Contents

Chapter 1

INTRODUCTION

Steels are used in the construction and fabrication of engineering structures, with service temperatures ranging from subzero to about 600 °C over long periods of time. The vast majority of iron alloys are ferritic because they are cheap and it is easy to modify their microstructures to obtain an impressive range of desirable properties.

The fabrication of steels unavoidably involves welding, a complex process incorporating numerous metallurgical phenomena. It is not surprising therefore, that the final microstructure both inside the weld metal and in all adjacent regions affected by the welding heat, is remarkably varied. Many of the important features of weld microstructure can now be calculated using a combination of thermodynamics and kinetic theory [1]. Such calculations are now being performed routinely in industry during the course of alloy design or when investigating customer queries.

Naturally, it is the mechanical properties of the weld which enter the final design procedures. There has been some progress in estimating the yield strength from the microstructure using combinations of solution strengthening, grain size effects, precipitation hardening and dislocation strengthening [1]. The ultimate tensile strength can in a limited number of cases be calculated empirically from the yield strength [2]. However, there has been no progress at all in creating models for vital properties such as ductility, toughness, creep and fatigue strength [3].

The failure of previous work [4, 5, 2] to create models with wide applicability comes largely from constraints due to the linear or pseudo–linear regression methods used, with poor error assessments and most importantly from the very limited variables and data considered in the analysis.

The purpose of the work presented in this thesis was to create quantitative models for the yield and ultimate tensile strength, ductility and toughness, using the special method of neural networks within a Bayesian framework [6]. This is non–linear regression analysis with many advantages which will be described later in the thesis. It was at the same time the intention to exploit the thousands of data in the published literature so that the models created are of the widest possible applicability. Model validation is a key feature of the work; this involves the design and experimental assessment of novel alloys which have never before been conceived, validation of a large variety of published data and testing against the known principles of physical metallurgy. The flow of the research is illustrated in Fig. 1.1.

