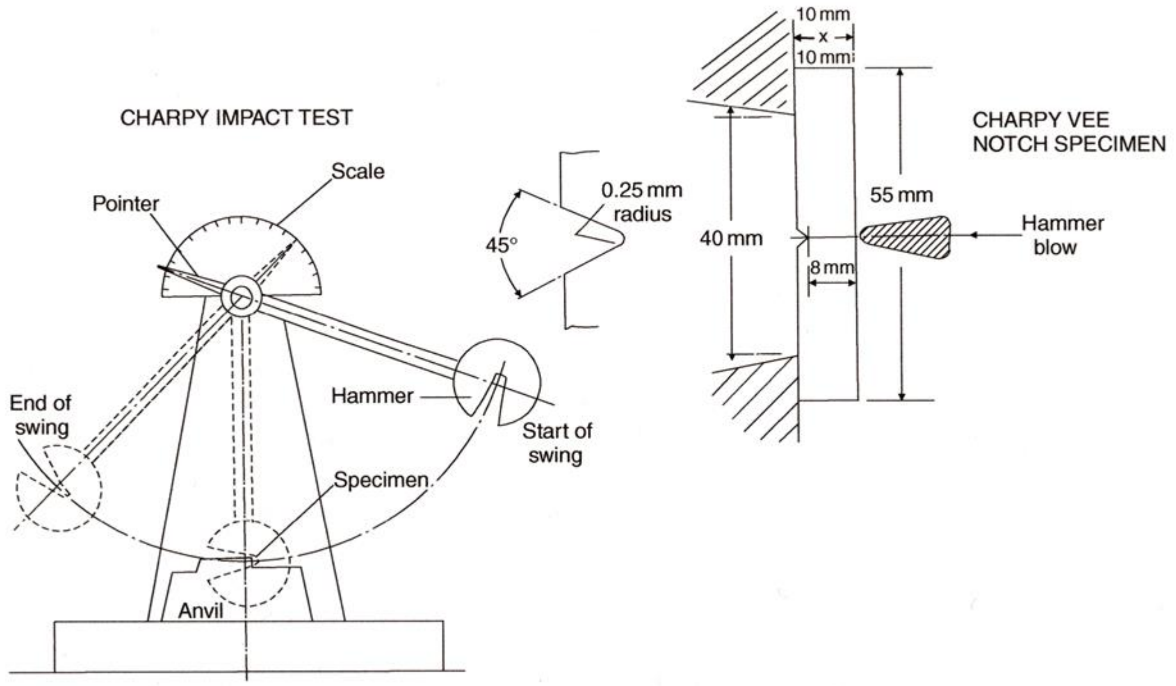


Figure 21. Charpy Impact Test

7.4 Aluminium Alloys Tests

Aluminum alloy plate and section material is subject to specified tensile tests. Bar material for aluminum alloy rivets is subject to a tensile test and also a dump test. The latter test requires compression of the bar until its diameter is increased to 1.6 times the original diameter without cracking occurring. Selected manufactured rivets are also subjected to the same dump test.

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INDEX (note pages - in black, slide nos. - in blue; 'a', 'b' & 'c' refer to slide sections)

W

Part 2: Processing, Construction Methods and Testing of Steel Products Used in Shipbuilding

Section a	**Ship Building: Materials Processing**
Section b	**Shipyard Practices: Material, Cutting, Bending and Welding**
Section c	**Weld Evaluation, Non Destructive Testing (NDT) and Mechanical Testing Techniques**

Professional Qualification

in Marine Corrosion

Presented by **Mike Lewus**

Module 2

(section a)

Ship Building: Materials Processing

Module 2 (section a)

Summary

- **World Production**
  - Trends in ship building
  - Growth of commodity types
- **Steel Processes for Ship Building**
  - From Ore to Blast Furnace and Steel Processing
  - Processing Plate and Sections
  - Sections used in shipbuilding
  - Thermomechanical controlled rolling (TMCP)
  - LR high strength steels
- **Aluminium Production**
- **Ship Assembly**
  - Shipyard process flow
  - Subassemblies and blocks
  - Constructing a cargo vessel

Module 2 (section a)

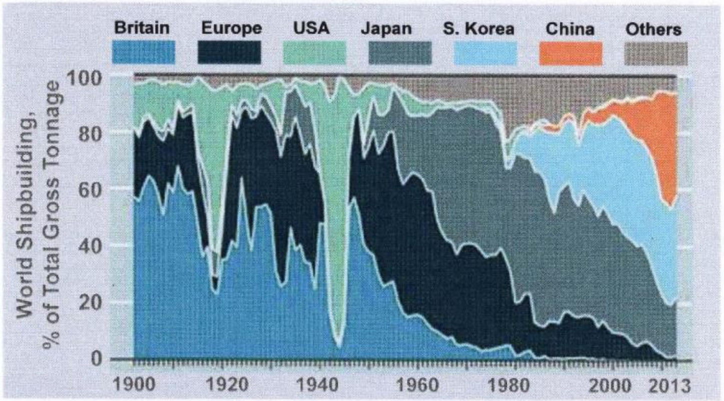
Historic Perspective

- **100 Years of Shipbuilding**
  - Britain once the biggest shipbuilding nation – first half of 20th century
  - USA ramped up production during world war years
  - Europe a sizeable player in commercial ship building market, but activities tailed off throughout the second half of the 20th century
  - Japan a dominant shipbuilding nation post WW2
  - Rise of S. Korea and China in 1980 and post 2000, respectively
    - A significant factor in the case of China is rapid economic growth in addition to heavily subsidized shipyards and steel industry and cheap labour
  - USA a minor player in current shipbuilding market – annual output accounts for <1% for new construction

Module 2 (section a)

A Hundred Years of Ship Building

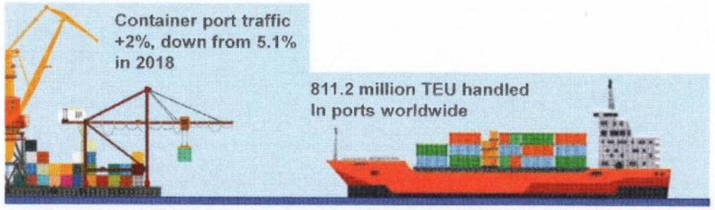
- 100 years of ship building



Module 2 (section a)

Recent History: Maritime Trade

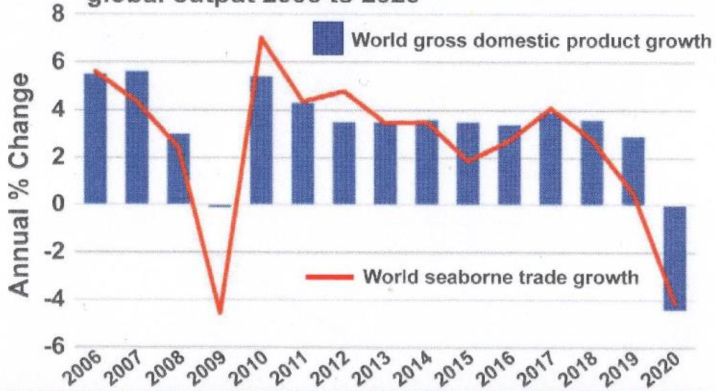
- In 2019, trade tensions and policy uncertainty undermined growth in maritime trade
  - Impact comparable to impact of 2007/08 financial crash
  - Covid added to problems with supply chain, shipping and port activities
- On a brighter note – International maritime trade projected to recover and expand by 4.8% in 2021



Module 2 (section a)

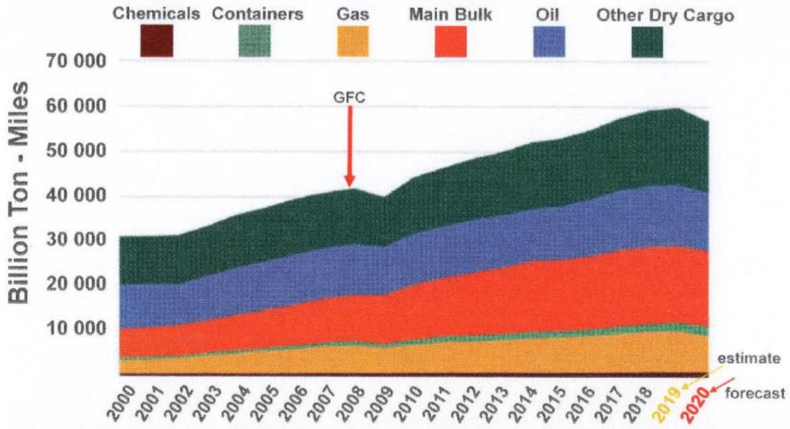
Recent History: Maritime Trade

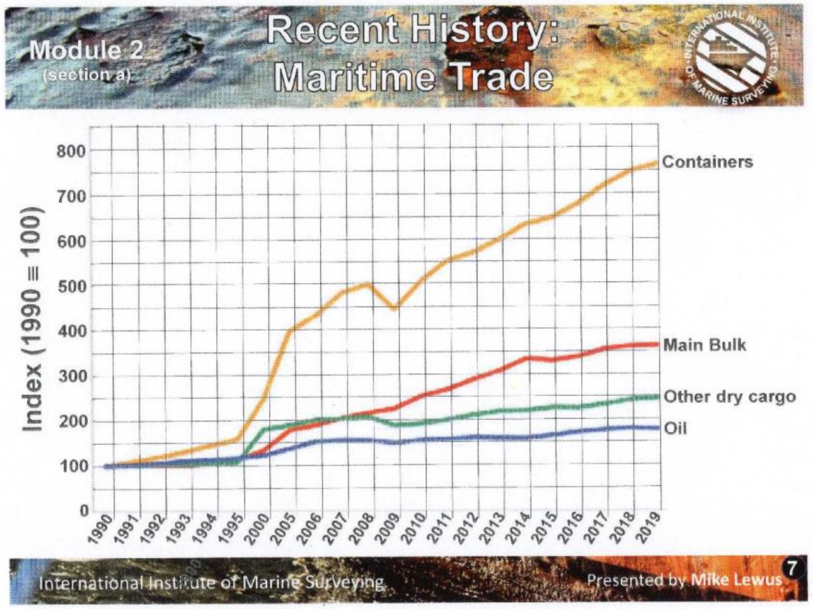
- Development of international marine trade and global output 2006 to 2020



Module 2 (section a)

Recent History: Maritime Trade




Module 2
(section a)
Recent History:
Maritime Trade
Containers
Main Bulk
Other dry cargo
Oil
Index (1990 = 100)
800
700
600
500
400
300
200
100
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1990 1991 1992 1993 1994 1995 2000 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
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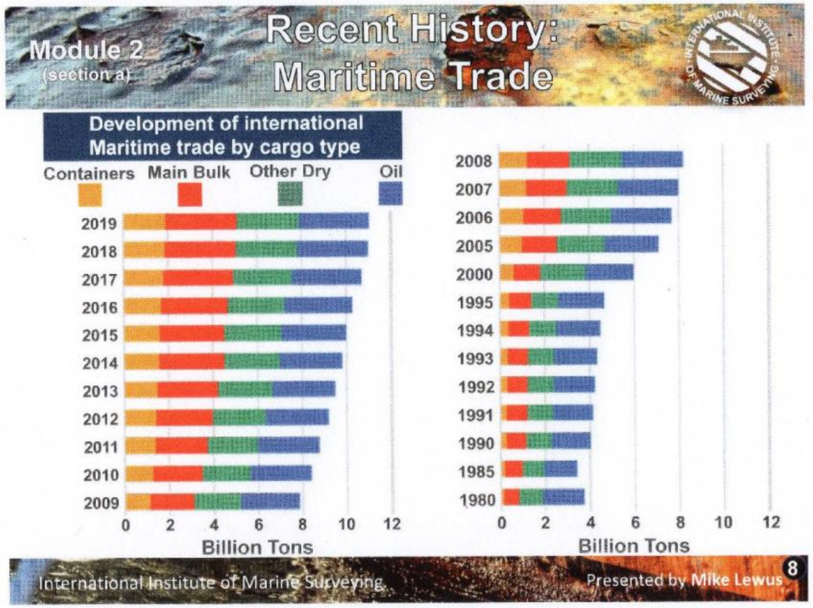
7


Module 2
(section a)
Recent History:
Maritime Trade
Development of international
Maritime trade by cargo type
Containers
Main Bulk
Other Dry
Oil
2019
2018
2017
2016
2015
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Billion Tons
0 2 4 6 8 10 12
Billion Tons
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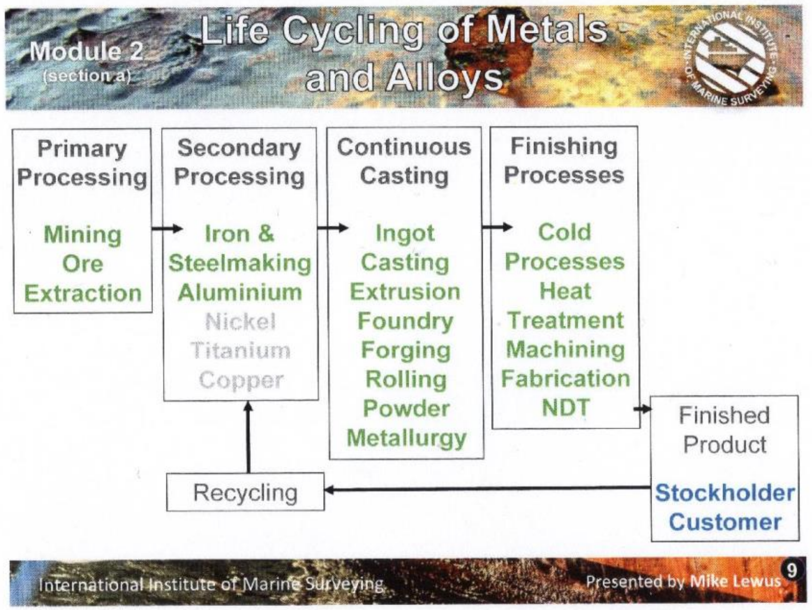
8


Module 2
(section a)
Life Cycling of Metals
and Alloys
Primary Processing
Mining
Ore
Extraction
Secondary Processing
Iron &
Steelmaking
Aluminium
Nickel
Titanium
Copper
Continuous Casting
Ingot
Casting
Extrusion
Foundry
Forging
Rolling
Powder
Metallurgy
Finishing Processes
Cold
Processes
Heat
Treatment
Machining
Fabrication
NDT
Finished
Product
Stockholder
Customer
Recycling
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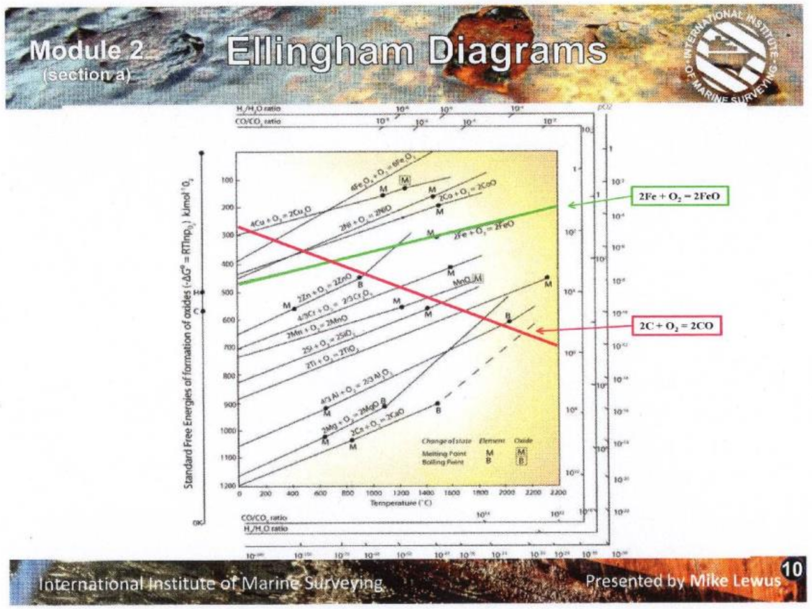
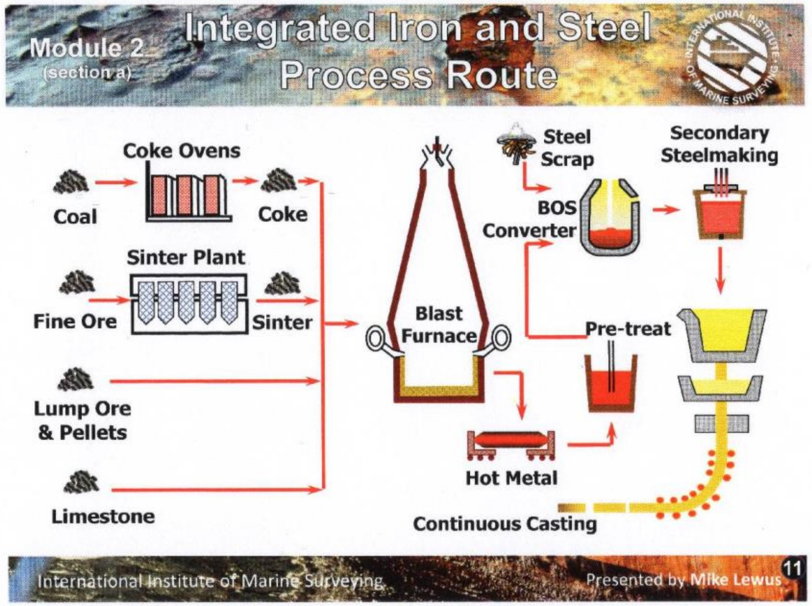
9


