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**Analysis of Fatigue Crack Properties of the Weld
Metal of Gas Metal Arc Welded 300WA Steel**

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Master of Technology (Mtech)**

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Abstract

Welded joints are major causes for concern in the engineering arena for two basic reasons. In the first instance the weld is known to be a region of weakness within a structure and is caused by residual and applied stress concentrations. Secondly, the behaviour of the stress patterns is somewhat difficult to predict accurately due to the difficulty of conforming to the geometry and process parameters.

The experimental procedure in this work commenced with specimens being welded with a technique very commonly used in industry. The residual stresses generated by thermal fluctuations from the welding process cannot be predicted easily and is viewed as a problem as increased stress levels promotes failure. Residual stresses were then determined with the use of an ultrasonic stress measuring device. Strain gauges were used to measure strains in the welded specimens and these strains converted to stresses. The results of the two methods were compared and analysed.

Compact tensile specimens were used to perform fatigue testing. The results confirmed findings from earlier research such as the proportion of cyclic life spent on initiating the crack. Hardness tests were performed to determine if any relationship existed between fatigue failure, yield strength and hardness. Finally metallurgical analysis revealed the phases and structures of the weld and heat-affected zones.

The findings of this research indicate that close relationships exist between the cycles to crack initiation and ultimate fracture, the hardness, yield stress and the fatigue life of the weld as well as between the grain diameter and the yield stress. Furthermore it is shown that there was not enough information gathered in this research to conclude that the life expectancy of 300WA welded steel can be predicted. However recommendations are made for future research in the prediction of failure of the 300WA welded steel.

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Chapter 1

Introduction

Carbon steel is the most commonly used engineering material, because of its abundance; its wide range of desired mechanical properties and the fact that it can be manufactured relatively cheaply in large quantities. Its uses include ship building, vehicles, aircraft, building construction, pressure vessels, etc. The joining process (welding) of steel is also a process that is learnt with ease and is widely used in industry for various applications.

Welded joints are found extensively in the manufacturing and process industry and because of the welding process, residual stresses occur within them. This is caused by changes in thermal cycles during welding. It is the residual stresses that pose the greatest threat to fatigue life and thus the stress distribution within the weld is a fundamental parameter to the prediction of its life cycle. Fatigue failure is an unwanted, disruptive and costly occurrence that industry can do without. This is why so many investigations are performed in order to predict the fatigue behaviour of the welded joints. The demand for better material and weld specification is a critical aspect in design, considering the low probability of fatigue and crack initiation detection, prior to material failure in operation.

The purpose of this research is to study the fatigue properties of a welded joint and how it relates to metallurgical phases in the weld. The project also will examine the effect of cyclic loading on the microstructure in a welded joint. Stress patterns associated with the evolution of the welded specimen will be analysed prior to fatigue failure, by using ultrasonic stress measurement as well as strain gauge measurement.

The use of the ultrasonic stress- measuring device (Debro-3.0) to determine the stress state of the material will be applied and described. This device has the capability to detect sub-surface macro stresses along a finite path length.

The Debro-30 stress-measuring device, which has been used for this research, applies the principle of the acousto-elastic effect. Ultrasonic waves, which are stress dependent, are generated and penetrate the material and record the subsurface stresses to a depth of two millimeters (2mm). For accurate measurements, the device relies on input parameters to be determined by experiment representing the reference time of flight on an unstressed test specimen, followed by measurements of the specimen while it is subjected to a tensile load.

Strain measurement is of particular importance in that it serves to compliment the ultrasonic stress measurements. Strain measurements are recorded from a material and are converted to stress. The results of the two techniques can be analysed and compared. It is of utmost importance that care should be taken when using the equipment to measure strain, especially if the rosette strain gauge is used. This technique employs the hole-drilling method and it is the accuracy of this drilled hole that determines the authenticity of the results.

Various organisations and institutions developed modern analytical and computational techniques in order to enhance the performance of material and weld specifications. The use of a fatigue-testing machine as an experimental analysis determines the life cycle of the welded material. Fatigue assessments of welded joints that have been applied recently in research laboratories include critical distance methods (CDM). This direct approach uses stress values at critical distances from the weld, taken from finite element analysis. The stress averaging method experiences the same effect by using a fictitious radius concept. The use of CDM in conjunction with FEA was found to generate

excellent results. These methods were applied to a fatigued T-shaped welded joint containing a drilled hole [3].