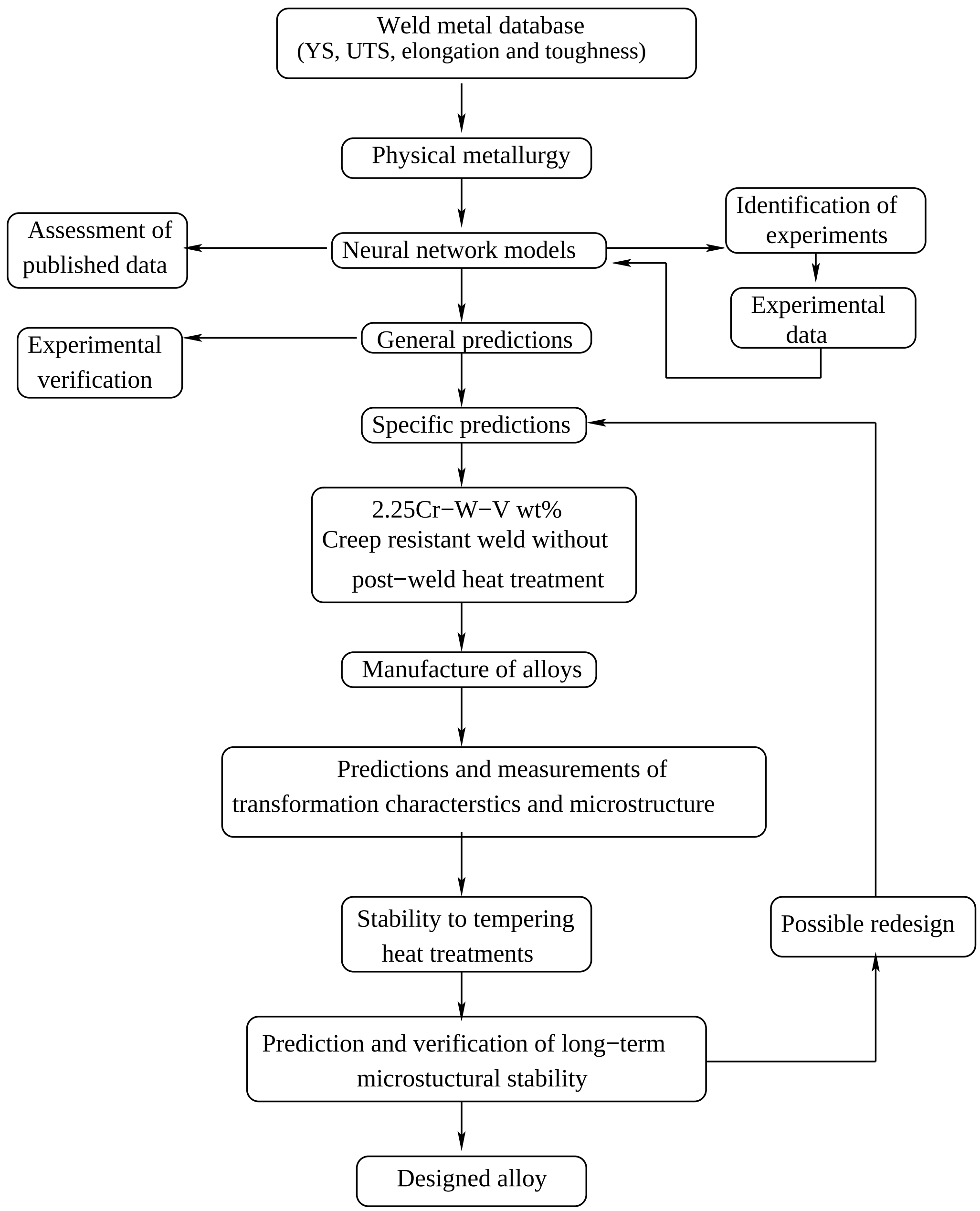


Figure 1.1: Flow diagram illustrating the research.

1.1 Welding Processes

Welding is one of the most popular joining methods for steels. The joining of two alloys can be done by melting the two surfaces to be joined by heat, with or without the help of a filler wire. The method by which heat is generated in order to fuse the base metal and filler wire defines the nature of the welding process: electric arc welding, electron beam welding, friction welding. The work presented in this thesis focuses on arc welds which are now described in some more detail.

1.1.1 Arc Welding

An electric arc is the source of heat to melt and join metals. As shown in Fig 1.2, an electric arc is struck between the work piece and the electrode which is manually or mechanically moved along the joint or electrode remains stationary while the work piece can be moved. The electrode may or may not be consumed during the process. The molten weld pool is protected by an inert or active gas shroud generated using flux or via an external supply of gases.

Manual Metal Arc Welding

This is also called the shielded metal arc welding (SMAW) process. Its simplicity and versatility makes it popular. A consumable electrode coated with flux (silicates, minerals and metals) is used as shown in Fig 1.3. The coating provides elements which act as arc stabilizers, generate gases and a slag cover to protect the weld pool from the environment and add alloying elements to the weld deposit. The electrode and workpiece are connected to a power source; usually the electrode is connected to the positive terminal of the power source. The arc is initiated by touching the electrode tip to the base metal and then forming an air gap. The heat generated as a consequence melts the base metal, the electrode core and its covering.

Gas Tungsten Arc (TIG) Welding

A non-consumable tungsten electrode is used together with an inert shroud. The key advantage of this process over manual metal arc welding is that higher quality welds can be produced. The equipment used in this process is portable and usable with all metals, for a wide range of thicknesses and in all welding positions.

Gas Metal Arc Welding

Gas metal arc welding (GMAW) uses a continuous wire which is consumed to form the weld metal together with an inert gas shield. The mode of liquid metal transfer from electrode to the base metal can be varied by choosing different types of gases. All metals can be welded by using argon or carbon dioxide. This process gives high weld metal deposition rates and can be automated.

Submerged Arc Welding

As the name indicates, the electric arc and molten weld metal are submerged under a layer of molten flux and unfused granular flux. The tip of a continuously fed consumable wire is the electrode. Because the arc is submerged under molten flux the radiation losses are minimised giving maximum energy efficiency. This is an automated process which can be used with the base metal in the horizontal position.

1.2 Variables Associated with Welding

The most important variables are the process, chemical composition of the weld deposit, heat input, the initial temperature of the base metal at the region to be welded (pre–heating), temperature of the weld deposit during multirun welding (interpass temperature) and heat treatment given to the weld metal after welding (post–weld heat treatment). The type of joint (Fig 1.4) and the material thickness have to be considered in selecting a weld process. The primary function of the heat source is to generate heat to melt the base metal and consumable electrode. The rate of melting is controlled by amount of heat input, defined as:

$$\text{Net heat input(J mm}^{-1}) = \frac{fIV}{S}$$

where I is the electric current in amperes, V is the voltage applied between power source terminal and electrode expressed in volts, S is the travel speed of the heat source in mm s^{-1} and f is the arc transfer efficiency. In most of the arc welding processes the efficiency is between 0.8 and 0.99. The weld metal composition plays a vital role in determining the mechanical properties of the weld joint and the microstructure of weld metal. A post–weld heat treatment is often given to the as–deposited weld to lower the hardness and restore the toughness.

1.3 Weld Microstructure

When a molten metal solidifies in the gap between components to be joined, this welds the components together. The basic metallurgy of the welded joint can be divided into two major regions: the fusion zone and heat affected zone (HAZ). The fusion zone experiences temperatures above the melting point of the material and represents both the deposited metal and the parts of the base metal melted during welding. The heat affected zone, (Fig. 1.5) on the other hand, represents the close proximity to the weld, where the temperatures experienced are below the melting point and there is a change in the microstructure of the base metal.

1.3.1 Weld Metal Solidification

In steels weld metal solidification starts at edge of the fusion zone into the weld metal with δ–ferrite as the initial phase (Fig 1.10). As it cools, δ–ferrite transforms into austenite and with further lowering of the weld metal temperature austenite decomposes to ferrite. Most steels contain small quantities of alloying elements and hence show similar crystal structure changes as pure iron. Therefore in weld metal solidification, weld deposits begin solidification with the epitaxial growth of columnar δ–ferrite from the hot grains of the base metal at fusion surface. The grains grow rapidly in the direction of highest temperature gradient and hence show an anisotropic morphology. Those grains with $<100>$ directions parallel to the heat flow direction dominate the final microstructure. On further cooling, austenite nucleates and grows along prior δ–ferrite grain boundaries, thus adopting the columnar shape of the δ–ferrite grains.