Module 2
(section a)
Ellingham Diagrams
2Fe + O₂ = 2FeO
2C + O₂ = 2CO
Temperature (°C)
International Institute of Marine Surveying
Presented by Mike Lewus
10


Module 2
(section a)
Integrated Iron and Steel Process Route
Coke Ovens
Coal
Coke
Sinter Plant
Fine Ore
Sinter
Lump Ore & Pellets
Limestone
Blast Furnace
Steel Scrap
BOS Converter
Secondary Steelmaking
Pre-treat
Hot Metal
Continuous Casting
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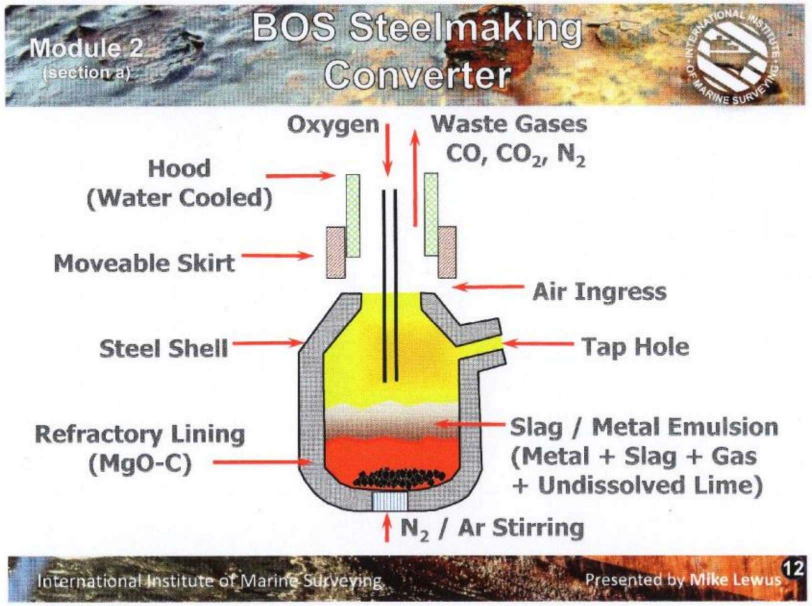
11


Module 2
(section a)
BOS Steelmaking Converter
Oxygen
Waste Gases
CO, CO_2, N_2
Hood
(Water Cooled)
Moveable Skirt
Air Ingress
Steel Shell
Tap Hole
Refractory Lining
(MgO-C)
Slag / Metal Emulsion
(Metal + Slag + Gas
+ Undissolved Lime)
N_2 / Ar Stirring
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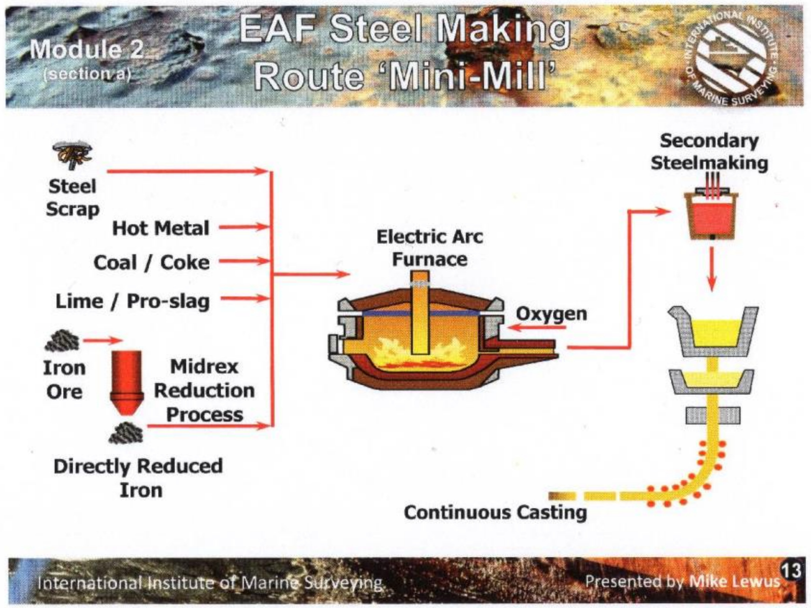
12


Module 2
(section a)
EAF Steel Making Route 'Mini-Mill'
Steel Scrap
Hot Metal
Coal / Coke
Lime / Pro-slag
Iron Ore
Midrex Reduction Process
Directly Reduced Iron
Electric Arc Furnace
Oxygen
Secondary Steelmaking
Continuous Casting
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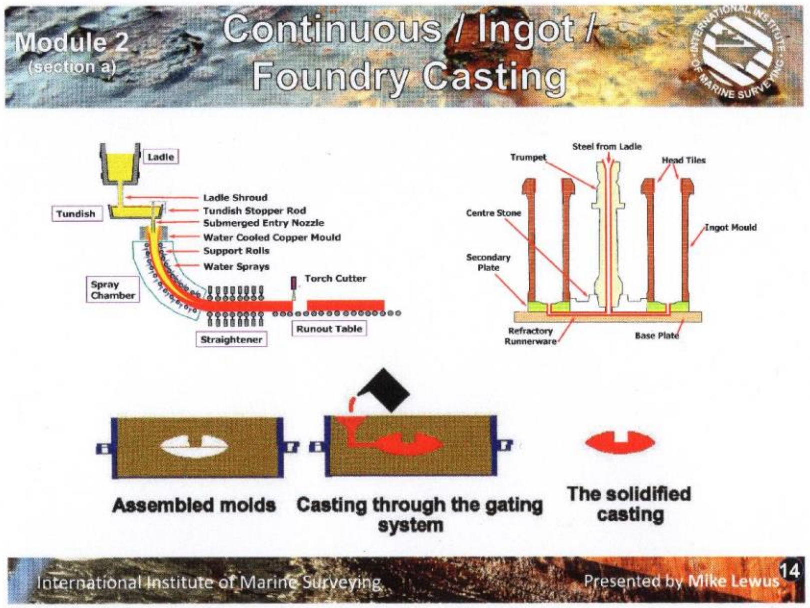
13


Module 2
(section a)
Continuous / Ingot / Foundry Casting
Ladle
Tundish
Ladle Shroud
Tundish Stopper Rod
Submerged Entry Nozzle
Water Cooled Copper Mould
Support Rolls
Water Sprays
Spray Chamber
Torch Cutter
Straightener
Runout Table
Steel from Ladle
Trumpet
Head Tiles
Centre Stone
Ingot Mould
Secondary Plate
Refractory Runnerware
Base Plate
Assembled molds
Casting through the gating system
The solidified casting
International Institute of Marine Surveying
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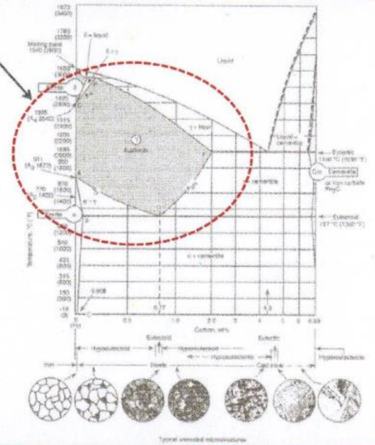
14

Module 2 (section a)

Materials: Plate and Sections

- Eutectoid steels 0.77wt. % carbon
- <0.3wt. % C: low carbon steels
- 0.3-0.6wt.% C: medium carbon steels)
- Hypoeutectoid steels <0.77wt. % carbon
- Hypereutectoid steels > 0.77wt. % carbon

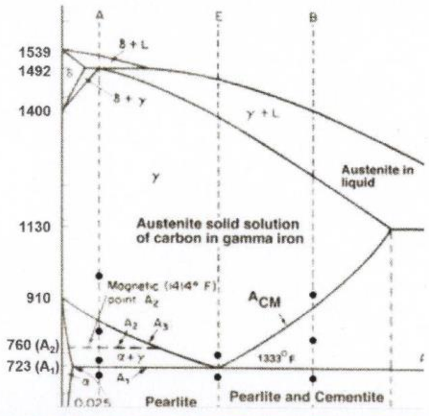
see next slide



Module 2 (section a)

Materials: Fe-Fe_3C Phase Diagram

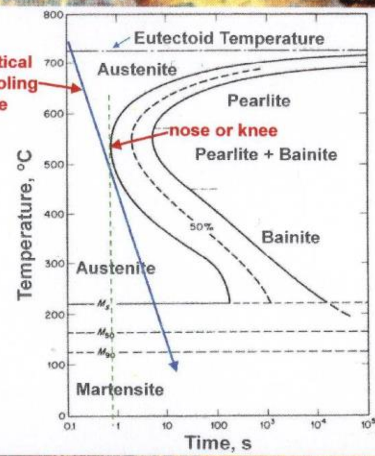
- A_1: temperature at which austenite begins to form during heating
- A_2: temperature at which α-iron changes to non magnetic β-iron; not important for heat treatment
- A_3: temperature at which transformation of α-iron to austenite is completed during heating
- A_{cm}: temperature at which the solution of cementite in austenite is completed during heating



Module 2 (section a)

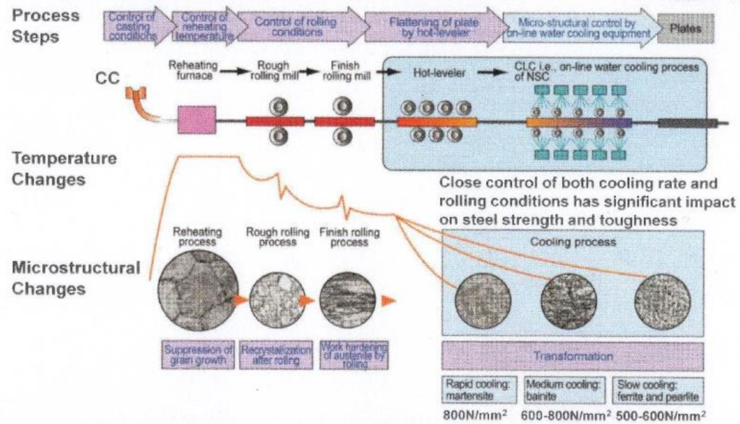
Materials: TTT Diagram

- Isothermal Time, Temperature, Transformation (TTT) diagram for AISI 1080 Steel containing 0.79wt.% carbon



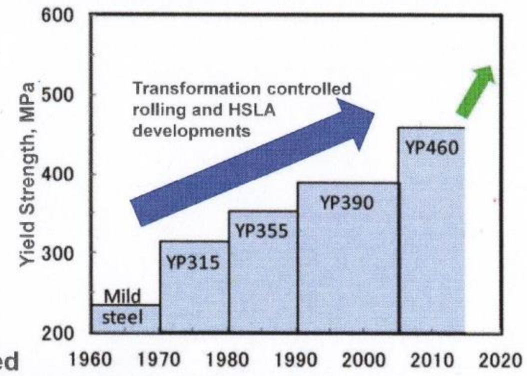
Module 2 (section a)

Thermo Mechanical Controlled Rolling (TMCP)

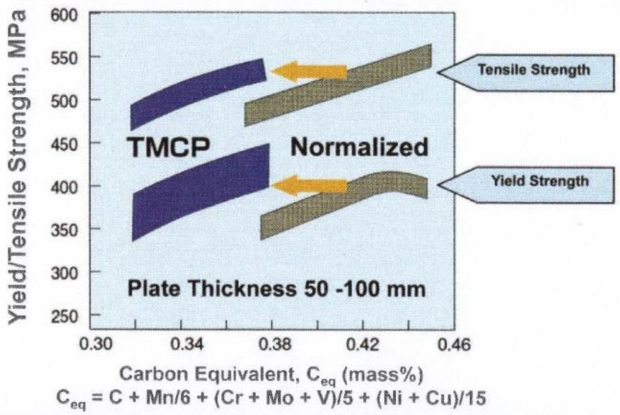


Module 2 (section a) Thermo Mechanical Controlled Rolling (TMCP)

- Manufacturing process: Controlled rolling & accelerated cooling are supplemented by reheating at a low temperature or addition of micro-alloying elements (MAEs) such as Titanium or Niobium in order to maximize the grain refining effects of controlled rolling and accelerated cooling



Module 2 (section a) Thermo Mechanical Controlled Rolling (TMCP)



Module 2 (section a) LR Ship Grade Steels A, B, D and E

Slide taken from module 7b

Grade	Plate t, mm	Deoxidation Treatment	Composition, wt. %[5] C	Mn	Si	S	P	Al
A	≤ 50	Any[1]	0.21 max[2]	2.5 x C	0.5 max	0.035 max	0.035 max	
	> 50	Killed						
B	≤ 50	Any[*]	0.21 max	0.80 min[3]	0.35 max	0.035 max	0.035 max	
	> 50	Killed						
D	≤ 25	Killed	0.21 max	0.60 min	0.10-0.35	0.035 max	0.035 max	0.15[4]
	> 25	Killed + Grain Refine with Al						
E		Killed + Grain Refine with Al	0.18 max	0.70 min	0.10-0.35	0.035 max	0.035 max	0.15[4]

NB Carbon + 1/6 Manganese Content not to exceed 0.6wt. %

Module 2 (section a) LR Ship Grade Steels A, B, D and E

Slide taken from module 7b

- Mechanical Properties for Acceptance Purposes

Grades	Yield Stress, (MPa)	Tensile Strength (MPa)	Elongation on $5.65\sqrt{S_0}$% (min)	Charpy V-Notch Tests: Thickness, mm	Average Energy, J (min.) Long.	Trans.
A, B, D, E	235	400-520	22	≤ 50	27	20
				50 < t ≤ 70	34	24
				70 < t ≤ 100	41	27

Module 2 (section a)

LR Ship Steel Grades A, B, D and E

- Note 1: Grade A, rimmed steel may only be accepted for sections up to a maximum thickness of 12.5mm, provided that it is stated on test certificates or shipping statements to be rimmed steel
- The maximum carbon content for Grade A may be increased to 0.23wt. % for sections
- Where Grade B is impact tested the minimum Manganese content may be reduced to 0.60wt. %
- The total aluminium content may be determined instead of the acid soluble content. In such cases the total aluminium content is to be less than 0.020wt. %
- Where additions of any other elements are made as part of the steel-making practice, the content is to be recorded

Module 2 (section a)

Ship Steel Grades: Material Definitions (1)