The Frost-Dugdale linear relationship that exists between the log of the crack length or depth and the service history (number of cycles) has been developed and serves as a first approximation [4].

$$\ln(a) = \beta N + \ln(a_0) \text{ or } a = a_0 e^{\beta N} \quad [1.1]$$

were: N = fatigue life

β = geometrical parameter (material & load dependant)

a = crack depth

N = time

a_0 = initial crack size

This relation has been used extensively, especially in the Australian Defence Science and Technology Organisation.

As in the case of welded joints between carbon steel pipe and 304 stainless steel elbows in a piping system of a petrochemical plant, cracks developed after a very short period. Light optical metallography and scanning electron microscopy, combined with energy dispersive X-ray spectroscopy, inductively coupled plasma and micro-hardness testing were employed in the quest to determine the root cause of failure [5].

Welding is commonly employed in the engineering industry and is considered to be the best joining method for metal. However, due to the heterogeneity induced by welding, the base metal, the weld and heat affected zones display varied mechanical behaviour, thus making welded joints complex under local stress-strain conditions [6].

Gas metal arc welding is a process where metal is melted and joined together by means of heat generated from an electric arc. Various welding techniques are applied in industry, but the one that is most prevalent and accounts for 50% of weld deposits, is the metal inert gas (MIG) welding technique. This welding technique takes less time and skill to learn than sheet metal arc welding or commonly know as stick welding. Yet technical expertise is required to draw up welding specifications that incorporates and compliments all aspects of the design to which the welding joint is applied. These specifications should include applied loads, life cycle, material properties of structure and weld filler material, welding heat generated, etc. A very important aspect of weld specification would be the control of residual stresses as these make the weld more susceptible to fracture.

The life cycle of a steel structure is dependent on the relationship between the imperfections within the welded joints and the stresses (residual and applied) to which it is exposed. Depending on the magnitude, the sign and the distribution of the stresses, it may either be of a beneficial or a detrimental nature to the service performance of the structure. Applied stresses are known stresses and can be accounted for when designing a component, but residual stresses are unpredictable and difficult to measure reliably.

With the advancement of technology and the drive to continually improve material performance and minimise material weight, there is an overwhelming emphasis placed on understanding the function of residual stress. Residual stresses are those stresses, which are inherent in a material resulting from manufacture, fabrication or assembly.

The significance of residual stresses is dependent on the material and its application and is classified by the scale over which they are significant. Macroscopic residual stresses exist over large distances, whereas microscopic

stresses are evident over single grains.

During the welding process complex thermal transitions take place and non-elastic or incompatible strains are produced in the weld area and heat affected zone (HAZ). These strains result in residual stresses in a material and the presence of cumulative stresses in large structures can result in premature failure.

Since the use of steel forms a large part of the industrial market, many studies have been conducted with the view to improving their strength, hardness, ductility, toughness, etc. In order to study the behaviour of a material, it is imperative to understand its microstructure at significant stages.

The heat-affected zone is the area close to the weld where the heat input during the welding process changes the microstructure of the base metal without melting the steel. The microstructure is indicative of the material properties. Various phase transformations and changes in grain size may be present in a microstructure and this is due to temperature variations caused by the heating and cooling cycles during welding particularly temperatures above the critical temperature

The understanding of the microstructure of a material is an important aspect of design specification and a direct relationship exist between the microstructure, material properties and the life cycle.

Fatigue failure is defined as the process of progressive localised permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations [2].

Failure analysis is a faultfinding procedure and a critical process in determining the root cause of so many problems experienced in industry today. A clear understanding of the definition of failure and the difference between an indicator, a cause, a failure mechanism and a consequence, is fundamental and a logical approach to failure analysis.

Fatigue cracks initiate and propagate in regions most prevalent to strain. The process of fatigue consists of three stages:

- Crack initiation
- Progressive crack growth
- Subsequent fracture

Design improvements to the fatigue performance of material and components, remain the most effective means of combating fatigue failure.

In order to prevent the occurrence of fatigue failure, it is very often required to have a sound knowledge of metallurgy so as to fully understand the fundamental root cause of fracture of the component or material. Fatigue failure suggests that a material has become completely or partially unsuitable for use or has deteriorated to such an extent that it is unreliable or unsafe for normal sustained service.

Chapter 2

Metal Inert Gas Welding

2.1 Introduction.

The following chapter reviews metal inert gas welding as it pertains to the engineering industry today.

Since the early ages man has been forming, shaping and working metal to be used in various industrial fields. Joining these metals was a tiresome, laborious and expensive process. The primary joining process was to hammer metals together by blacksmiths. Riveting also became a common joining technique in the Iron Age. As the demand for metal products increased, more improved metal joining techniques were sought after.