Fine austenite grains provide more grain boundary nucleating sites; on the other hand coarse grains increase the hardenability of the weld metal. The columnar shape of the austenite results in few grain boundary junctions when compared with an equi–axed structure. This also contributes to an increase in hardenability.

The cooling rates in the weld metal depend on the distance from the heat source, heat input, interpass temperature and the geometry of the joint. Because the cooling rates are in practice quite high, weld solidification is a non-equilibrium phenomenon and thus solidification–induced segregation promotes an inhomogeneous microstructure in the weld metal. The amplitude of these concentration and microstructure variations become larger as the alloy concentration increases.

Another important feature, in flux based welding processes, is non–metallic inclusions. During welding, the flux reacts with atmospheric oxygen and cleans and protects the weld metal by forming oxides and rejecting them into slag. However, the process is not ideal due to convection and rapid solidification, so oxide particles are entrapped in the fusion zone during solidification. These are called slag inclusions, which can serve as nucleation sites within the weld pool. A small volume fraction of inclusions is desirable in welding, as they serve as heterogeneous nucleation sites for acicular ferrite. Large fractions are detrimental to the mechanical properties of weld metal.

1.3.2 As–deposited Weld Microstructure

The as–deposited microstructure is that which forms when the liquid weld pool cools to room temperature. This structure contains allotrimorphic ferrite, Widmanstätten ferrite and acicular ferrite, Fig. 1.6. In a few cases, microstructures containing martensite, bainite and traces of pearlite can be found. High–carbon martensite is a hard microstructure with low toughness and ductility.

Allotriomorphic Ferrite

Allotriomorphic ferrite (α) usually forms between 1000 and 650 °C during cooling of steel weld deposits. Nucleation occurs heterogeneously at the columnar austenite grain boundaries. As the austenite grain boundaries are easy diffusion paths, austenite grain boundaries are decorated with thin layers of allotriomorphic ferrite and the thickness of which is controlled by the diffusion rate of carbon in austenite. In weld deposits, allotriomorphic ferrite appears to grow without the redistribution of substitutional alloying elements during transformation [8]. This mechanism of growth is termed "paraequilibrium", and occurs as a consequence of the fast cooling rates experienced by welds. In welds, allotriomorphic ferrite is detrimental to the toughness because the continuous network along grain boundaries offers less resistance to crack propagation than acicular ferrite [9].

Widmanstätten Ferrite

This microstructure results from further cooling below the temperature at which allotriomorphic ferrite forms. Primary Widmanstätten ferrite nucleates directly from the regions of austenite grain boundaries not covered by allotriomorphic ferrite. Secondary Widmanstätten ferrite nucleates at austenite/ferrite boundaries and grows as sets of parallel plates separated by thin regions of austenite. The austenite remains as retained austenite, or transforms to martensite or pearlite. These latter transformation products are collectively known as microphases in weld metal terminology, because they are generally present in small fractions. Widmanstätten ferrite is not desirable in weld metals.

Acicular Ferrite

Oxides and non-metallic inclusions serve as nucleation sites for acicular ferrite. Acicular ferrite forms within the columnar austenite grains in competition with Widmanstätten ferrite. It appears as a fine grained interlocking array of non–parallel laths. The microstructure is highly desirable in welds. The large number of non–parallel grains improve the weld metal toughness by increasing the resistance to crack propagation [10].

Microphases

These are last constituents to form in weld metal. Microphases correspond to the small carbon–rich regions in the weld metal where the last remaining volumes of austenite transform, and consist of mixtures of martensite, carbides, degenerated pearlite, bainite and retained austenite.

1.3.3 Secondary Microstructure

In many circumstances it is difficult to fill the gap at the joint by a single weld pass. Therefore thick sections are welded using many layers of deposited metal, Fig. 1.7. The deposition of each successive layer heat treats the underlying microstructure formed during cooling of the previous run. Some regions of the underlying layers are reheated above the austenitisation temperature, whereas others become tempered. All of the reheated regions contribute to the secondary microstructure.

The Heat Affected Zone

The heat affected zone is the portion of the metal which has not experienced melting, but whose microstructure is altered due to welding heat. There are well–defined microstructures in the heat affected zone as illustrated in Fig. 1.8. The region immediately adjacent to the fusion boundary is heated to very high temperatures (just below melting temperature) and forms coarse austenite. The austenite grain size decreases sharply with distance from the fusion line and the fine grained zone will have superior mechanical properties than the coarse grained zone. Moving further away, the peak temperature decreases and will result in partial austenite formation and tempered ferrite in that region; this is called the "partially austenitised zone". The region adjacent to this zone, which is not transformed to austenite will be tempered.