- Killed
  - Refer to steels that have been deoxidized usually with aluminium and/or silicon. Killed steels have lower porosity levels than semi-killed or rimmed steel
- Rimmed
  - Refer to steels that have not had deoxidizing agents added, such steels are characterised by marked differences in chemical composition across the section and from top to bottom of an ingot; outer rim is lower in carbon, phosphorus and sulphur than the average R
  - Most rimmed steels have been largely replaced by killed steels
- Acid Soluble Aluminium (Al)
  - A limit is placed on acid soluble aluminium as increased amounts can result in presence of Al_2O_3 inclusions which can reduce fatigue life and clog nozzles during

Module 2 (section a)

Ship Steel Grades: Material Definitions (2)

- Normalised
  - Normalisation is an annealing process designed to produce a steel with a uniform, fine-grained structure and to avoid excess softening in steel. It involves heating the steel to 20–50°C above its upper critical point (A_3 temperature), soaking it for a short period at that temperature and then allowing it to cool in air
- Normalising Rolled
  - Involves two process steps; forming at high temperatures to change shape followed by rolling at lower temperature to minimise grain growth
- Thermo Mechanical Controlled Rolling (TM or TMCR)
  - Involves use of successive temperatures starting at a conventional temperature ~1200°C, but final hot roll passes are carried out at temperatures below the A_3 temperature i.e. 775°C. Plastic deformation at these lower temperatures promotes finer recrystallised grain size and hence, higher strength
  - Variables in controlled rolling include material composition, structure, deformation levels, temperatures at various stages, and cool-down conditions

Module 2 (section a)

LR High Strength Ship Steel Grades

Slide taken from module 7b

Grades	Yield Stress N/mm² (Pa x 10⁻⁶)	Tensile Strength N/mm² (Pa x 10⁻⁶)	Elongation on $5.65\sqrt{S_o}$ % (min)	Charpy V-Notch Tests: Average Energy, Joules (minimum)					
				t ≤ 50mm		50 < t ≤ 70mm		70 < t ≤ 100mm	
				Long.	Trans.	Long.	Trans.	Long.	Trans.
AH27S, DH27S, EH27S, FH27S	265	400-530	22	27	20	34	24	41	27
AH32, DH32, EH32, FH32	315	440-570	22	31	22	38	26	46	31
AH36, DH36, EH36, FH36	355	490-630	21	34	24	41	27	50	34
AH40, DH40, EH40, FH40	390	510-650	20	39	26	46	31	55	37
EH47	460	570-720	17	----	----	53	35	Note 1	Note 5

Note 1. Where the thickness of grade EH40 materials exceed 85mm the material is to achieve a crack arrest temperature (CAT) below -10°C. The CAT may be measured directly from large scale isothermal tests or be estimated from small scale tests that determine the Nil Ductility Temperature using,

$$CAT = (NDTT + 10) + \left[\left(\frac{ln\sigma}{0.046}\right) - 105\right] + \left[153\left(B-5\right)^{\frac{1}{13}} - 190\right]$$

Where CAT = crack arrest temp. in °C, NDTT = nil ductility test temperature in °C
σ = 2/3 of minimum specified yield strength in N/mm², B = plate thickness in mm

Materials: Long and Flat Products

Long Products

CONCAST BLOOM >180mm sq.

CONCAST BILLET 100-180mm sq

- *NARROW SLABS* <500mm wide → *HOT ROLLED STRIP*
- *LARGE ROUNDS* >150mm dia. → *SEAMLESS TUBES*
- *SECTIONS* Channels, Beams, Special Sections
- *RAILS*
- *BILLETS* 50-150mm sq → *BARS, RODS & LIGHT SECTIONS*

Flat Products

CONCAST SLAB >200mm thick x 2000mm wide

- *HEAVY SECTIONS* → Universal Beams 1016x305mm
- *PLATES* - Up to 3000mm wide in flat lengths → *WELDED TUBE*
- *HOT ROLLED STRIP* 450-2000mm wide in coils → *COLD ROLLED STRIP* up to 1600mm wide

Materials: Rolling

- The Purpose of Rolling
  - To transform cast metal into finished product capable of meeting dimensional and property requirements

Slabs
Blooms
Billets

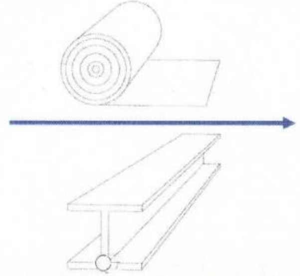
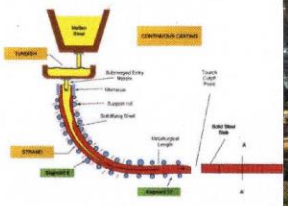


Plate
Strip
Beams & Columns
Sections
Rails
Rod and Bar
Pipe and Tube

Materials: Plate Rolling Mill

- Plate Rolling Mill



Materials: Rolling

- Benefits of Hot Rolling
  - Achieve large shape changes, requiring plastic flow, with reduced loading on equipment and reduced energy consumption
  - Workpiece can undergo large shape changes without cracking
  - Improved metallurgical structure and mechanical properties
  - Elimination/Reduction of blow holes and porosity
  - Reduction of segregation through increased chemical diffusion at high temperature

Module 2 (section a)

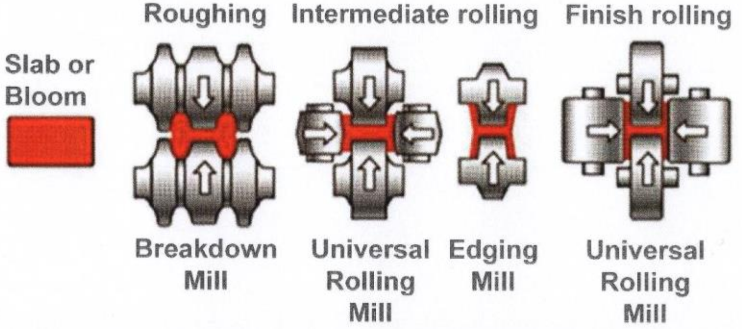
Materials: Rolling

- Disadvantages of Hot Rolling
  - Surface reactions
    - Yield losses due to oxidation
  - Surface Quality
    - Rolling in scale
  - Effects of expansion and contraction on dimensional tolerances
  - Property inhomogeneities due to variable deformation at surface and centre
  - Difficulty measuring during the process
  - General handling of hot metal
  - Need for a controlled cooling process

Module 2 (section a)

Materials: Sections

- Universal beam mills for rolling H sections



Module 2 (section a)

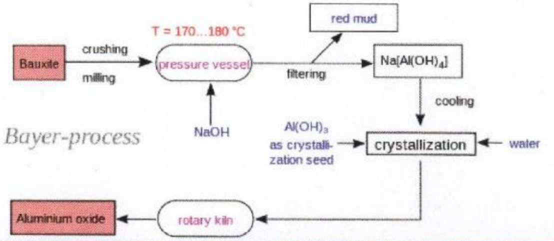
Aluminium Production

- Three steps involved in aluminium production
  - Step 1: Bauxites (aluminium ores) are mined
  - Step 2: Bauxites converted to alumina (aluminium oxide)
  - Step 3: Pure aluminium produced by electrolytic reduction
  - Primary aluminium remelted and alloyed
- Advantages of aluminium alloys
  - Light weight, fuel efficient
  - Excellent corrosion resistance (5000 series)
  - Few standard sections but relatively inexpensive to extrude in a variety of section shapes
- Disadvantages of aluminium alloys (c.f. steel)
  - Lower strength and fire resistance
  - Risk of galvanic corrosion when joined to steel

Module 2 (section a)

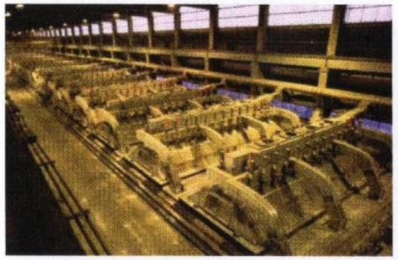
Aluminium Production

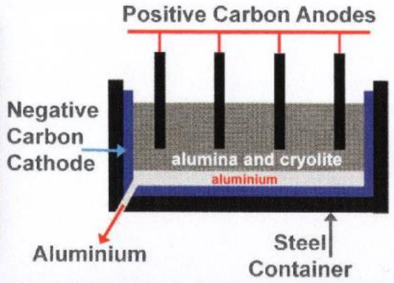
- Step 2: Bayer Process:
  Bauxite is washed with hot sodium hydroxide at 175°C which converts aluminium oxide to sodium aluminate, $2NaAl(OH)_4$.
  On cooling, aluminium hydroxide precipitates as a white fluffy solid:
  i) $Al_2O_3 + 2NaOH + 3H_2O \rightarrow 2NaAl(OH)_4$
  ii) $NaAl(OH)_4 \rightarrow Al(OH)_3 + NaOH$
  iii) $2Al(OH)_3 + 3H_2O$ (on heating to 980°C)



Module 2 (section a) — Aluminium Production

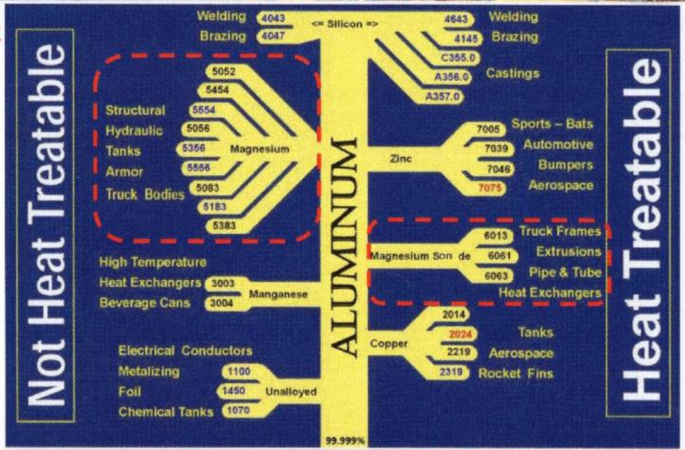
- **Step 3: Hall-Heroult Process,**
  Aluminium is more tightly held to the oxygen than iron is, so a more powerful electrolytic process is required to separate aluminium metal from alumina





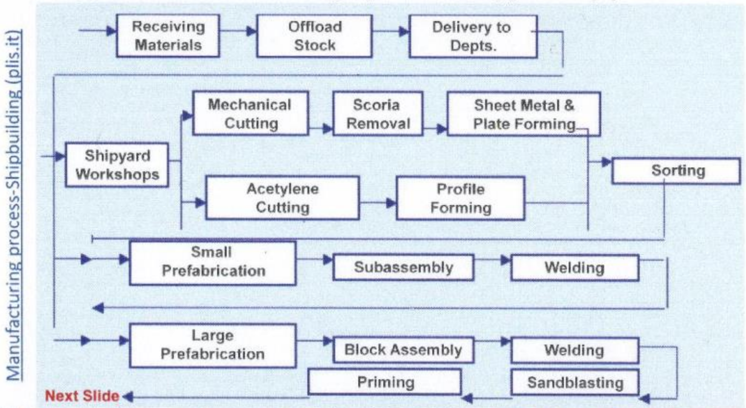
Module 2 (section a) — Aluminium Alloy Designations

From Module 7



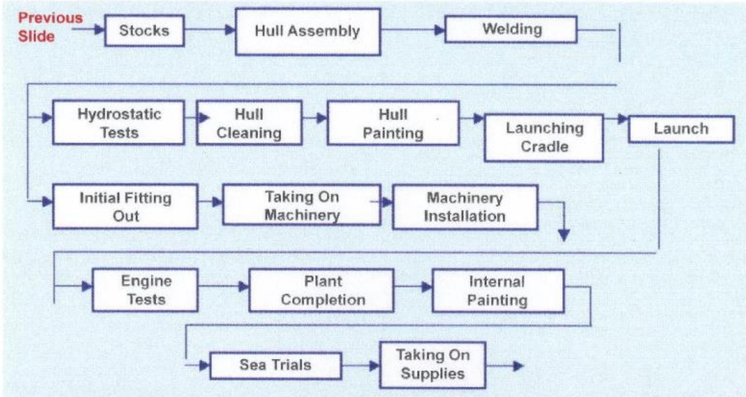
Module 2 (section a) — Shipbuilding: Process Steps and Flow

- **Typical manufacturing cycle in shipyards (1)**



Module 2 (section a) — Shipbuilding: Process Steps and Flow

- **Typical manufacturing cycle in shipyards (1)**



Module 2 (section a)

Ship Assemby

- There is not really a typical ship!
- Assembly is the process in which small steel parts, or larger structures, are combined into larger units
- Typically the build sequence starts from bottom to top and from aft to forward in the following sequence
  - Double bottom t tanks
  - Transverse bulkheads
  - Side shell with frames
  - Wing tanks
  - Deck units with girder
  - Accommodation modules
  - Deck fittings
  - Wiring
  - Final Painting

Module 2 (section a)

Ship Assemby

- As an illustration, consider a Panamax bulk carrier with ~ 10,000 tonnes of steel, a length of ~250m and a breadth of 32m, then the following assemblies might be described
  - Minor assembly:
    Brackets, intercostal floors or girders, bulwarks, 2D assemblies with 5 parts and a max. size of 2 x 5m, weight < 2 tonne
  - Subassembly:
    A flat curved panel, 'egg box' structure up to 12 x 12m, weight < 20tonne
  - Unit assembly
    A structure erected in the building dock, typically 1-2 panels with associated internal structure, weight <60 tonne

Module 2 (section a)

Ship Assemby

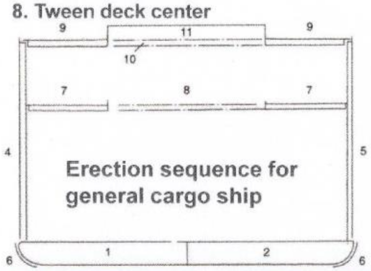
- Block
  An assembly of two or more units into a bottom or side block, weighing up to 200 tonne
- In most instances 2-D subassemblies will be built into 3D unit assemblies
- In erecting the ship units it is important to employ the correct welding sequences. These are arranged to avoid excessive 'locked-in' stresses and overlapping frames, longitudinals and stiffeners – these may be left unwelded across unit seams and butts so final adjustments and checks can be made before completion

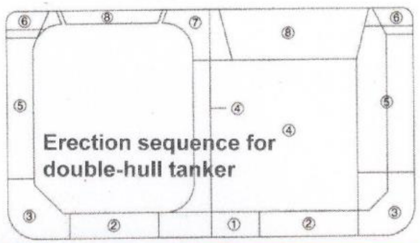
Module 2 (section a)

Ship Assemby

1. Double-bottom port
2. Double-bottom stbd.
3. Trans. bulkhead
4. Side shell
5. Side shell
6. Bilge plates
7. Tween deck sides
8. Tween deck center
9. Main deck sides
10. Main deck center
11. Main deck hatch

1. Double-bottom center unit
2. Double-bottom wing unit
3. Bilge unit
4. Longi/trans, bulkhead unit
5. Double-hull side unit
6. Deck/side unit
7. Center deck unit
8. Deck units

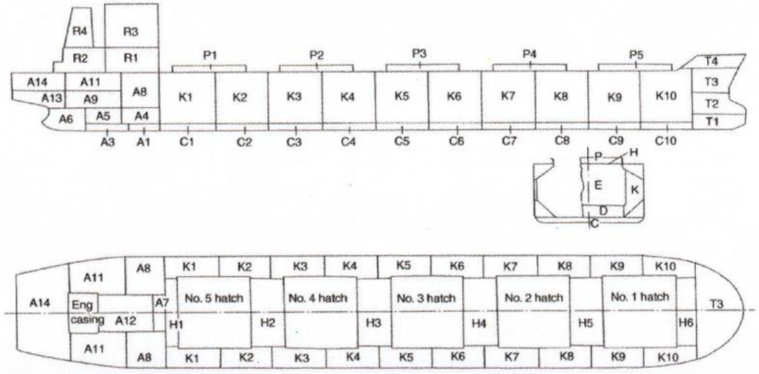




Module 2
(section a)

Ship Assemby

- **Typical block erection for a single-hull bulk carrier**



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Professional Qualification
in Marine Corrosion

Presented by Mike Lewus

Module 2
(section b)