Presently welding is used as a metal joining technique and is considered to be an important industrial skill and is the most common, economic and efficient way of permanently joining metals. Welding is also classed amongst the highest industrial processes that include science and variables. Research to improve welding and welding processes has been and is an important issue in mechanical engineering design. Due to the increase in technological requirements, e.g. taller buildings, bigger ships, safer industrial equipment, etc. metal joining methods are becoming inadequate and thus research in this field is driven by a constant technology boost.

In the welding process enough heat is applied to two metal objects, causing them to melt. The molten metal fuses and solidifies, resulting in a permanent bond.

This contamination is caused primarily by nitrogen, oxygen and water vapour present in the atmosphere [16].



Figure 2.1: A modern MIG welding machine with consumable wire [23].

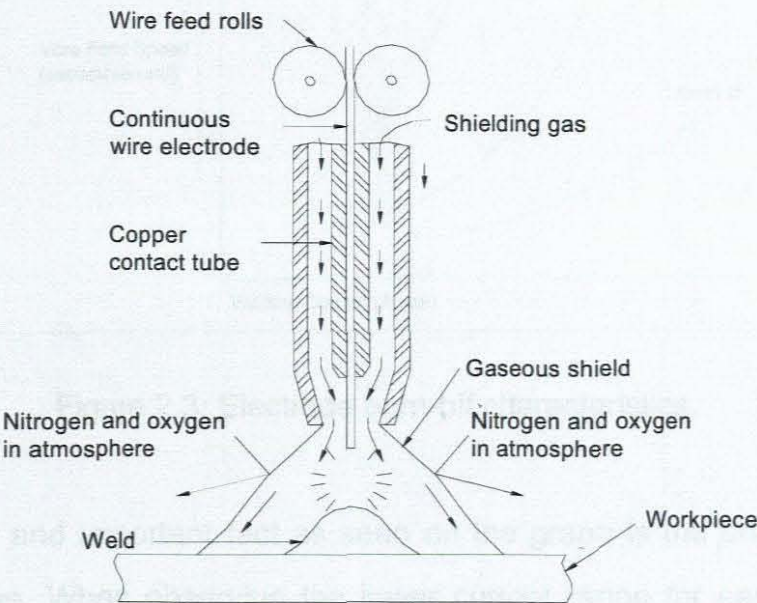


Figure 2.2: A sectioned view of a MIG welding nozzle in operation [10].

The welding process can be either semi-automatic or automatic due to most or all of the welding parameters being controlled by the machine. Before welding

commences, the welding operator sets the controls to achieve the desired weld. If during welding, the welding nozzle is held too close to the work piece, the current automatically increases and the wire is burned up faster than it is fed so as to correct the arc length. If the nozzle is raised too high from the work piece, the current automatically decreases and the wire is fed faster than it is burned up so as to re-establish the correct arc length [35].

The welding current and welding speed is interlocked resulting in the welding arc being self-correcting. Therefore when the electrode feed speed is increased according to the electrode diameter, the welding current will vary in a similar manner to maintain a constant burn-off rate by the electrode. This relationship is commonly termed the burn-off characteristics.

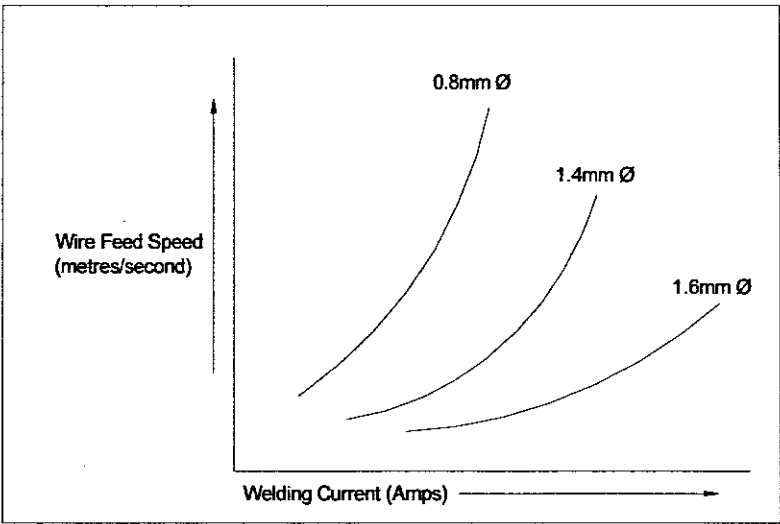


Figure 2.3: Electrode burn-off characteristics.