1.4 Ferritic Steels

Pure iron at room temperature has a body–centered cubic crystal structure, with the common designation α–ferrite, Fig 1.9. Between 910 and 1410 °C, face–centered cubic austenite (γ) becomes the stable phase, to be replaced again by δ–ferrite at higher temperatures, Fig. 1.10. The δ and α forms of ferrite have identical crystal structures. Steels usually contain alloying elements such as carbon, manganese, silicon, etc. Some are added deliberately, whereas others are present as impurities. Carbon is the main alloying element in steels, frequently present in the form of cementite. Cementite has the chemical formula Fe_3C. Some alloying elements such as carbon, manganese and nickel stabilise austenite, whereas tungsten, chromium, vanadium and niobium stabilise ferrite [11]. The latter also tend to form alloy carbides. The alloying of steels is a very large subject which has been reviewed [12].

1.4.1 Heat Resistant Steels

A power station converts fuel into electrical energy; in the case of fossil fuels, this is via steam. A power generation loop is shown schematically in Fig 1.11. Water is converted into steam in an evaporater before entering into the steam drum, where it is collected in headers. It is then superheated before passing into the high pressure (HP) turbine, after which it is reheated before enters into the intermediate pressure (IP) turbine. After leaving the IP turbine it enters the low pressure (LP) turbine. The exhaust steam is finally condensed and returned to boiler.

Steels are used widely in the construction of power plant. They have to resist creep deformation, oxidation and corrosion. The superheater pipes carrying steam from boilers to high pressure (HP) turbines typically experience steam at 565 °C under 15.8 MPa pressure and are made of low–alloy steels. In HP turbines the rotor is fabricated as a single forging of 1Cr-MoV steel. Tempering at 700 °C leads to the formation of stable carbides which are distributed uniformly in the ferrite matrix. These carbides improve the creep resistance at the service temperature [13]. Turbine blades experience both erosion and high tensile forces. High strength and corrosion resistant 12CrMoV steel is used in fabrication of turbine blades [14]. The $3\frac{1}{2}$Ni–Cr–Mo–V alloy has good hardenability combined with high strength of about 1100 MPa and good toughness. These steels are air cooled from 870 °C and tempered at 650 °C. Due to their high strength and toughness these materials are used to fabricate the low pressure turbine rotor, which is nearer to the generator. The generator rotor is also fabricated with this material [15].

Steel	**C**	**Si**	**Mn**	**Mo**	**Cr**	**V**
$2\frac{1}{4}$Cr–1Mo	0.15	0.50	0.45	1.0	2.25	-
12Cr–1Mo	0.15	0.40	0.6	1.0	12	-
$3\frac{1}{2}$Ni–Cr–Mo–V	0.15	0.30	0.70	0.19	1.5	0.11

Table 1.1: Chemical composition of some steels have been used in power plant [16], all units are in wt%.

Cr-Mo Steels

These materials are resistant to corrosion by sulphur products and hence were used first in the petroleum industry. Once their oxidation resistance and high temperature strength were appreciated, they began to be applied in the steam power generating industry. More recently, these steels have been used in fabricating thick pressure vessels. The oxidation resistance and high temperature strength depends on the amount of chromium and molybdenum present in that alloy. Excellent high–temperature (565 °C) strength is obtained in $2\frac{1}{4}$Cr–1Mo steels (Table 1.1), which are generally used in the bainitic condition. A tempering heat–treatment gives the required alloy carbides; the most important are M_2C, M_7C_3 and $M_{23}C_6$, where M represents a metallic element.

1.4.2 Structural Steels

Steels for structural applications are used at ambient temperatures and the main property requirements are strength, ductility and toughness. The vast majority of these steels have a yield strength in the range 350–550 MPa with a mixed microstructure of ferrite and pearlite. These are used in critical applications, such as bridges, buildings or ship construction and may undergo sophisticated thermomechanical processing to refine the microstructure and greatly improve the toughness. Such alloys may contain quantities of fine bainite or even martensite when the overall carbon concentration is small.

All structural steels have to be welded. For this reason and to minimise the cost, the total alloy concentration is generally less than 5 wt%. The weld metals used for joining structural steels also range in yield strength between 350 and 550 MPa, but can be much stronger (900 MPa) for special steels used in the construction of submarines. The preferred weld microstructures contain large quantities of acicular ferrite which, because of its scale and chaotic arrangement, gives good toughness. However, quantities of allotriomorphic ferrite, Widmanstätten ferrite, martensite and retained austenite may also be present.