Shipyard Practices: Material, Cutting, Bending and Welding

Module 2 (section b) Summary

- Shipyard Practices
  - Stowage of plate and rolled sections
  - Surface preparation
  - Mill scale removal
- Cutting
  - Gas cutting
  - Plasma arc cutting
  - Laser and water jet methods
- Forming Methods
  - Roll bending, Hydraulic Pressing etc.
- Welding Methods
  - Electric arc processes
    - Slag shielded
    - Inert gas shielded

Module 2 (section b) Shipyard Practices: Material Storage

- Stowage of plate
  - Once steel plates are procured they are kept in a stockyard
  - Plates of different thicknesses and grades are available in standard dimensions (4, 6, 8, 10 meters etc.). There are two positions of stowing plates - vertical stowage and horizontal stowage
  - Vertical stowage of plates is preferred because it enables mill scale to fall of naturally due to gravity, reducing time required for blasting in later stages.
    - Vertical stowage also has a smaller footprint than horizontal stowage and picking individual plates by crane is easier
  - Shipyards with multiple projects practice methods of plate stowage scheduling – marking and storing in-sync with work schedules

Module 2 (section b)

Shipyard Practices: Material Storage

- Stowage of rolled sections
  - Rolled sections (Flat bars, Tee sections, Bulb bars, Equal Angles, Unequal angles) are used as stiffening members for shell and deck plating. They are ordered by the tendering department based on the scantlings provided by the structural drawings of every project
  - Rolled sections are stored in the stockyard, mostly in the same stockyard in which steel plates are stored

Module 2 (section b)

Shipyard Practices: Surface Preparation

- Surface preparation of plate
  - Two major process applied to plate, straightening and removal of residual stress
    - Straightening – use multiple rolls
    - Removal of residual stress – heat to stress relieve

Module 2 (section b)

Shipyard Practices: Millscale Removal

- Residual mill scale needs to be removed because,
  - It does not contribute to strength of the plate.
  - If plates are painted without the removal of mill scale, adhesion of paint will be poor
  - It promotes corrosion when in contact with seawater
  - Presence of mill scale contaminates the weld, reducing weld quality
  - mill scale can be an advantage when steel plates are stored for long periods, the oxide layer can act as a barrier to further corrosion
  - 3 main removal methods
    - Natural Removal: Vertical stacking of plates results is mill scale loss, but this method is not reliable because removal is non uniform

Module 2 (section b)

Shipyard Practices: Millscale Removal

- 3 main removal methods…. continued
  - Flame Treatment: The steel plate is heated to a certain temperature. Since the coefficient of expansion of mill scale is different from that of steel, heating results in removal of mill scale
  - Shot Blasting: In this process, the plate is passed through a chamber within which, steel shots are blasted at high velocity on the steel plate. Each shot incident on the plate scrapes away mill scale

Module 2 (section b)

Shipyard Practices: Priming

- 3 main removal methods…. continued
  - After mill scale removal, the plate is cleaned and passed into a chamber in which a primer is sprayed on both surfaces
  - The primer applied is usually a zinc-rich coating, and its formulation is chosen such that it does not interfere with the welding and bending of plates
  - After the plate is primed, it is immediately passed on to the drying chamber, where hot air dries the surface and prevents moisture from interfering with the process

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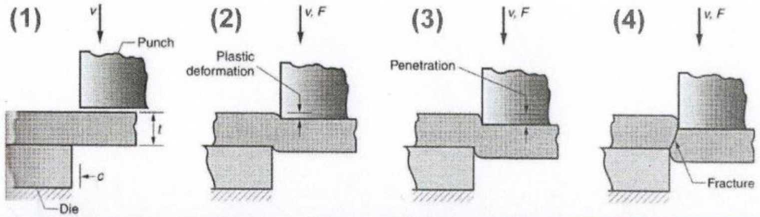
Module 2 (section b)

Mechanical Cutting: Shearing

- Shearing: Difference between blanking and punching
  (1) Punch (upper cutting edge) makes contact with work
  (2) Punch pushes into work causing plastic deformation
  (3) Punch compresses and penetrates into work causing a smooth cut surface
  (4) Fracture is initiated at opposite cutting edgs that separate the sheet



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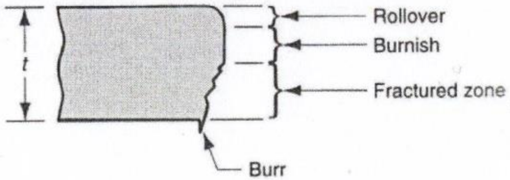
Module 2 (section b)

Mechanical Cutting: Shearing

- Characteristics of a sheared edge



- Rollover: depression made by punch
- Burnish: smooth region caused by penetration of punch into the work material
- Fracture Zone: a relatively rough surface where downward movement of punch caused fracture
- Burr: a sharp corner on the edge caused by metal elongation during final separation

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Module 2 (section b)

Mechanical Cutting: Shearing

- Variation in clearance allowance with material group

Metal Group	A_c
1100S and 5052S Aluminium Alloys, All Tempers	0.045
2024ST and 6061ST Aluminium Alloys; Brass, All Tempers; Cold-Rolled Steel, Stainless Steel	0.060
Cold-Rolled Steel, Half-Hard; Stainless Steel, Half and Full Hard	0.075

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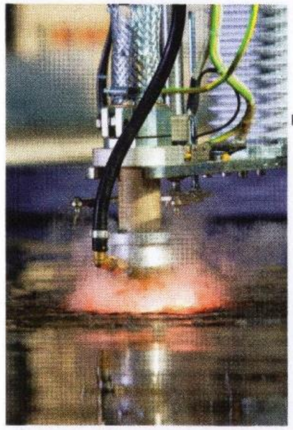
Module 2 (section b)

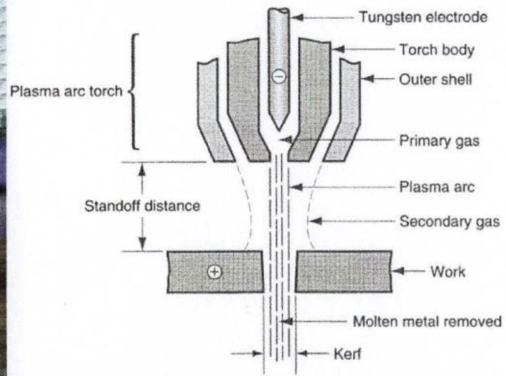
Plasma Cutting

- Plasma Cutting Characteristics
  - A process used to cut steel and other metals of different thickness (sometimes other materials)
  - Uses a gas (oxygen, air, inert and others dependant on material) blown at high speed out of a nozzle
  - An arc is struck between an electrode and the material being cut, the arc passing through the gas blown from nozzle turning some of the gas into a plasma
  - The plasma is hot enough to melt any metal being cut (>20000°C, quite hot ☺)

Module 2 (section b)

Plasma Cutting

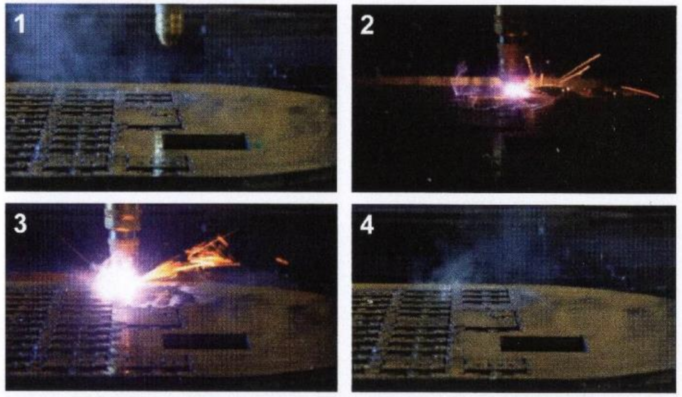




Module 2 (section b)

Plasma Cutting

- CNC Plasma Cutting



Module 2 (section b)

Plasma Cutting

- Key questions and other points
  - What thickness of metal will you routinely cut ?
  - What is the maximum thickness you might cut ?
  - How fast do you want to cut ?
- Like welding machines, a plasma cutter's amperage and voltage capacity determine its 'size'
- A plasma cutter requires relatively high voltage and low amperage levels, the opposite to welding
- Do not judge a plasma cutter solely by amperage, power W = I x V

Module 2 (section b)

Laser Cutting

- Laser cutting: 3 Variants:
  - Laser fusion cutting
    - A focussed laser beam heats the metal to a temperature above its melting point. Air, nitrogen
      or argon is used to blow molten metal out of the cut groove
    - Cut edges are smooth without burrs
    - Used to cut CrNi steel, non ferrous metals, glass, plastics
  - Laser gas-jet cutting
    - Uses a combusting gas, O_2
    - Cut quality worse, burrs present
    - Used to cut Carbon and low alloyed steels

Module 2 (section b)

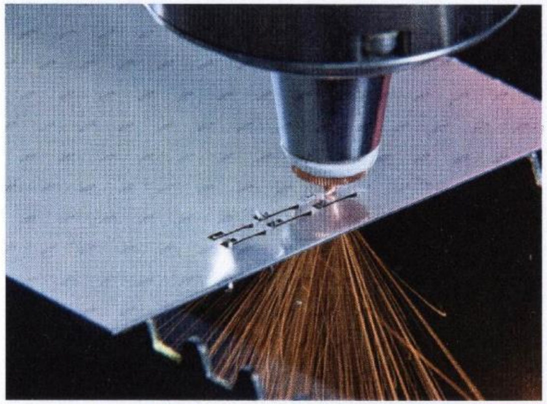
Laser Cutting

- Three laser cutting variants:
  - Laser sublimation cutting
    - High power densities used to promote metal vapourisation with as little melting as possible
    - Not suitable for aluminium
    - Used to cut plastic, paper, wood and ceramics

Module 2 (section b)

Laser Fusion Cutting

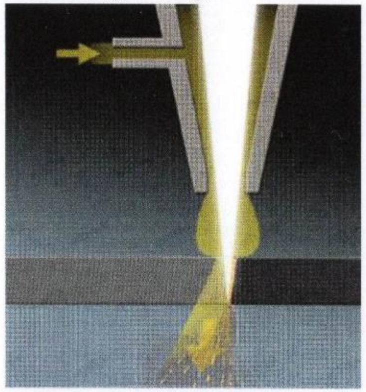
- Laser fusion cutting of 1mm thick stainless steel



Module 2 (section b)

Laser Fusion Cutting

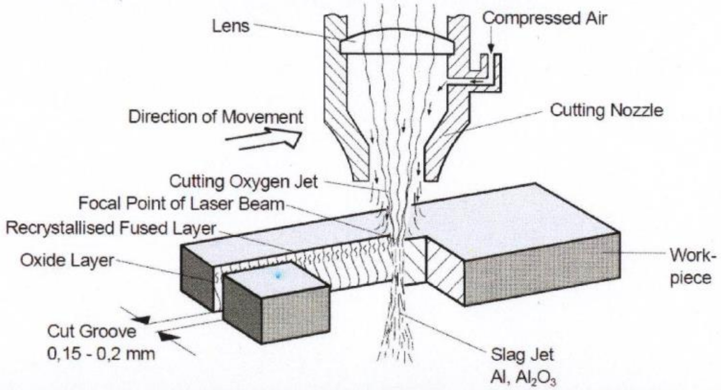
- Laser fusion uses reaction inhibiting nitrogen or argon as the cutting gas
- The gas is driven into the cutting joint at pressures up to 20bar
- The gas cools the material preventing oxidation of the cutting edge
- Process is ideal where high visual quality is required
- Produces a virtually oxide free cutting edge



Module 2 (section b)

Laser Gas Jet Cutting

- Schematic of laser gas jet cutting process



Module 2 (section b)

Laser Gas Jet Cutting

- CO_2 laser heat input for different material thicknesses/watts

Material	Material Thickness				
	0.51mm	1.0mm	2.0mm	3.2mm	6.4mm
Stainless steel	1000	1000	1000	500	250
Aluminium	1000	1000	1000	3800	10000
Mild steel	–	400	–	500	–
Titanium	250	210	210	–	–
Plywood	–	–	–	–	650
Boron/epoxy	–	–	–	3000	–

Module 2 (section b)

Laser Gas Jet Cutting

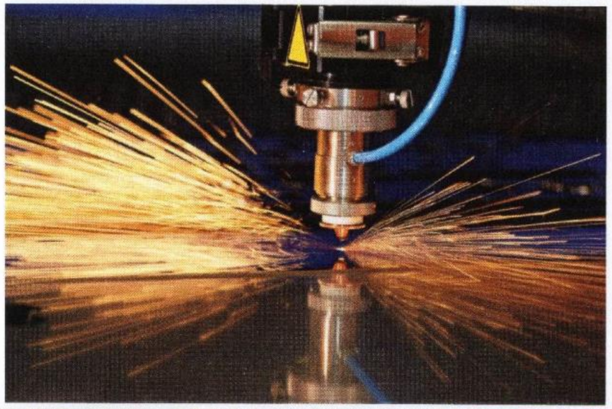
- Cutting rates for various materials and thicknesses using a CO_2 laser (cm/second)

Material	Material Thickness				
	0.51mm	1.0mm	2.0mm	3.2mm	6.4mm
Stainless steel	42.3	23.28	13.76	7.83	3.4
Aluminium	33.87	14.82	6.35	4.23	1.69
Mild steel	–	8.89	7.83	6.35	4.23
Titanium	12.7	12.7	4.23	3.4	2.5
Plywood	–	–	–	–	7.62
Boron / epoxy	–	–	–	2.5	2.5

Module 2 (section b)

Laser Gas Jet Cutting

- Laser gas jet cutting of 1mm thick stainless steel



Module 2 (section b)

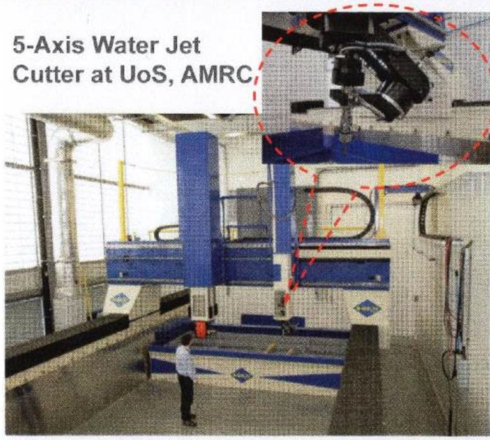
Laser Cutting

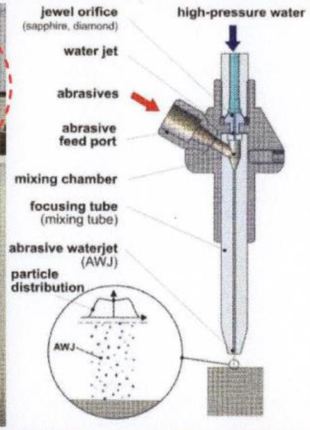
- **The relationship between laser cutting and cutting quality is a complex; relevant parameters include:**
  - **Variable laser parameters:** power, speed, assist gas pressure, lens focal length
  - **Fixed laser parameters:** laser beam quality or beam polarisation direction
  - **Machine performance:** focus position, stability of movement
  - **Operator influence:** individual and at company level
  - **Material composition:** carbon, manganese, silicon, phosphorus and sulphur
  - **Surface condition:** presence of mill scale, surface preparation methods
  - **Material dimensions:** flatness and thickness control

Module 2 (section b)

Water Jet Cutting

5-Axis Water Jet Cutter at UoS, AMRC





Module 2 (section b)

Water Jet Cutting

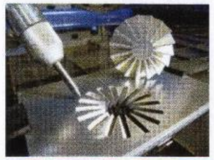
Module 2 (section b)

Water Jet Cutting

- **Tolerances**
  - **Depends on material, thickness and productivity; typically 0.15mm (as low as 0.025mm claimed)**

separation cut | through cut | clean cut | good edge finish | excellent edge finish