A noticeable and important fact as seen on the graph is the shape of each burn-off curve. When observing the lower current range for each electrode diameter, the curve is nearly linear. Thus as the current increases, there is a proportional and constant burn-off rate of the electrode. However at higher welding currents and using small diameter electrodes, the burn-off curve becomes more non-linear.

In the MIG welding process the filler metal is transferred directly through the arc and there are two basic types of metal transfer, viz. the open arc method and the short circuit method. In the open arc method the molten metal is transferred across a gap from the electrode to the material to form a weld. In the short circuit method the electrode must be in contact with the material in order for weld metal to be deposited [17].

The spray transfer, globular transfer, pulsed transfer and the submerged arc transfer are all known as open arc transfer. The metal transfer category depends on the welding current, voltage, shielding gas and the electrode size. The spray transfer is a high heat, high current welding method with high deposit rates and deep penetration. Fine molten metal droplets are transferred from the electrode to the parent metal in a spray form. These droplets are equal in diameter or smaller than that of the electrode. Spray transfer is applied with the use of inert gas, bare electrode and direct current reversed polarity [18].

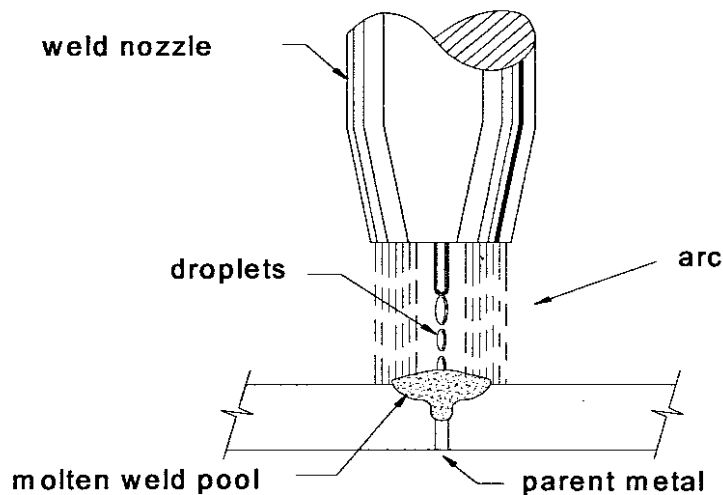


Figure 2.4: Spray transfer clearly shown in the diagram [35]

Globular transfer varies according to the current. This current has a considerable effect on the metal transfer. At high currents, the filler material is transferred as a spray and with lower currents it is transferred in large globules.

The globules may increase up to three times the size of the electrode before the globule is transferred across the arc to the parent metal. A large amount of spatter is experienced with globular transfer and is primarily used for thin sheet material. [35]

Pulsed arc transfer is achieved by a pulse being sent back and forth between the spray transfer and the globular transfer current ranges. Spray transfer can take place in evenly spaced pulses instead of continuously. Thus spray is separated from the electrode at regular intervals corresponding to the pulsing frequency. The pulsing current is highest in the spray transfer and lowest in the globular transfer modes respectively [17].

Short circuit transfer takes place when the electrode is in contact with the parent metal only. Thus no transfer takes place across the welding arc. This welding technique results in the molten filler metal being less fluid and shallow penetration is achieved. Contact between the electrode and the parent metal causes a short circuit and an arc is observed. At this point the electrode heats up to such an extent that a globule is formed and contact between the electrode and the parent metal is lost. As the electrode is fed, contact is resumed again. This process is a series of short periodic short circuits [18].

The MIG welding process provides a number of advantages in semi-automatic and automatic applications and includes [20]:

- High quality welds at high speeds.
- No post weld flux cleaning is required.
- Thin and thick material can be welded.
- Operational costs are minimised.
- The MIG welding process is easy to learn.
- Starting and stopping of welds due to the changing of electrodes as in other welding processes are eliminated.

- Weld spatter is minimised.
- Welding in all positions can be achieved.

2.3 The Mig Welding Electrode (Filler Wire)

The choice of Mig welding electrode, which also acts as a filler rod should be considered as one of the most important aspects for the correct weld parameters. A combination of the correct shielding gas and welding filler material will result in the desired mechanical properties for the weld, being achieved. There are a few considerations to adhere to when selecting a filler wire prior to welding, viz. [20]

- The base/parent metal chemical composition.
- The base/parent metal mechanical properties.
- The type of the joint to be welded.
- The shielding gas to be used.
- The weld specifications.