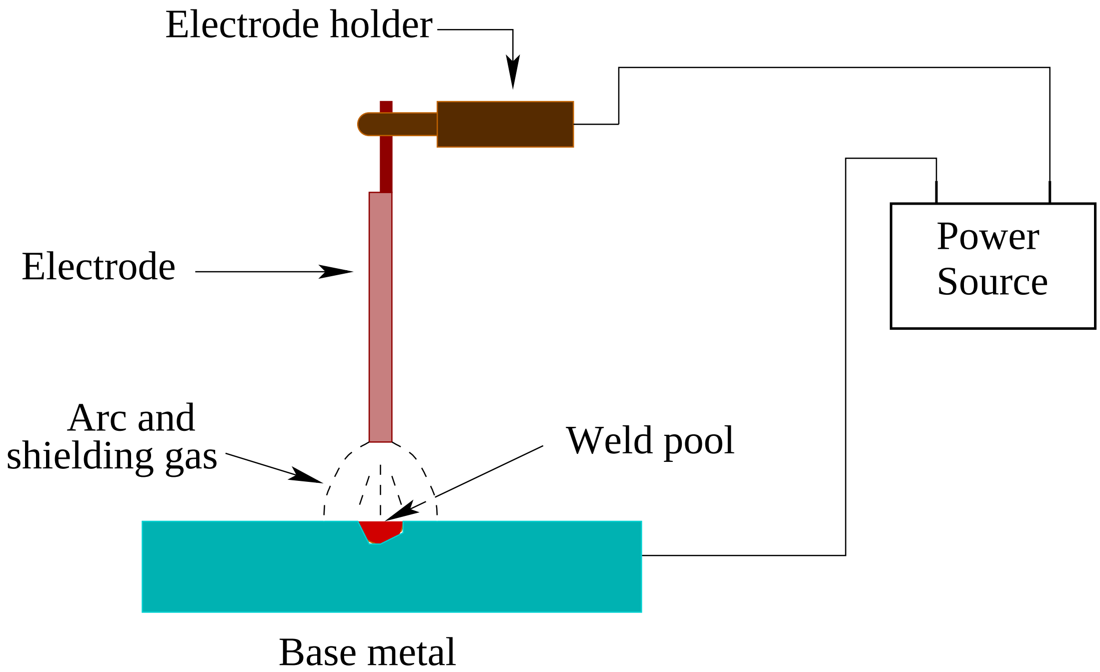


Figure 1.2: Schematic view of arc welding process.

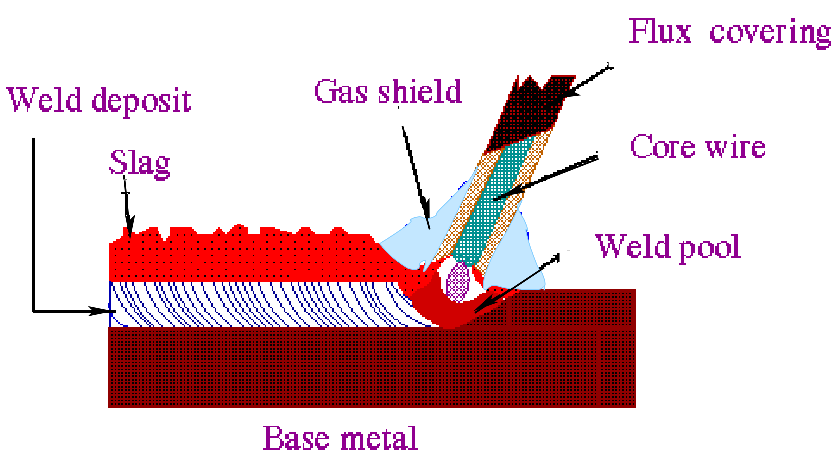


Figure 1.3: Schematic view of manual metal arc welding (MMAW).

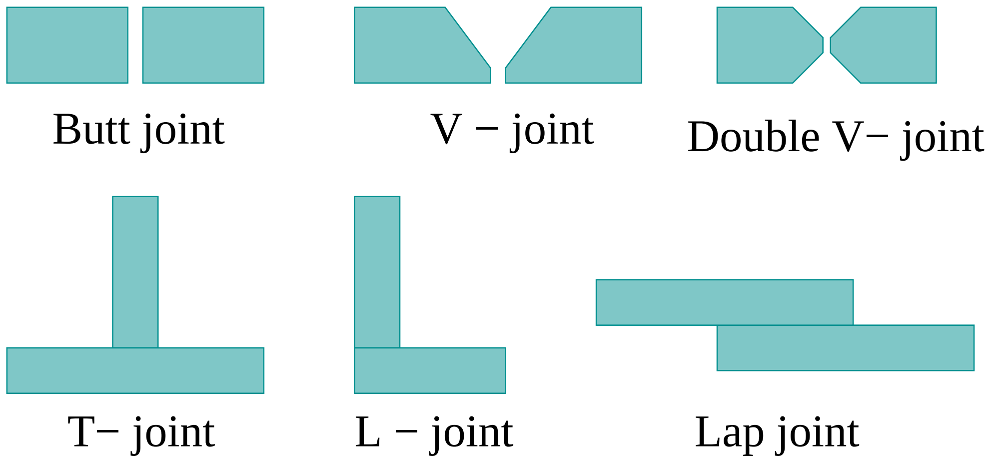


Figure 1.4: Different types of joint preparations.