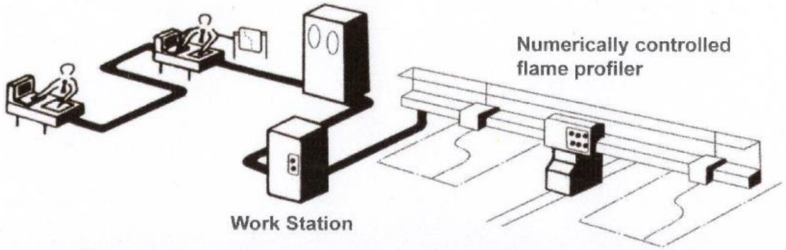
  - **5-axis machine cuts complex geometries**
  - **Machine is expensive; $1.5M**



Module 2 (section b)

CNC Flame Cutting

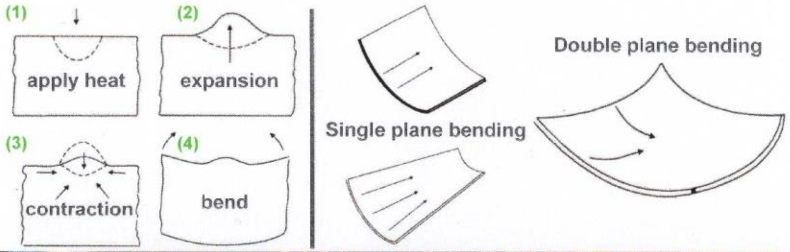
- Cutting plate into many parts or a series of complicated parts
  - Use of oxy-fuel or plasma-arc flame or plasma-arc profilers in numerically controlled facilities provides higher productive



Module 2 (section b)

Bending Methods

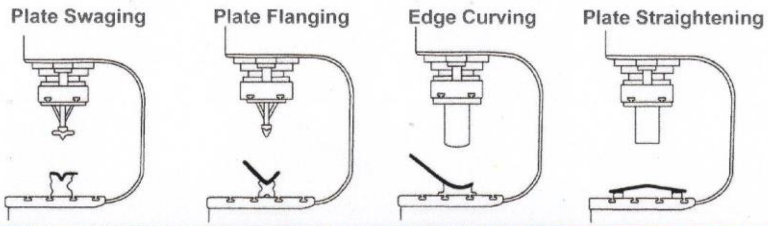
- Bending Shell Plates
  - Heat line bending widely used to obtain curvature in steel plates for shipbuilding purposes - highly skilled, consistency and precision not guaranteed
  - In recent years fully automated CAD heat-line bending systems have been installed in shipyard's



Module 2 (section b)

Bending Methods

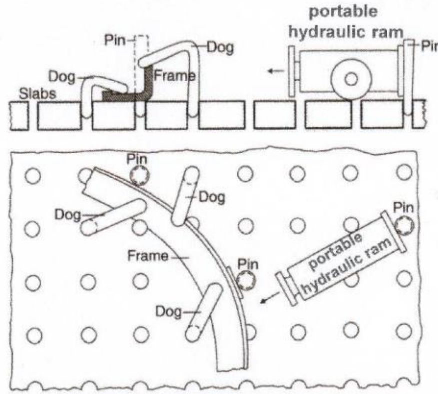
- Hydraulic Presses
  - Presses used extensively in shipyatds for a variety of operations including bending, straightening, flanging, dishing and swaging plates
  - All work is done with cold plates – cheaper alternative to a set of rolls, but bending is slower and requires more skill



Module 2 (section b)

Bending Methods

- Traditional Heated Frame Bending
  - Universal practice is to cold-bend ship frames using commercially available machines designed for the purpose
  - Correct frame curvature can be obtained using 'inverse curve' method and CAD/CAM systems

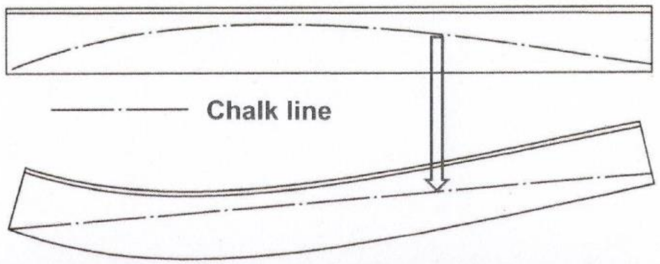


Module 2 (section b)

Bending Methods

- In the 'inverse curve' bending principle a curved line is marked onto the straight frame and the frame bent until the marked line becomes straight on a now bent frame

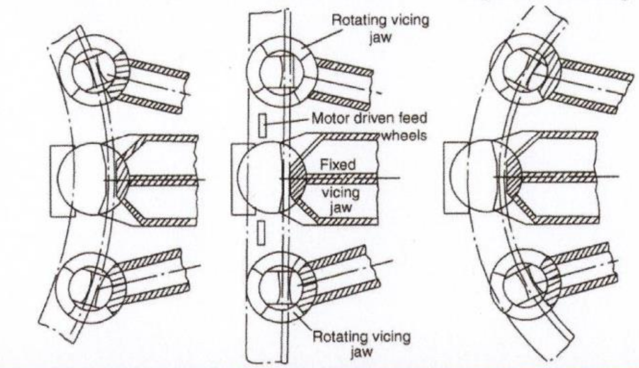
Inverse curve bending principle



Module 2 (section b)

Bending Methods

- Modern Hydraulic Cold Frame Bending Machine



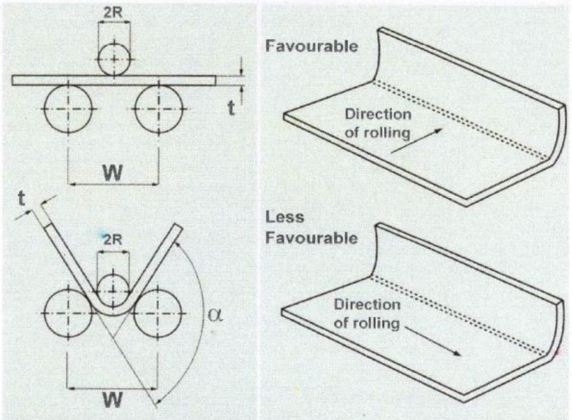
Module 2 (section b)

Roll Bending

- Roll Bending
- Strain at the surface can be estimated from

$$\varepsilon = \frac{1}{1+\frac{2R_i}{t}}$$

where R_i inner radius of the plate



Module 2 (section b)

Welding: Techniques, Practice and Testing

Arc Welding

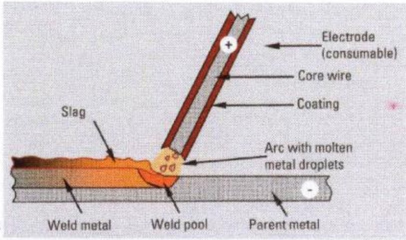
- GMAW Gas Metal Arc "MIG" Welding
- FCAW Flux Cored Arc "FCA" Welding
- GTAW Gas Tungsten Arc "TIG" Welding'
- SMAW Manual Metal Arc "Stick" Welding
- SAW Submerged Arc Welding

Module 2 (section b)

Welding: Manual Metal Arc (MMA)

MMA Welding Process

- Electric current is used to strike an arc between the base/parent material and a consumable electrode rod
- The base material and electrode melt simultaneously
- The electrode is made of filler material (steel) and is covered with a flux coating that melts and vaporises during the process and protects the weld area from oxidation & contamination by producing carbon dioxide (CO_2) gas during the welding process



- The electrode core also melts & becomes a filler material which reinforces the welded joint

Module 2 (section b)

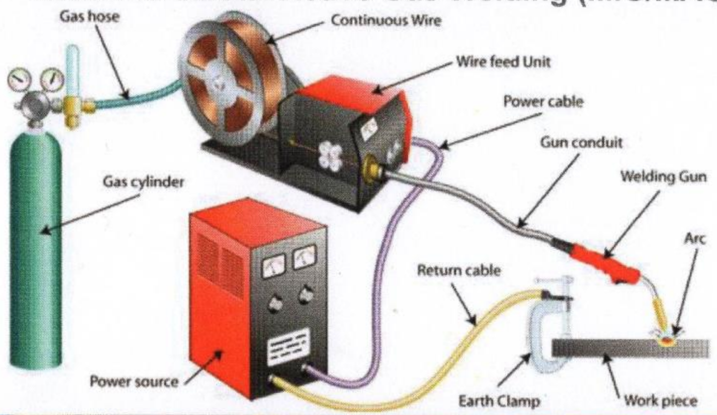
Welding: Manual Metal Arc (MMA)

- **Positives**
  - Versatile
  - Basic equipment relatively cheap
  - Most MMA equipment can be used for TIG welding too
  - Perceived as being easy to use
  - Electrode composition can be tailored to material
  - Generates own gas shield so can be used outside
- **Negatives**
  - Low productivity
  - Relatively high levels of wastage
  - Some electrodes can be difficult to use
  - Doesn't lend itself to automation
  - Each rod diameter welds a limited range of thickness'
  - Skill level for high quality and positional welding

Module 2 (section b)

Welding: MIG and MAG

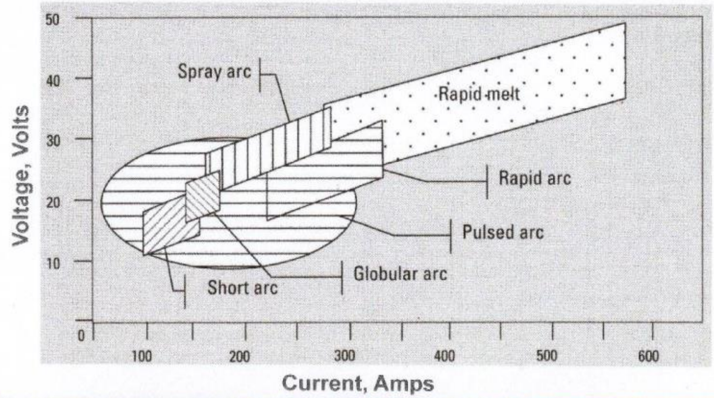
- Metal Inert/Metal Active Gas Welding (MIG/MAG)



Module 2 (section b)

Welding: MIG and MAG

- Metal transfer modes for MIG welding (Wire diam. 1.2mm)



Module 2 (section b)

Welding: MIG and MAG

MIG Welding Process

- In order to produce sound welds it is vital that the heat (welding voltage) and the wire feed speed (amperage) are correctly balanced otherwise serious faults can occur.
- The way the molten filler wire is deposited into the weldpool is called the mode of metal transfer and dependant upon the machine settings falls into one of several distinctive forms
  - Dip transfer/short arc (thin material or precise applications,1.00mm wire diameter 70-200amps, & 17-22volts)
  - Globular transfer (not satisfactory 1.00mm wire diameter 210amp, and 22-23volts)
  - Spray transfer (thicker materials 1.00mm wire diameter 230-300amps, and 26-35volts)
  - Pulse transfer (high quality work)
  - Rotating arc (high deposition rates)

} Specialised Equipment Needed

Module 2 (section b)

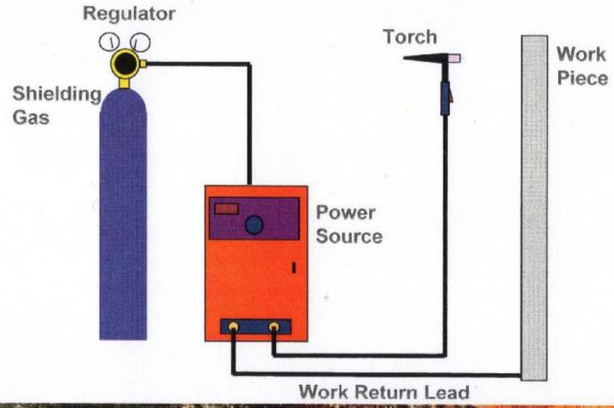
Welding: MIG and MAG

- **MIG Welding Process**
  - MIG welding uses the heat generated by an electric arc to fuse the metal in the joint area
  - The arc is struck between a continuously fed, consumable filler wire and the workpiece, melting both the filler wire and the workpiece simultaneously
  - The entire arc area is covered by a shielding gas, which protects the molten weld pool from the atmosphere
- **MAG - needs addition of active components**
  - CO_2 was originally first choice for MAG welding carbon steels, now superseded by mixed gases which produce far better results, added to argon to stabilise the arc
  - CO_2 additions improve penetration profile and increase heat input – additions rarely exceed 20%

Module 2 (section b)

Welding: Tungsten Inert Gas (TIG)

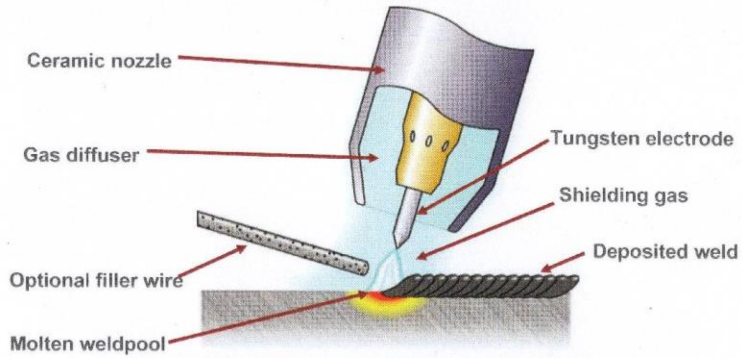
- **Tungsten Inert Gas Welding (TIG)**



Module 2 (section b)

Welding: Tungsten Inert Gas (TIG)

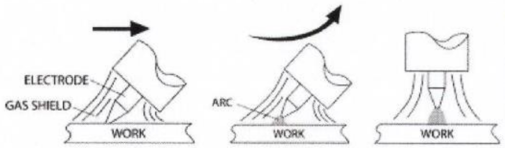
- **Tungsten Inert Gas Welding (TIG)**



Module 2 (section b)

Welding: Tungsten Inert Gas (TIG)

- TIG Process: Arc Initiation (striking the arc)



Lift arc
Basic welding equipment, tendency to leave tungsten inclusions in the weld and contaminate the tungsten electrode

High frequency
More sophisticated equipment ensures contamination free weld starts and prolongs electrode life

Module 2 (section b)

Welding: Tungsten Inert Gas (TIG)

TIG Process

- The Tungsten Inert Gas, or TIG process, uses the heat generated by an electric arc struck between a non-consumable tungsten electrode and the workpiece to produce a molten weld pool and fuse metal in the joint area
- The arc area is shrouded in an inert gas shield to protect the weld pool, adjacent parent material and non-consumable electrode
- The process may be operated autogenously, that is, without filler, or filler may be added by feeding a consumable wire or rod into the established weld pool. This allows the welder to precisely control the size and shape of the weld bead in a way not possible with MMA or MIG/MAG welding

Module 2 (section b)

Welding: Tungsten Inert Gas (TIG)

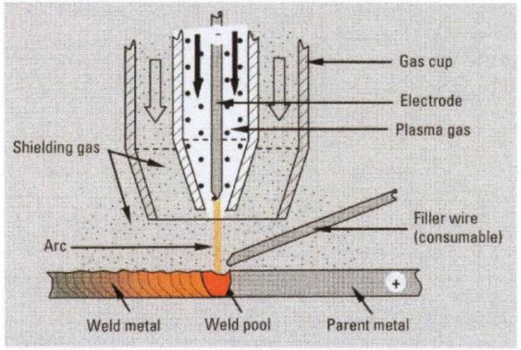
- **Positives**
  - High quality
  - Versatile
  - Relatively simple equipment (in it's most basic form)
  - Control
  - Clean
- **Negatives**
  - Slow deposition rates (production costs)
  - Skill levels (labour costs)
  - High heat input (distortion or damage to metallurgical qualities)
  - Automation can be difficult

Module 2 (section b)

Welding: Plasma Arc Welding (PAW)

Plasma Arc Welding

- Similar to TIG welding, but the tungsten electrode is positioned within the body of the torch, the plasma arc is separated from the shielding gas envelope
- The plasma is forced through a fine-bore copper nozzle that constricts the arc



Module 2 (section b) — Welding: Plasma Arc Welding (PAW)