Due to extensive research done by various welding institutes such as the American Welding Society, filler wire have been developed, manufactured and standardised to such a degree that a single type of wire can be used for various parent metals with the desired results [20]. Mig welding filler wire is substantially thinner than that of stick-welding as it requires no shielding flux. Also with the thinner wire it is easier to control the weld in awkward positions and a good weld can be achieved with very thin plate. A high burn-off rate due to a high current, results in a continuous and uninterrupted weld deposition. Also various size welds can be deposited in various size weld joints with a minimal amount of weld beads.

All metallic filler wires share similar alloying elements that are added to steel. When welding carbon steel, the primary function of the alloying elements is to control de-oxidation of the weld puddle and in so doing help establish the

mechanical properties inherent to the electrode. Oxygen from the weld puddle combined with an element, results in a glass-like formation on the surface of the weld called slag. Silicon (Si) is the most commonly used de-oxidizing element for MIG welding filler wire. Depending on the intended use, filler wires usually contain between 0.4%-1% Si. An increased amount of silicon increases the strength and decreases the ductility and toughness minimally. Increasing the silicon to between 1-1.2% will induce crack sensitivity in the material [14]. Other elements include Manganese (Mn), which strengthens the material, Aluminium (Al), Titanium (Ti) and Zirconium (Zr) being very strong deoxidisers [14].

The Carbon (C) content has a more profound influence on the structural and mechanical properties of the weld than any other element and is usually between 0.05-0.12%. This amount is sufficient to ensure the provision of strength without affecting ductility and toughness [14].

2.4 The Mig Power Supply

The Mig welding process uses a direct current reverse polarity (DCRP) power supply for optimum efficiency. DCRP contributes to better melting, deeper penetration, and an excellent cleaning action [35]. The positive electrode also removes the oxide layer and expels oxide inclusions and in so doing facilitates the fusion process. Rectifiers and motor generators are mainly used in the Mig process with the electrode connected to the positive terminal. One of three categories of power sources can be used viz., a Constant Voltage (CV), Constant Current (CC) or a power supply that is capable of both (CV/CC) [35]. CC machines are primarily used for other welding applications such as Tig and Stick welding but by simply adding a wire feeder, Mig welding is possible.

2.5 Constant Voltage Power Supply

As the current flows through the gap between the tip of the electrode and the work piece, heat is created and an arc is formed. As this arc varies, so does the amperage. In order for a weld to be uniform, the arc and the voltage must remain constant, hence a CV power supply [35]. Even if the current drawn varies, the voltage that has been set prior to welding, will remain constant and the power supply is self correcting. Therefore no current adjustments can be done on a CV machine because the current is regulated by the wire speed. The power source supplies enough current to burn the electrode off as fast as it is fed and to maintain the correct arc dictated by the voltage adjustment [10].

2.6 Wire Feeding Unit and Control.

A wire-feeding unit is used in conjunction with a CV power supply. The wire reel is driven by rolls and is fed through a cable and the welding gun and eventually through the contact tube. The wire feed speed can be set according to the correct welding current as required for different applications. This can be done by adjusting the variable speed mechanism, which is situated in the control panel. Wire feed and gas flow is actuated by this mechanism because it employs automatic devices that allow it to start and stop as soon as the gun trigger is activated. The mechanism also contains the components that actuate the contactor in the power source in order for the current and voltage to be applied to the electrode. [17] The wire-feeding unit is portable and allows the welding operator to detach the feeder from the rest of the machine when necessary, with only the power supply which links the two, attached. The portability of the feeder depends entirely on the length of the power supply. Various size welding wire can be used in this unit provided that the rolls that drive the wire is appropriate. Two types of wire feeders exist, viz., the push and the pull type. The push type is still utilized in the modern machines and is more suited for thicker wire, whereas the pull type machines are suited for thinner and more flexible wire such as aluminium. [10]

2.7 Mig Shielding Gas

The primary function of the shielding gas system is to supply gas to shield the weld arc from contamination by the surrounding atmosphere. The shielding gas displaces the air in the arc area and the arc is then struck under the blanket of shielding gas and the welding is accomplished [14]. Shielding gas therefore plays a huge part in the properties of the weld. Without shielding gas impurities from the atmosphere enters the weld pool with destructive effects to the weld.

Contamination is caused mainly by nitrogen, oxygen and water vapour in the atmosphere. Nitrogen reduces the quality of the weld, in that it reduces the ductility and impact strength of the weld and causes weld porosity [14]. If excess oxygen is combined with the carbon in steel it forms carbon monoxide, which can be trapped in the weld and results in porosity [14]. Similarly, hydrogen in water vapour, if combined with iron or aluminium may result in the weld cracking [14].