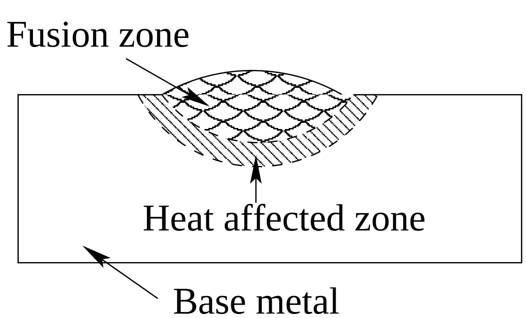
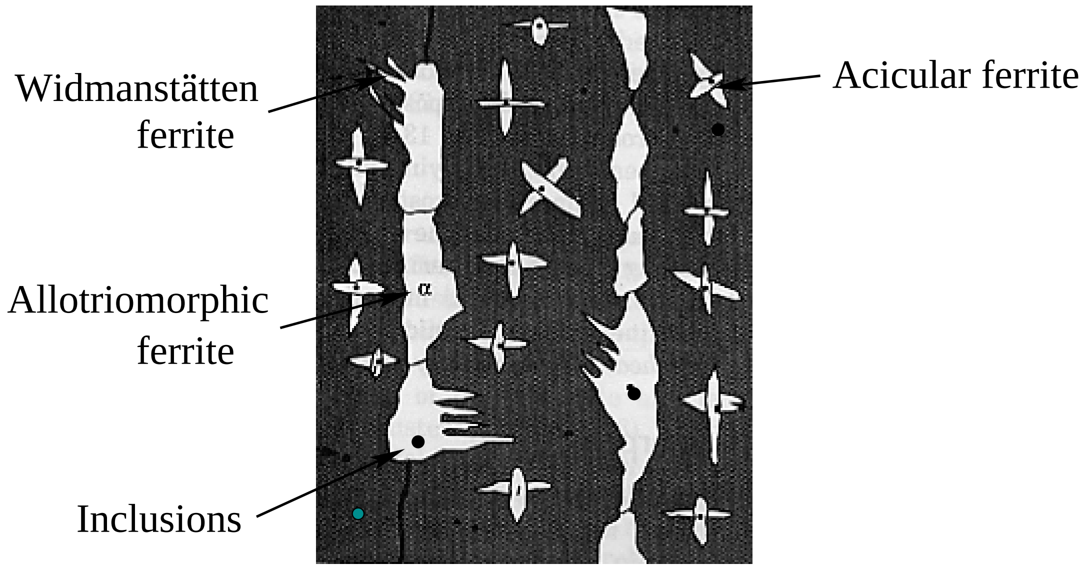
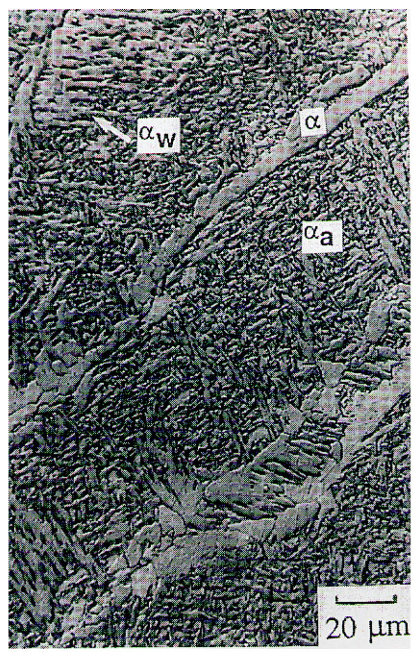


Figure 1.5: Schematic view of the various zones in a single pass weld metal.



(a)



(b)

Figure 1.6: a) Schematic diagram showing different constituents of the primary microstructure in the columnar austenite grains of a steel weld [3], b) scanning electron micrograph of the primary microstructure of a steel weld [7]. α–allotrimorphic ferrite, α_w–Widmanstätten ferrite and α_a–acicular ferrite.