- Plasma Arc Welding
  - By varying the bore diameter and plasma gas flow rate, three different operating modes can be achieved
    - Microplasma: the arc is operated at very low welding currents (0.1-15amps) and used for welding thin sheets
    - Medium current: the arc is operated at currents ranging from 15-200amps. Plasma welding is an alternative to TIG welding, but under these conditiona has the advantage of achieving deeper penetration and being more tolerant to surface contamination
      - The bulkiness of a plasma torch makes it more suited to mechanized welding
    - Keyhole plasma: the plasma is operated at currents above 100amps and can achieve penetration depths up

Module 2 (section b) — Welding: Shielding Gases

Shielding Gases: Primary Function

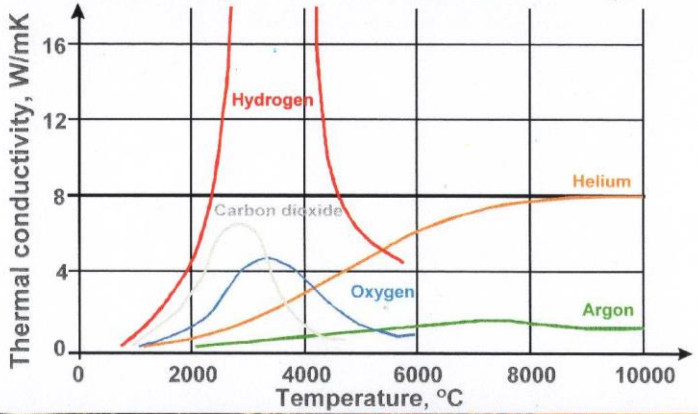
- Protect the molten weld pool and adjacent parent material from contamination caused by coming into contact with the atmosphere

Shielding gases also have a significant influence over :-

- Deposition rates
- Mode of metal transfer
- Cosmetic appearance/profile
- Fusion
- Penetration
- Corrosion resistance
- Weld integrity

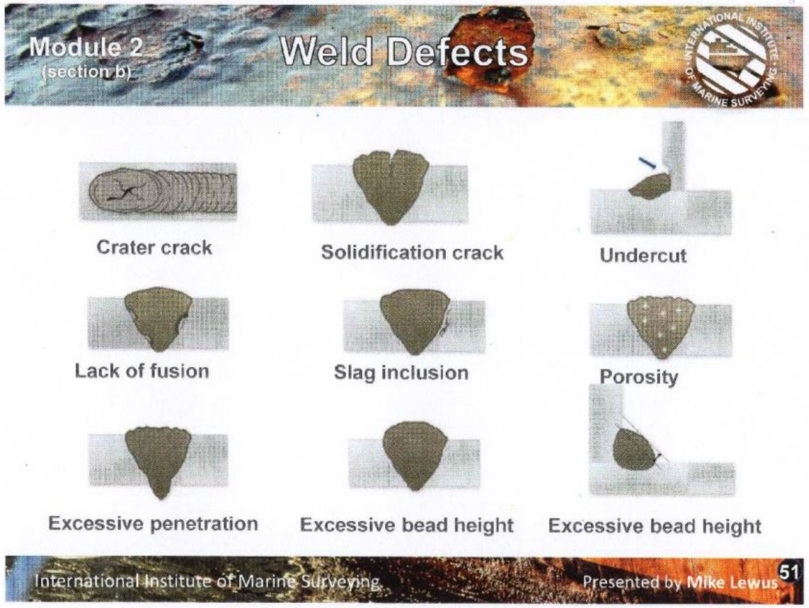
Module 2 (section b) — Welding: Shielding Gases

Shielding Gas Thermal Conductivity



Module 2 (section b) — Weld Defects

- Cold cracking
- Hot cracking
- Lamellar tearing
- Lack of fusion
- Lack of penetration
- Porosity (uniform)
- Crater pipes
- Undercut
- Overlap
- Excess penetration
- Root concavity
- Inclusions
- Arc strikes
- Weld spatter
- Weld geometry imperfections and their assessment



Module 2 (section b) — Testing Welds

- Testing of weld joints falls into two basic types, destructive testing and non destructive testing (NDT)
  - Destructive testing
    - Tensile tests
    - Bend Tests
    - Impact Tests
    - Metallographic cross sections
  - Non Destructive Tests
    - Surface flaws
      - Dye penetrant, magnetic particle & eddy current
    - Sub surface/bulk flaws
      - Ultrasonic testing
      - radiography

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Professional Qualification
in Marine Corrosion

Presented by **Mike Lewus**

Module 2
(section c)

Weld Evaluation, Non Destructive Testing (NDT) and Mechanical Testing Techniques

Module 2 (section c)

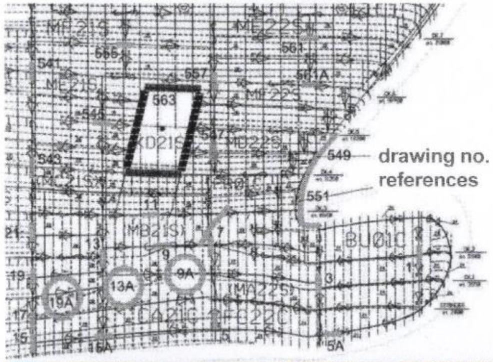
Summary

- **Weld Evaluation**
  - NDE Inspection Plan
  - Weld Defects and Optimum NDE
  - Classification Society Rules
- **Non Destructive Testing (NDT) Techniques**
  - Magnetic particle inspection
  - Dye penetrant
  - Ultrasonic testing
  - Radiography
- **Mechanical Testing Techniques & Test of Weldments**
  - Tensile Tests
  - Pendulum Impact Tests
  - 3-Point Bend Tests

Module 2 (section c)

A Typical NDT Inspection Plan

- Part of an NDE scheme of a ship; this is aimed at assessing general welding quality and ensuring that critical structural elements are defect-free



critical monitoring areas

radiographic testing

ultrasonic testing

magnetic particle/ dye penetrant testing

NDE Checkpoint

Module 2 (section c)

Weld Imperfections and Structural Integrity

- There is evidence that weld imperfections reduce the fatigue life of welded joints
- Standards such as,
  - BSEN ISO, 6520-1: 2007, 'Welding and allied processes: Classification of geometric imperfections in metallic materials'
  - D3.5:1993(R2000) 'Guide for Steel Hull Welding', American Welding Society

provide a comprehensive guide to the classification of weld imperfections & are widely adopted by marine industry

- Imperfections can be classified into three categories:
  - Planar flaws
  - Non-planar flaws
  - Geometrical imperfections

Module 2 (section c)

Weld Defect Categories

Planar Flaws
- Cracks
- Lack of fusion or penetration
- Undercut and overlap. (sometimes is treated as shape imperfections.)

Non-Planar Flaws
- Cavities
- Solid inclusions

Geometrical/Shape Imperfections
- Axial misalignment
- Angular misalignment
- Imperfect weld profile
- Shape imperfection

Module 2 (section c)

Optimum NDE Inspection Regimes

- Classification Societies are keen to rationalise their rules and achieve a more robust philosophy for their NDE checkpoint regimes
- IACS members in particular strive to establish, review, promote and develop minimum satisfactory technical requirements in relation to design, construction and survey of ships, and other marine units as part of their commitments to IACS directions
- Manufacturers claim that their general workmanship quality is good, and hence, more inspection is 'redundant' (or no value added)
  - some rules are considered overly conservative and do not take into account the welding quality achieved

Module 2 (section c)

Optimum NDE Inspection Regimes

Classification Society
- Ensure vessel safety
- Increase reliability
- Verify vessel is built to relevant rules

Ship Builder
- Reduce cost
- Increase speed of construction
- Reduce inspection & remedial costs

Ship Owner
- Achieve best quality
- Reduce through-life maintenance costs

Optimised NDE Inspection

Module 2 (section c)

Current Approaches to NDE Inspection

- Current approaches of classification societies are centred around two main concepts:
  - assess the general quality of the ship by defining a number of checkpoints with recommendation of allocating these checkpoints to more critical members
  - focus on the relative criticality of areas and specify the extent of inspection accordingly without specifying a set minimum number for the whole structure
  - Most classification societies' approaches have elements from both these concepts. lean more to the first concept and some to the other

Module 2 (section c)

Current Approaches to NDE Inspection

- Classification Societies define NDE in terms of the minimum number of checkpoints or % of welded lines to be carried out
- Some Classification Societies define the number for whole structure using an equation which is function of dimensions of ship or its members
  - ABS: defines the minimum number of checkpoints at 0.6L of amidship, using following equation

$$N = \frac{L \times (B + D)}{46.5}$$

Where *L* is length of vessel between perpendiculars
B is greatest moulded breadth
D is moulded depth at *L*/2

Module 2 (section c)

Current Approaches to NDE Inspection

- RINA:
  - Mandates ABS equation for 0.6L amidship areas and instructs additional spot examination for areas outside 0.6L area and sensitive locations
- DNV GL:
  - Does not specify a minimum number of checkpoints and instead requires a minimum percentage of weld seams needed to be examined
  - Critical areas receive the most attention
    - 20% of the weldment needs inspection
    - followed by deck/bottom plating within 0.4L amidship (5% of the weldment needs inspection)
    - 2% of weld seam length in general areas

Module 2 (section c)

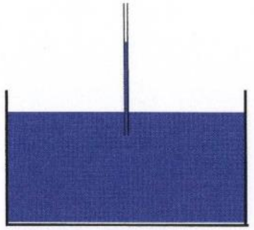
Current Approaches to NDE Inspection

- LR:
  - Similar to DNV, Lloyds Register doesn't specify a minimum number of checkpoints for the whole ship
  - It recommends the extent of inspection be defined based on type and location of structural members
  - Structural members with higher susceptibility to crack initiation receive significantly higher examination extent, either 50% or 100% examinations
  - More attention is paid to the intersection of butt and seams of fabrication and section welds where 50% examination is required and, if these are at highly stressed areas 100% is required
  - Bilge keel butt welds within 0.4L amidship are also required to be inspected 100% and 33% outside 0.4L amidship. Other items, require less examination (1%-5%)

Dye Penetrant and Magnetic Particle Inspection

Module 2 (section c)

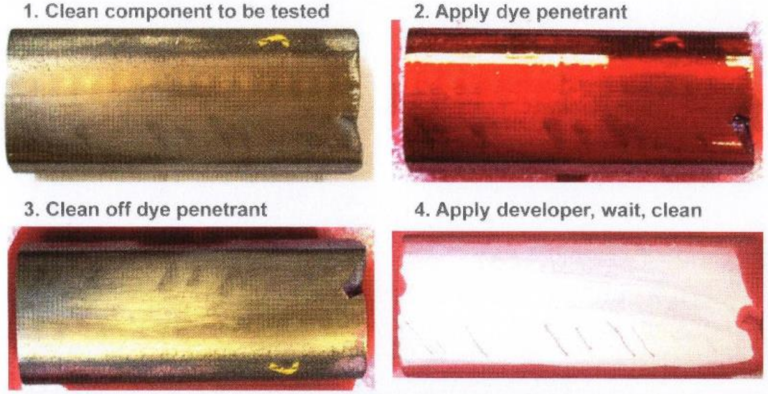
- Dye Penetrant and Magnetic Particle Inspection
  - Little used in ship hull construction, but more common for assessing the presence of surface cracks in stern frames and castings
- Dye Penetrant
  - Principle: relies on capillary action - Surface tension causes liquid to be drawn into thin tubes and fissures
  - Procedure
    - Clean component to be inspected
    - Apply penetrant
    - Allow penetrant to be drawn into defects
    - Wipe off excess penetrant
    - Apply developer paint
    - Allow paint to draw penetrant from defects, then clean



Magnetic Particle Inspection & Dye Penetrant

Module 2 (section c)

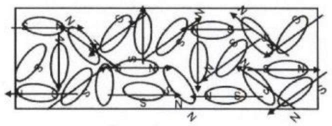
- Dye penetrant procedure



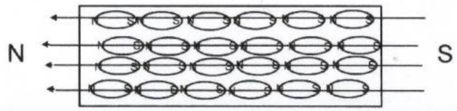
Magnetic Particle Inspection & Dye Penetrant

Module 2 (section c)

- Magnetic particle Inspection (MPI) is a nondestructive testing (NDT) method for detecting surface and shallow subsurface discontinuities in ferromagnetic materials such as iron, nickel, cobalt, and some of their alloys



Virgin material has random orientation of magnetic domains within the material and little reinforcement in any one direction and so net field.

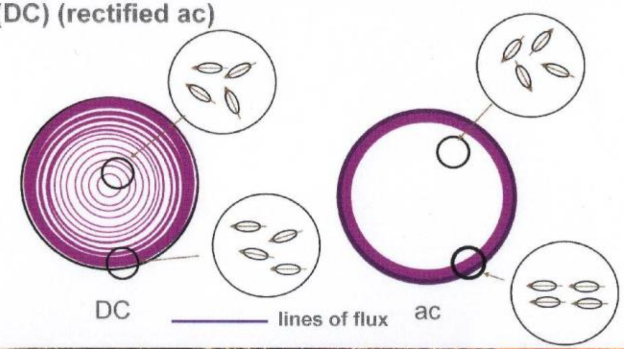


Material still under the influence of a magnetising force now has all of the magnetic domains within the material aligned in the same direction. (Saturated)

Magnetic Particle Inspection & Dye Penetrant

Module 2 (section c)

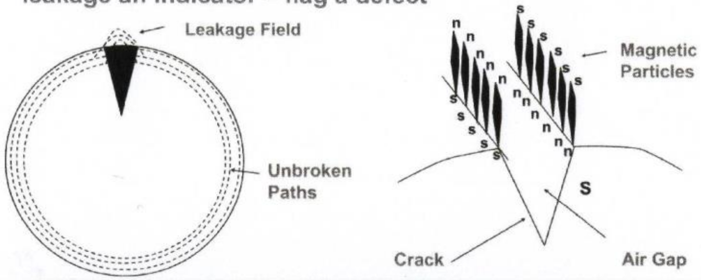
- Magnetic lines of force are perpendicular to the direction of the electric current, which may be alternating current (ac) or some form of direct current (DC) (rectified ac)



Module 2 (section c)

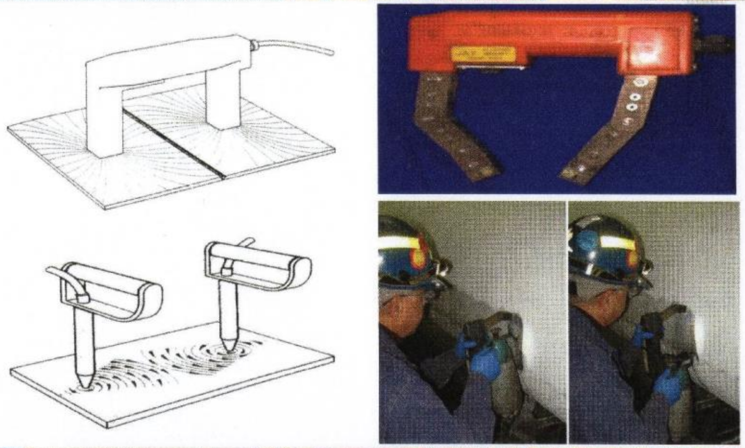
Magnetic Particle Inspection & Dye Penetrant

- Presence of a surface or subsurface discontinuity in the material allows magnetic flux to leak, since air cannot support as much magnetic field per unit volume as metals
- Ferrous particles, either dry or in a wet suspension, are applied to a part. These are attracted to an area of flux leakage an indicator – flag a defect



Module 2 (section c)

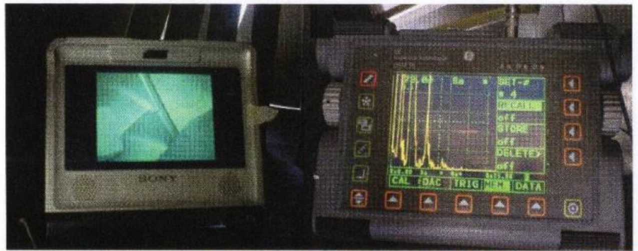
Magnetic Particle Inspection & Dye Penetrant



Module 2 (section c)