Argon, helium and carbon dioxide are the three main shielding gases used in the MIG welding process and the gas selection depends entirely on the type of material being welded. Certain other gases such as oxygen, nitrogen and hydrogen, in small amounts are used in conjunction with the three primary gases to enhance certain welding applications [14]. Of all the gases used only argon and helium are inert gases. Argon, helium and carbon dioxide are the only gases that can be used in combination or as a mixture with other gas to produce a specific mig weld.

2.7.1 Gas Properties

The mig welding gas has three basic properties that has an effect on the

welding process and are [14]:

- The chemical reaction of the gas with the various elements in the parent metal and the filler wire.
- The effect of the gas on the mode of metal transfer.
- Their thermal properties at high levels.

The arc voltage and the thermal energy present at the weld area is influenced by the thermal conductivity of the gas at arc temperatures. With an increase in thermal conductivity an increase in voltage is required to sustain the arc. When welding with Helium (He) and Carbon Dioxide (CO₂) an increase in voltage and power is necessary to maintain a stable arc. This is so because helium and carbon dioxide have a higher thermal conductivity than that of argon and deliver a greater amount of heat to the weld area. The compatibility of each gas with the wire and base metal determines the suitability of the various gas combinations [14].

Carbon dioxide and most oxygen bearing shielding gases should be avoided when welding aluminium since aluminium oxide will form. However carbon dioxide and oxygen are beneficial at times and even essential because it promotes arc stability and good fusion between the molten weld and the parent metal. Shielding gas also determine the mode of molten metal transfer as well as the depth of weld penetration in the base metal [14].

A weld produced with argon, results in a narrow weld with deep penetration at the centre of the weld deposit. This narrow bead is achieved due to the arc being constricted by the gas and high arc densities are produced [10].

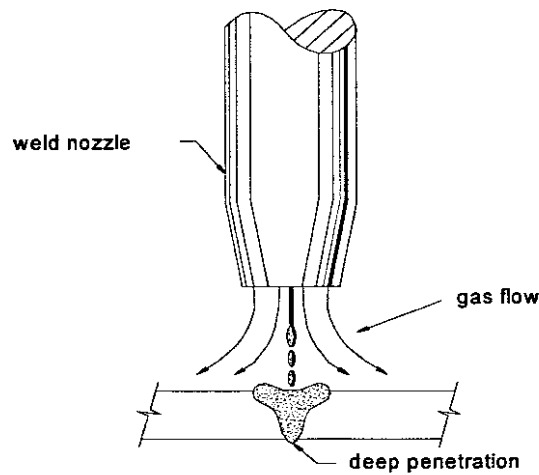


Figure 2.5: Narrow weld bead with deep penetration produced by argon [35].

When applied to thicker plate this deep penetration characteristic is not evident and argon is best suited for nonferrous metals and carbon steels when combined with other gases. Because the thermal conductivity of argon is low, this gas is well suited for thin plate. For a specified arc length, argon will produce a lower arc voltage than helium. Argon gas produces a laminar flow to the arc, which results in a stable arc, which in turn results in drastically reduced spatter and weld contamination. Manual or mechanised operations can be used with this gas since a change in the arc will not result in a marked change in arc voltage and heat input. [10]

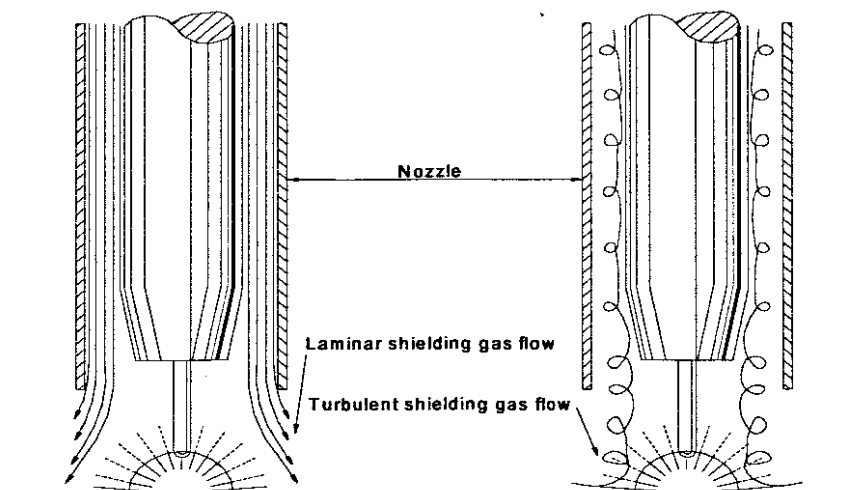


Figure 2.6: Turbulent and laminar gas shielding flow [35].