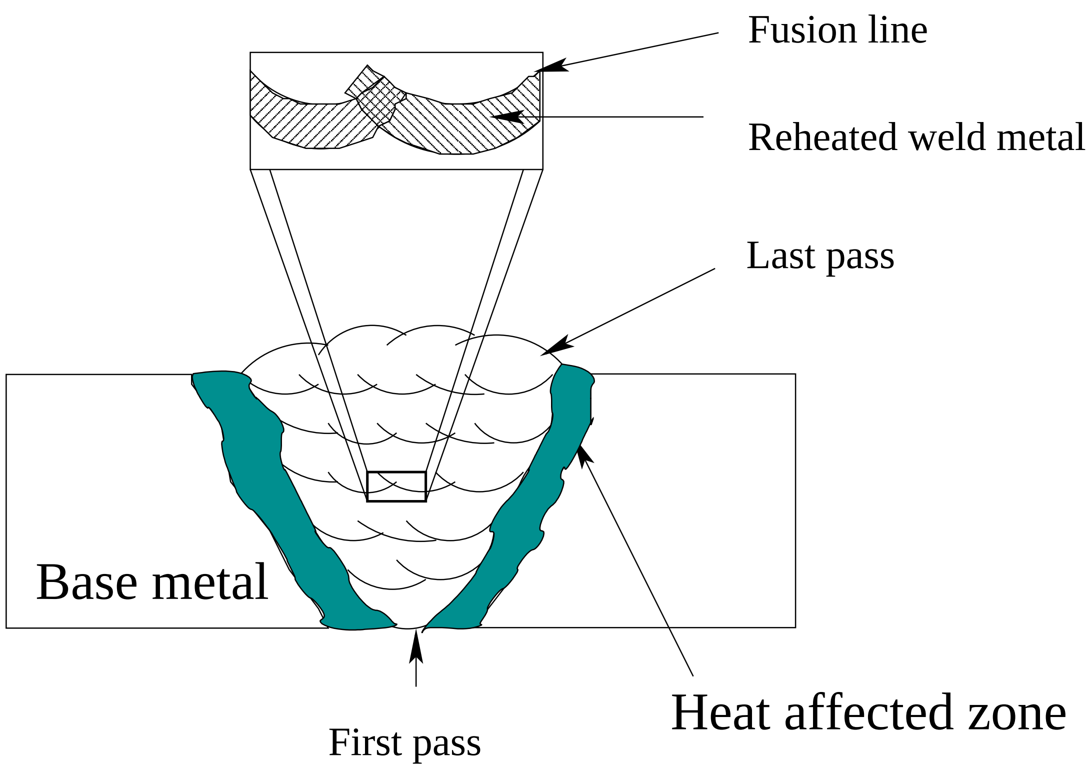


Figure 1.7: Various regions in a multilayer welding.

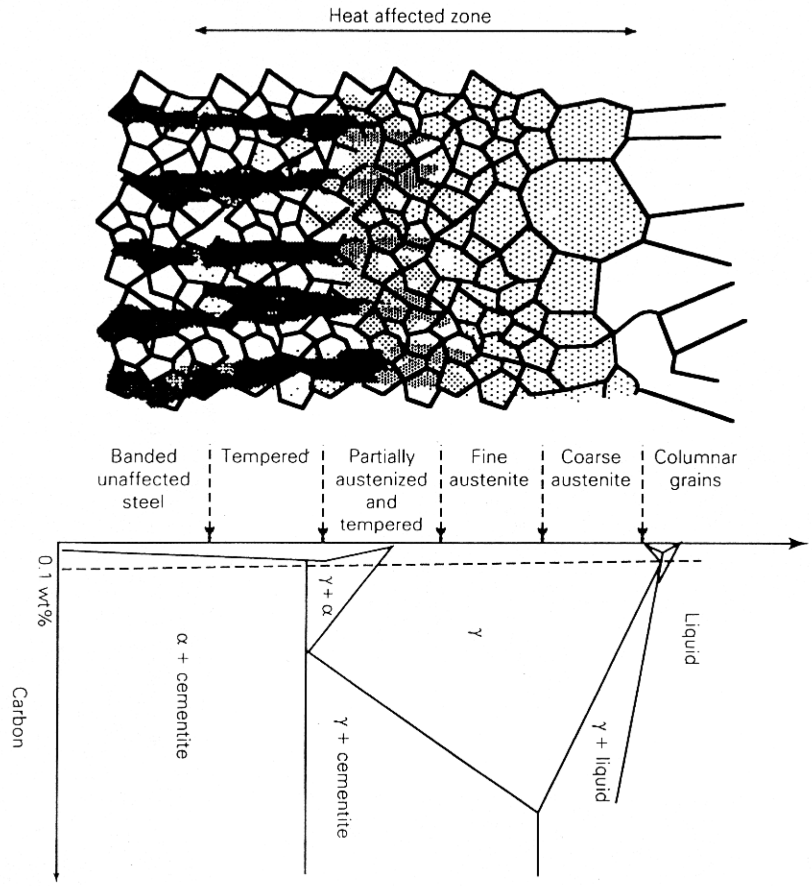


Figure 1.8: Microstructural variations in heat affected zone [7]. The banded structure is a characterisitic feature of segregated steels which have been rolled.

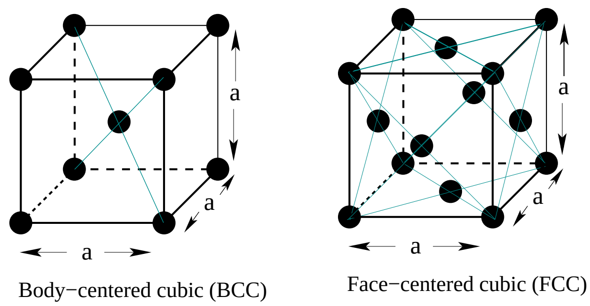


Figure 1.9: Schematic view of frequently observed crystal structures in steels.