Ultrasonic Testing

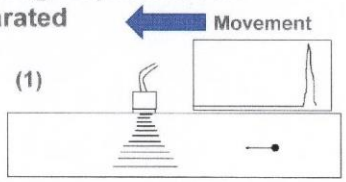
- Ultrasonic testing (UT) is a family of non-destructive testing techniques based on the propagation of ultrasonic waves in an object or material being tested. In most common UT applications, very short ultrasonic pulse-waves with center frequencies ranging from 0.1-15 MHz, and occasionally up to 50 MHz, are used

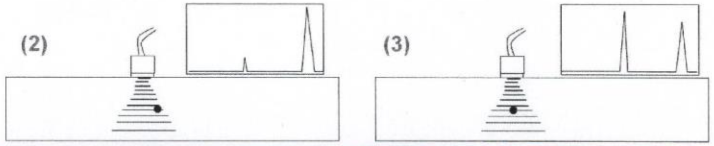


Module 2 (section c)

Ultrasonic Testing

- Application: In ultrasonic testing, an ultrasound transducer connected to a diagnostic machine is passed over the object being inspected. The transducer is typically separated from the test object by a couplant such as a gel, oil. If an EMAT is used a coupling agent isn't required





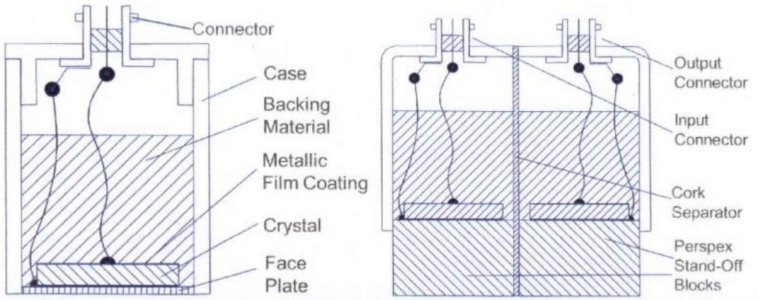
Module 2 (section c)

Ultrasonic Testing

- Ultrasonic probe types

Single piezo crystal probe for reflection (or pulse-echo) mode

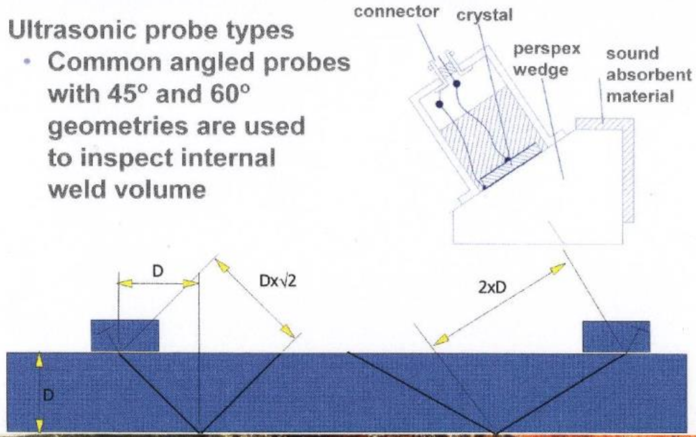
Double piezo crystal probe for attenuation (or through transmission) mode



Module 2 (section c)

Ultrasonic Testing

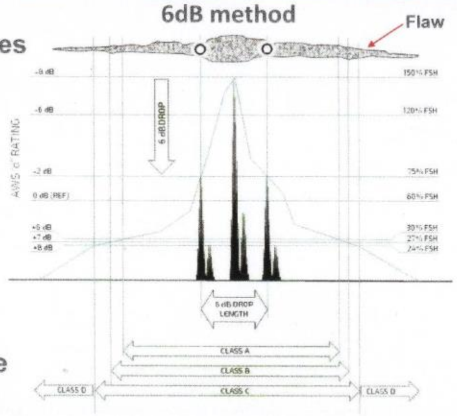
- Ultrasonic probe types
  - Common angled probes with 45° and 60° geometries are used to inspect internal weld volume



Module 2 (section c)

Ultrasonic Testing: Defect Sizing Techniques

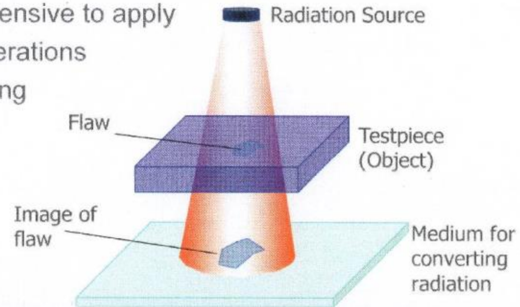
- Defect Sizing Techniques
  - Back Wall Method
  - 6dB Drop Method
  - 20dB Drop Method
  - DAC (distance amplitude curve) Method
  - DGS (distance gain size diagrams) Method
  - Maximum Amplitude Technique



Module 2 (section c)

Radiographic Testing

- Based upon differential absorption of penetrating radiation; source either X-rays from an x-ray tube or γ-rays from a radioactive source
  - Relatively expensive to apply
  - Safety considerations
  - Time consuming
  - Provides a permanent record



Module 2 (section c)

Radiographic Testing

- X-rays
  - Generated by interaction of high energy electrons and a target
  - Equipment tends to be bulky
  - Portable equipment limited in application (although capable of penetrating 75 mm of steel)
  - Generally high operating costs
- γ-rays
  - Produced during radioactive decay of certain isotopes (Iridium-192 and Cobalt-60)
  - High energy, thus good penetration
  - Intensity of source decreases with time (half-life)
  - Stored in a lead shielding material

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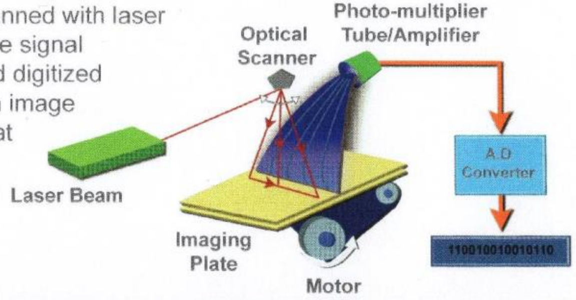
Module 2 (section c)

Radiography Testing: Digital Imaging

- Computed Radiography can be used with X-ray systems formerly used with film, but is much faster than film imaging. Computed Radiography uses a special phosphor plate or imaging plate (IP) to store the radiation signal not fully attenuated by the test object
- The IP is scanned with laser optics and the signal amplified and digitized producing an image in pixel format



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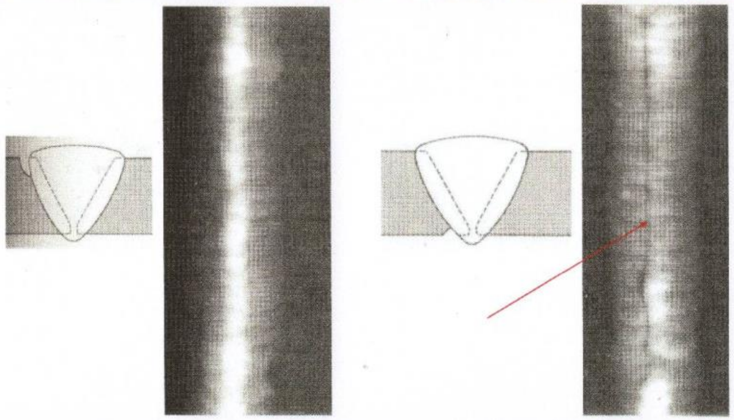
Module 2 (section c)

Radiographic Imaging: Undercut



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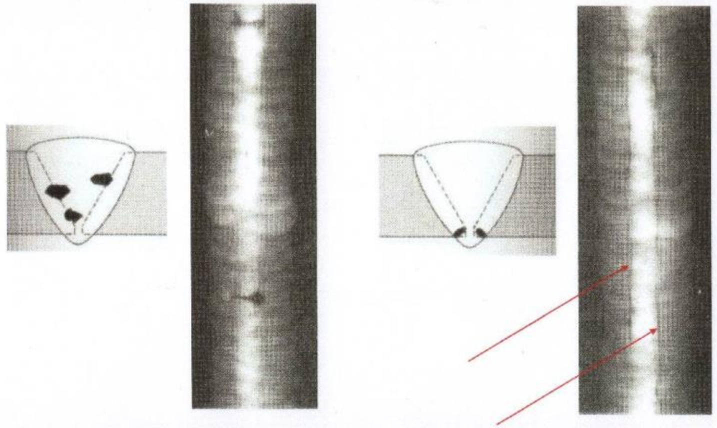
Module 2 (section c)

Radiographic Imaging: Entrapped Slag



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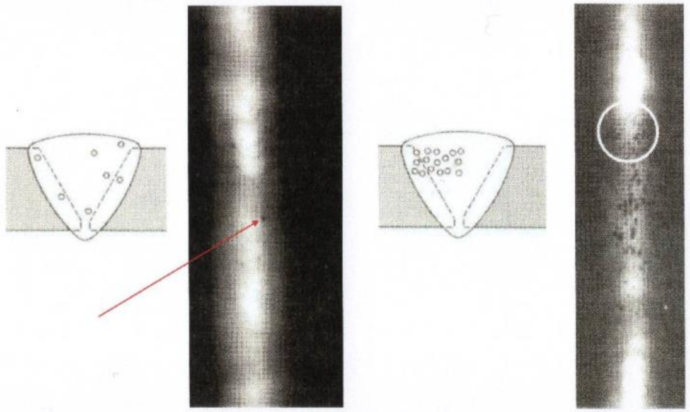
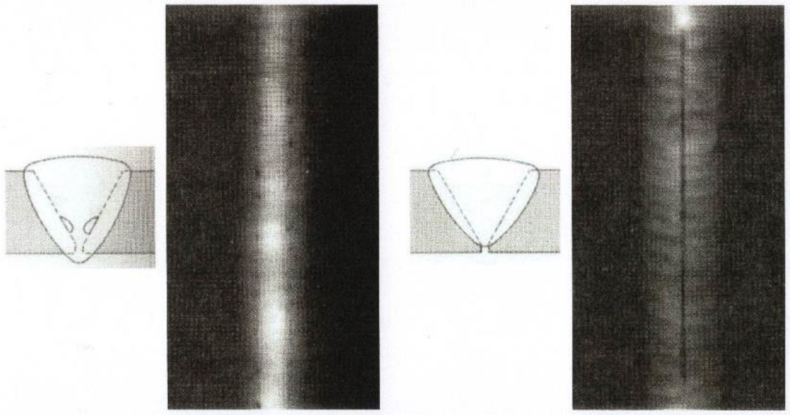
Module 2 (section c)

Radiographic Imaging: Porosity



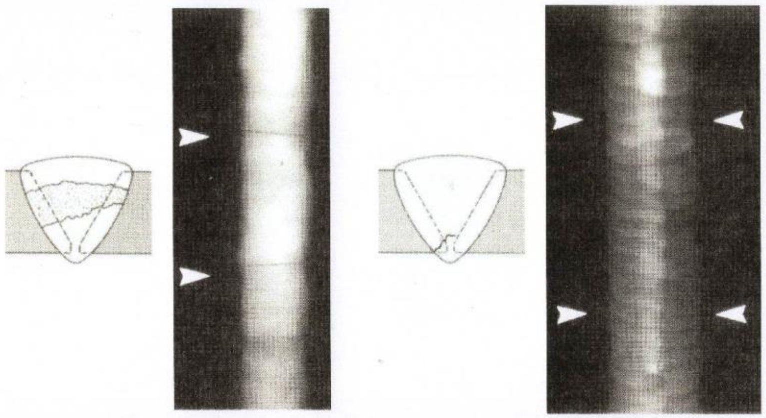
Module 2 (section c)

Radiographic Imaging: Lack of Fusion/Penetration



Module 2 (section c)

Radiographic Imaging: Cracking



Module 2 (section c)

Mechanical Properties: Tensile Tests

- Tensile testing is the most common method to use a force measurement system during testing
- Tensile tests are used primarily to assess the mechanical behaviour of a component, part or material under axial loading
- Test Principle:
  - A typical 'dog-bone' shaped sample is gripped at the ends and an axially applied force is applied causing the material to stretch, testing may continue until failure
  - During testing test piece extension and applied force data is captured and plotted in a stress-strain curve

Module 2 (section c) — Tensile Tests

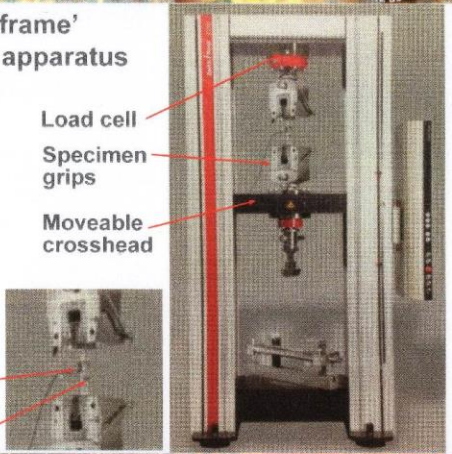
- **Mechanical property parameters**
  - Yield strength: R_{eh} , R_{el}
  - Proof strength: R_p
  - Ultimate tensile strength (UTS): R_m
  - Young's modulus; measure of stiffness E
  - Ductility measures (%): A , Z
  - Poisson Ratio (ν) computed from trans. & axial strain
  - Strength coefficient (K)
  - Work hardening index (n)
  - Toughness (energy absorbed): area of σ - ε strain plot
  - Relationship with fatigue parameters estimated

Module 2 (section c) — Tensile Tests

- **Specimen Shape**
  - The shape and dimensions of test pieces may be constrained by the shape and dimensions of the metallic product from which the test pieces are taken
- **Representative Samples/Specimens**
  - Processing by melting, casting, hot and cold forming results in steel products that are not homogeneous, consequently…
  - ….Samples, rough specimens and test pieces selected in accordance with BSEN ISO 377: 2017 **(Annex A) shall be considered to be representative of the product (slide 13)**
- **Sample Production**
  - A test piece is usually obtained by machining a sample from the product or, it can be a pressed blank or casting
  - Products of uniform cross-section (sections, bars, wires, etc.) and as-cast test pieces (for cast iron and non-ferrous alloys) can be tested without being machined

Module 2 (section c) — Tensile Tests

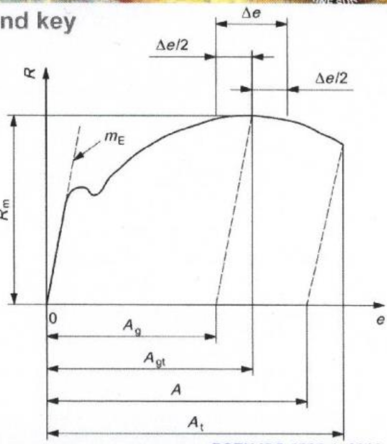
- **Key components of 'H-frame' uniaxial tensile testing apparatus**
  - Indirect extension measurement: by change in crosshead distance
  - Direct extension measurement: by measuring extension directly from specimen



Module 2 (section c) — Tensile Tests

- **Typical Stress-strain plot and key parameters**

A % elongation after fracture
A_g % plastic extension at maximum force
A_{gt} % total extension at maximum force
A_t % total extension
m_E slope of the elastic part of the stress-strain curve (Young's modulus E)
R Stress
R_m tensile strength (UTS)
Δe plateau extent (for determin of A_g)

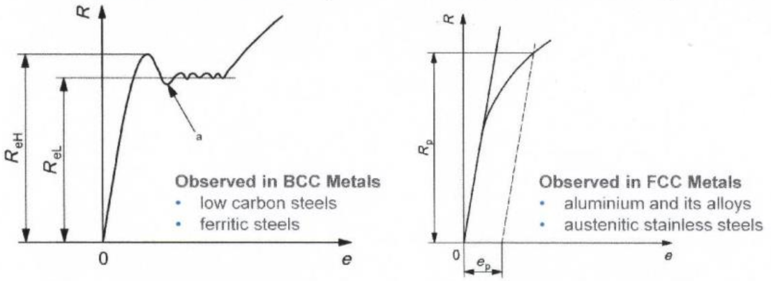


BSEN ISO 6892-1: 2019

Module 2 (section c)