Helium characteristics are more appropriately suited for thicker materials because of its high thermal conductivity with a greater arc heat and its greater wire burn-off rate. A weld produced with helium results in less penetration and a wider bead. Because of the high heat input to the weld, the metal transfer from the electrode is large and this causes a rather wide and flat bead with excess spatter [35].

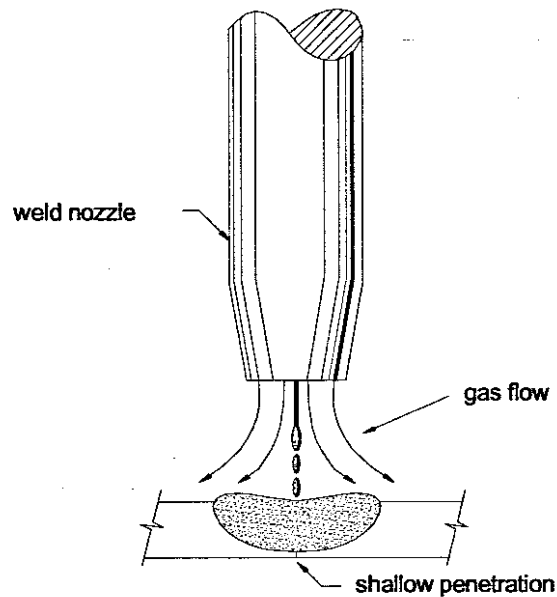


Figure 2.7: Wide weld bead with shallow penetration produced by helium [35]

Carbon dioxide, which is not an inert gas, is more cost effective than argon and helium. The use of CO_2 as a shielding gas is quite common and proves to have a number of the required characteristics. The weld penetration is good combined with a broad and well-rounded weld bead and undercutting non-existent. Excessive welding spatter is evident with CO_2 due to an unstable arc and this is true especially with thin plate. However welding spatter can be controlled and kept to a minimum by maintaining a smaller arc. Moisture in the CO_2 causes porosity and therefore only welding grade gas is advisable [14].

2.7.2 Gas Mixtures

Two or more gases are mixed in specified percentages in order for the desired weld characteristics to be achieved.

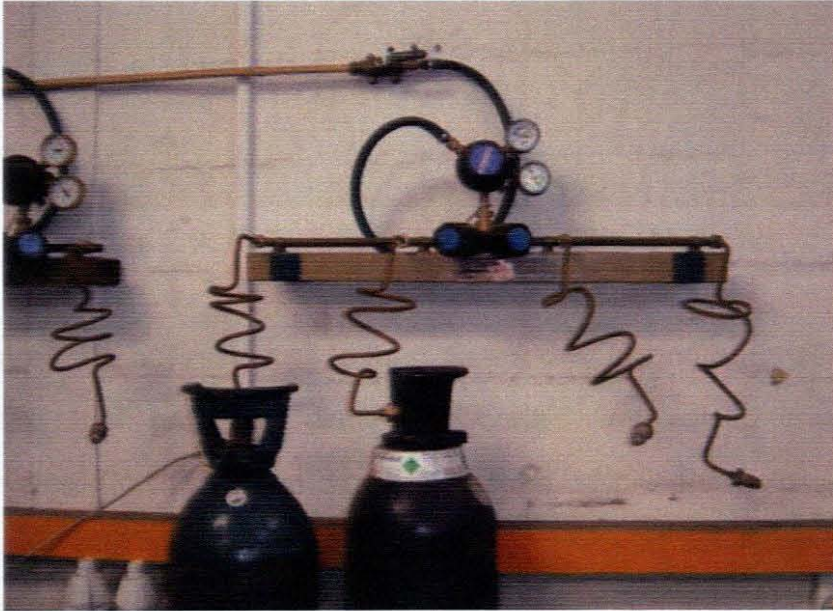


Figure 2.8: Argon flows into a single tube leading to a mixer.

The figure above shows cylinders connected to a flow regulators mixer. The gas regulators as seen, is required in conjunction with the mixer so as to reduce the tank pressure to a working pressure and is equipped with three control knobs for this purpose. The welding operator can thus adjust the pressure of each individual gas independently. Gas mixtures can vary and the operator is at liberty to experiment with different gas percentages in order to obtain the desired weld (see Appendix A).



Figure 2.9: A modern gas mixer and flow controller.

Gas mixtures are not restricted to inert gases only. Argon and helium can be mixed with other gases to achieve a certain weld or to improve weld characteristics. Adding carbon dioxide to argon, stabilises the arc, promotes metal transfer and reduces spatter. Penetration changes when welding carbon and low alloy steels in that undercutting is prevented due to the molten weld pool being very fluid along the fusion edges. Therefore carbon-argon mixtures are used predominantly in the welding of mild steel, low alloy steel and some types of stainless steel [35].