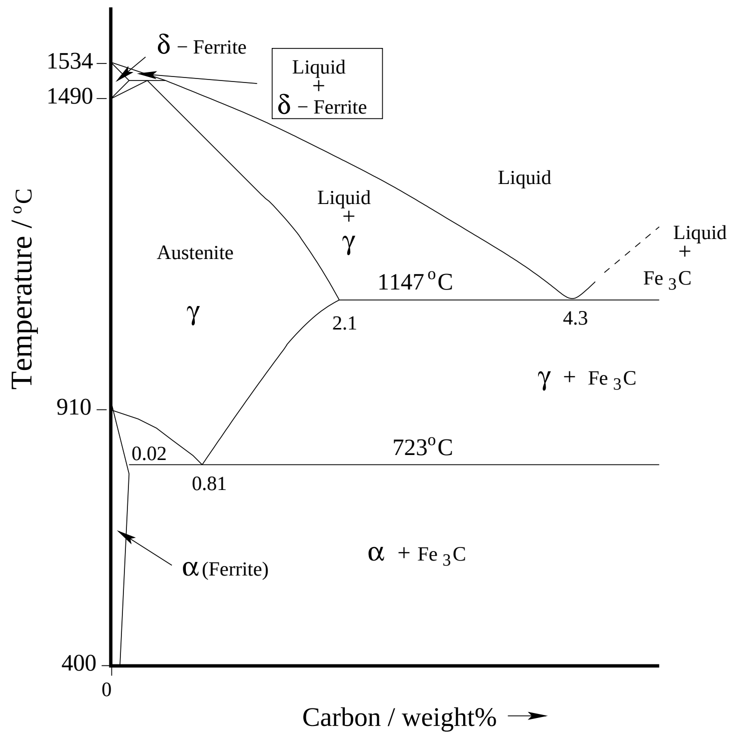


Figure 1.10: Schematic iron–cementite equilibrium phase diagram.

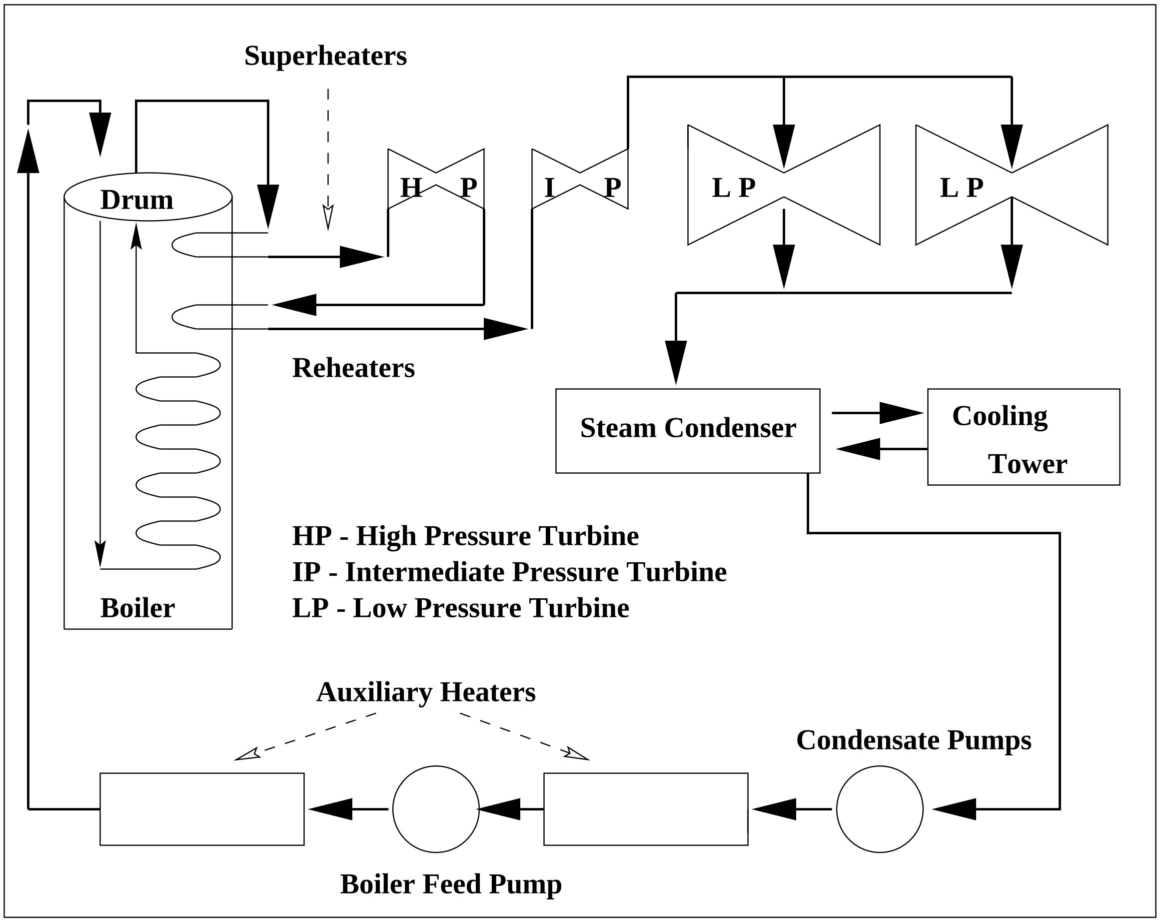


Figure 1.11: Schematic view of the components of a steam power plant.