Tensile Tests

Discontinuous Yielding | **Continuous Yielding**



e	% extension (ε strain)
R	Stress (σ force/unit area)
R_{eH}	upper yield strength
R_{eL}	lower yield strength
a	initial transient effect

e	% extension (ε strain)
e_t	% total extension
R	stress
R_t	proof strength, total extension i.e. $R_{0.2\%}$

BSEN ISO 6892-1: 2019

Module 2 (section c)

Transverse Tensile Tests: ISO 4136: 2012

- **Scope:** Specifies the size of test specimens and procedures for carrying out transverse tensile tests to determine the tensile strength and location of fracture of a welded butt joint
- **Normative References:**
  ISO 4063: 2009; Welding and allied processes – Nomenclature of processes and reference
- ISO 6892-1; Metallic materials - Tensile testing at ambient temperature – Part 1: Method of test at room temp.
- ISO 6892-2; Metallic materials - Tensile testing at ambient temperature – Part 1: Method of test at elevated temp.
- **Principle:** An increasing tensile load is continuously applied until rupture occurs in a test specimen taken transversely from a welded joint
  - Unless otherwise specified the test is carried out at 23±5°C

Module 2 (section c)

ISO 4136: 2012, Terminology

- **Symbols and Terminology:**

Symbol	Term	Unit
b	Width of the parallel length	mm
b_1	Width of shoulder	mm
d	Diameter of the plug	mm
D	Outside diameter of the pipe†	mm
L_c	Parallel length	mm
L_0	Original gauge length	mm
L_s	Max. width of the weld after machining	mm
L_t	Total length of test specimen	mm
r	Radius of shoulder	mm
t	Thickness of the welded joint	mm
t_s	Thickness of the test specimen	mm

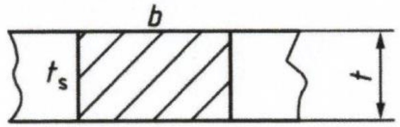
† "pipe", term to mean pipe, tube or hollow section – non rectangular

Module 2 (section c)

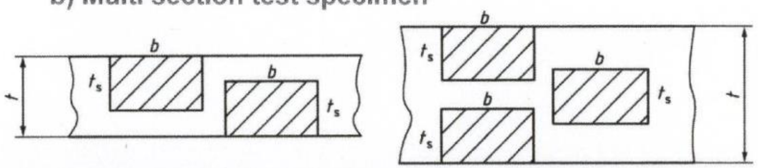
ISO 4136: 2012, Specimen Location and Dimensions

- **Location of test specimen in joints**

a) Full section test specimen



b) Multi section test specimen



Module 2 (section c) ISO 4136: 2012, Specimen Location and Dimensions

- Dimensions of test specimen for plates and pipes

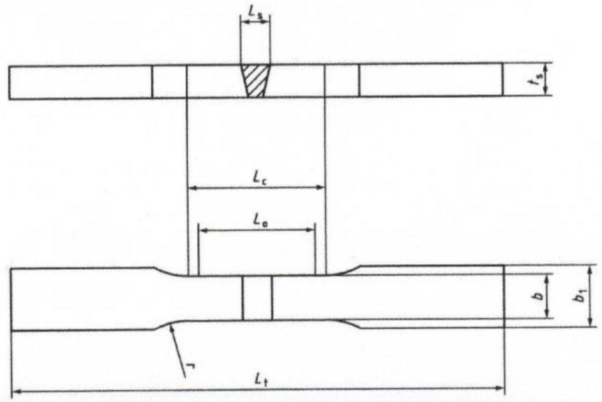
Denomination		Symbol	Dimensions, mm
Total Length of test specimen		L_t	to suit testing machine
Width of shoulder		b_1	$b + 12$
Width of the parallel length	plates	b	12 for $t_s \le 2$
			25 for $t_s > 2$
	pipes	b	6 for $D \le 50$
			12 for $50 < D \le 168.3$
			25 for $D > 168.3$
Parallel length [a, b]		L_c	$\ge L_s + 60$
Radius of shoulder		r	≥ 25

a For pressure welding and beam welding (process groups 2, 4 and 5 in accordance with ISO 4063: 2009), $L_s = 0$

b For some other metallic materials (e.g. aluminium, copper and their alloys) $L_c \ge L_s + 100$ may be necessary

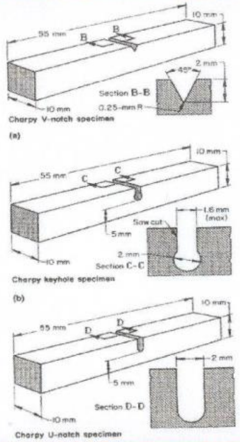
Module 2 (section c) ISO 4136: 2012, Specimen Location and Dimensions

- Test specimen for plates



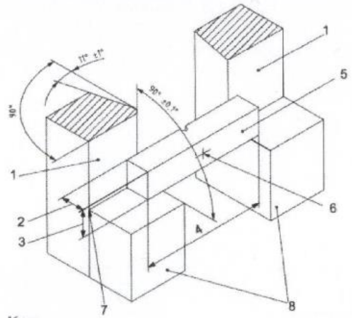
Module 2 (section c) Pendulum Impact Tests: Measuring Toughness

- **Test Requirements**
  - A test sample, which when struck will fracture at a particular location i.e. use notched samples!
  - Notch is generally V- or U-shaped with depths of 2 and 5mm, respectively
- **Two basic tests: Charpy and IZOD**
  - Both involve striking a sample with a pendulum weight ('hammer')



Module 2 (section c) Pendulum Impact Tests

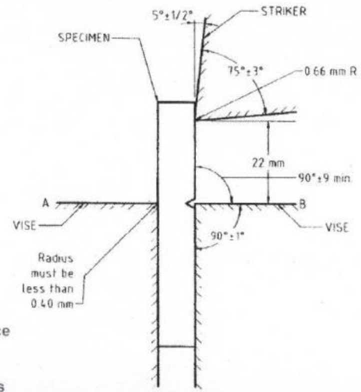
Charpy sample/test setup



Key

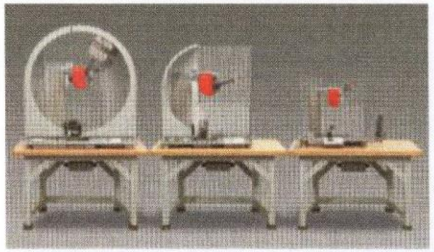
1	Anvil	5	Reference test piece
2	Height of test piece	6	Centre of strike
3	Width of test piece	7	Recess
4	Length of test piece	8	Test piece supports

IZOD sample/test setup



Module 2 (section c) Pendulum Impact Tests

- **Modern Pendulum Impact Equipment**
  - **Facility to interchange Charpy anvil or IZOD vice sample support**
  - **Different sizes for different energy/toughness level**



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Module 2 (section c) Impact Tests on Welds, ISO 9016: 2012

- **Scope:** Specifies method to be used when describing test specimen location and notch orientation for the testing and reporting of impact tests on welded butt joints
  - Applies to impact tests on metallic materials in all forms of product made by any fusion welding process
- **Normative References:** ISO 148-1; Metallic materials – Charpy pendulum impact test – Part 1: Test method
- **Principle:** Impact testing shall be in accordance with ISO 148-1. The test temperature, location, type and size of test specimen and notch orientation shall be in accordance with the relevant application standard
  - In addition to the requirements of ISO 148-1, the notch position may be located by macroetching

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Module 2 (section c) Impact Tests on Welds, ISO 9016: 2012

- **Sample denomination, Uses a 5 lettering System:**
  - **1st character:** 'U' for Charpy U-notch, 'V' for Charpy V notch
  - **2nd character:** 'W' notch in the weld metal (reference line is the weld centre line) 'H' notch in the heat affected zone, HAZ (reference line is the fusion or joint line)
  - **3rd Character:** 'S' notched face parallel to the surface 'T' notch through the thickness
  - **4th Character:** '*a*' the distance of the centre of the notch from the reference line (if '*a*' is at the centre line of the weld, *a* = 0)
  - **5th character:** '*b*' the distance from the weld joint face side to the nearer face of the test specimen (if '*b*' is at the surface of the weld, *b* = 0)

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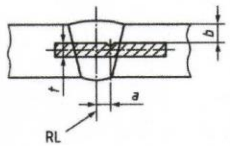
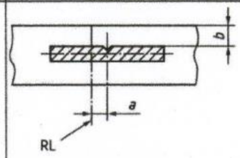
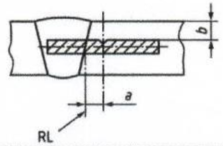
Module 2 (section c) ISO 9016: 2012, Sample Orientations

- **Notched face parallel to the surface of the test piece ('S' position)**

Denomination	Centre of the weld — Representation	Denomination	Fusion/joint line — Representation
VWS a/b		VHS a/b (pressure weld)	
		VHS a/b (fusion weld)	

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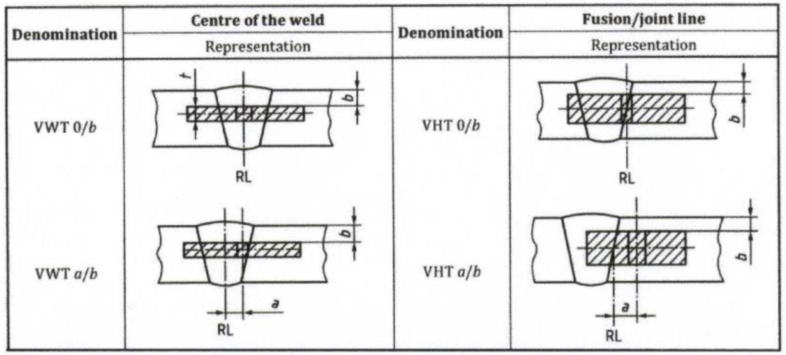
Module 2 (section c)

ISO 9016: 2012, Sample Orientations

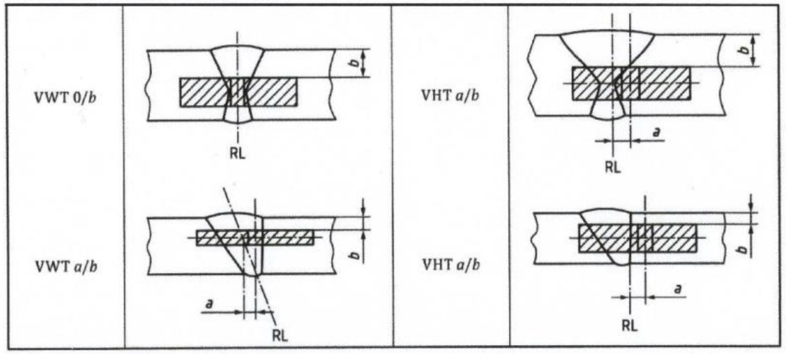
- **Notched face perpendicular to the surface of the test piece ('T' position)**



Module 2 (section c)

ISO 9016: 2012, Sample Orientations

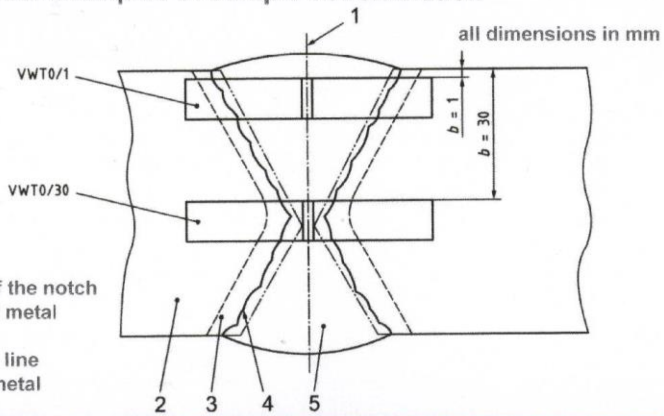
- **Notched face perpendicular to the surface of the test piece ('T' position)**



Module 2 (section c)

ISO 9016: 2012, Sample Denominations

- **Typical examples of sample denomination**



1. axis of the notch
2. parent metal
3. HAZ
4. fusion line
5. weld metal

Module 2 (section c)

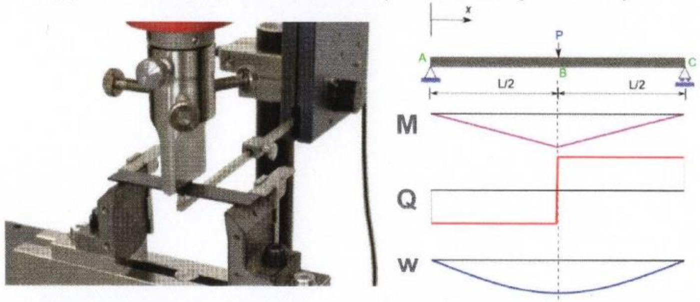
ISO 5173: 2009; Bend Tests on Welds

- **Scope:** Specifies a method for making transverse root, face and side bend tests on test specimens taken from **butt welds**, **butt welds with cladding** and **cladding without butt welds** in order to assess ductility and/or absence of imperfections on or near the surface of the test specimen
- **Principle:** Submitting a test specimen, taken transversely or longitudinally from a welded joint, to plastic deformation by bending it, without reversing the bending direction, in such a way that one of the surfaces or cross sections of the weld joint is in tension
  - Unless otherwise specified the test is carried out at 23±5°C
  - The test shall be made in accordance with one of the methods described in clause 6 – this standard, see later slides

Module 2 (section c)

3-Point Bend Tests: Basic Principles

- 3-point bend test employs a beam of length *L*, positioned on two roller supports with a load *P* applied at the beam centre (mid roller position)

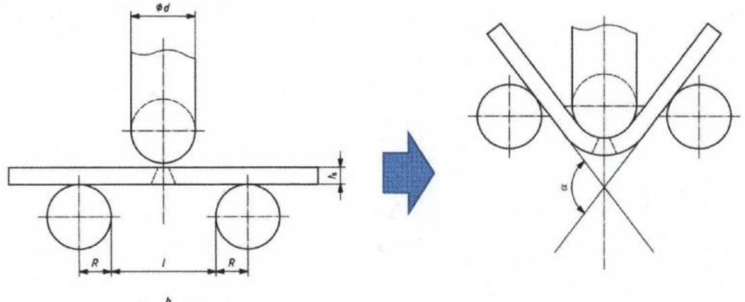
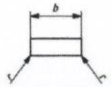


- M bending moment, Q shear stress and w deflection versus beam position plots above

Module 2 (section c)

ISO 5173: 2009 3-Point Bend Test Method

- Transverse face or root bend test method (TFBB & TRBB)

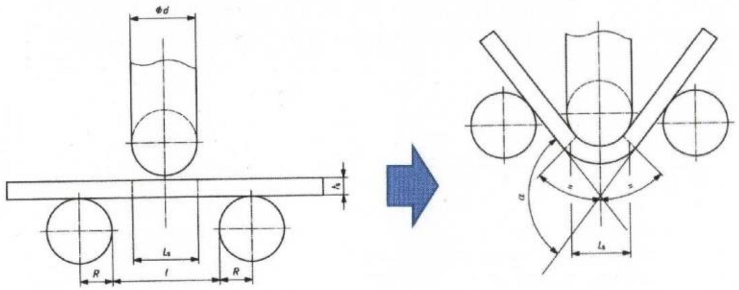



$$d + 2ts + 3 \leq l \leq d + 3ts$$

Module 2 (section c)

ISO 5173: 2009 3-Point Bend Test Method

- Transverse side bend test method (SBB)




$$d + 2ts + 3 \leq l \leq d + 3ts$$

$$d \geq 1.3Ls - t_s$$

Module 2 (section c)

ISO 5173: 2009; Bend Tests on Welds

- **Bending Angle: Completion of the test:**
  The test is completed when the test reaches the definition of test completion given in the relevant application standard, otherwise the following definitions maybe applied
  - For 3-point bend test, the test is completed when the specimen is ejected from the bottom of the fixture
  - For U-type jig bend test, the test is completed when a 3mm wire cannot be inserted between the specimen and the lower fixture
  - For roller type bend test, the test is completed when the outer roller has moved 180° from the starting point