Diverse gas mixtures exist for various weld applications and the manufacturers of welding equipment make gas selection easy. Even though premixed gas is available, it is more cost efficient to purchase gas in individual tanks and mix them according to your requirements. It is also useful for experimentation in research. Various opinions exist as to the percentage of gas mixture to obtain the best welding results and it is therefore advisable to perform some experiments with these mixtures before commencing a job. With modern mixers this is easily possible.

Chapter 3

Residual Stress Analysis

3.1 Introduction

In modern design of metal parts with stringent requirements for endurance and reliability, the knowledge of surface function behaviour is of great importance. A material property, which is a function of the material's state, is the criteria for product design and therefore, it is also one of the assessment criteria for product testing.

Among the physical properties, residual stress is one of the most important functions, which has great influence on the fatigue life, corrosion, and wear of the surface. Both premature fatigue failure and unexpected stress corrosion cracking are common symptoms of an unrecognised detrimental residual stress condition.

Applied stresses can be easily justified and calculated but this becomes more difficult when dealing with residual stresses because of the difficulty of prediction and measure. This is not only due to the inherent randomness of the type of stresses but also because of its physical complexity. Residual stresses have various origins and are affected by a wide range of variables associated with material properties, metallurgical processing and operational conditions of specific mechanical components [40].

A sound knowledge of the residual stress distribution of material that will be subjected to various loading during its use is essential to ensure that the material satisfies the design criteria.

3.2 Residual Stress Definition

Residual stresses are unavoidable accompanying effects, which arises during the production, mechanical forming, thermal treatment, phase transformation, bonding and any shaping of components and parts. These residual stresses are an inherent component of the material in the absence of external loading and represent a datum stress over which the service load stresses are subsequently superimposed [40].

The stresses exist prior to any application or service of the component as well as the application of other external loads and are considered to be stresses of the first kind. Residual stresses are results of interactions among time, temperature, deformation and microstructure in the material [42]. The material or the material related characteristics that has an influence in the evolution of residual stress includes thermal conductivity, heat capacity, thermal expansivity, elastic modulus and Poisson's ratio, plasticity, yielding and hardening and kinetics of phase transformations, mechanisms of transformation and transformation plasticity.

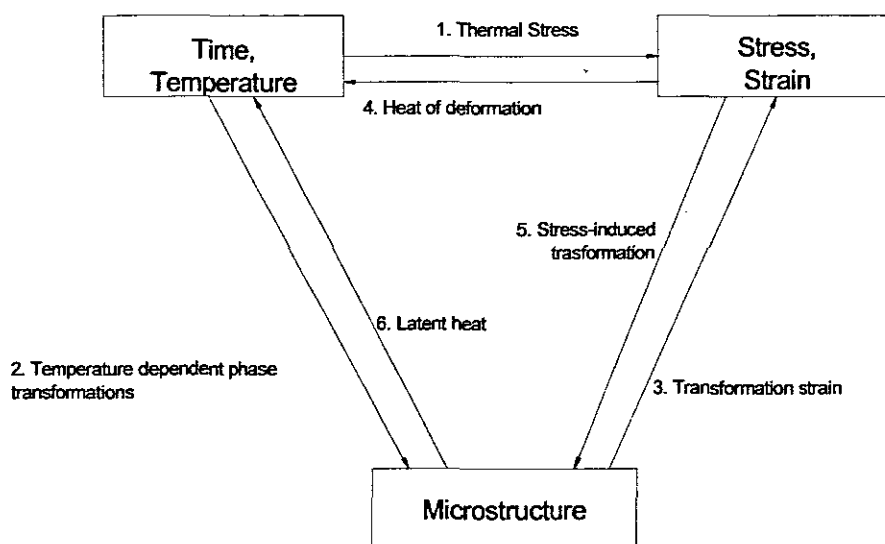


Figure 3.1: The coupling of temperature, stress and microstructure [42].

The thermal and/or mechanical manufacturing processing of the steel is the most common and primary cause of the internal stress state. Since all metals are subjected to some form of initial mechanical process, they all will inherently possess some residual stress. In-service modifications and repair, installation, erection and assembly is also a common cause, of residual stresses.

There are usually three types of residual stresses and are namely:

Type 1: residual stresses (σ_1) are nearly constant with reference to value and direction along long material distances, i.e., over many grains (macro stresses).

Type 2: residual stresses (σ_2) are only constant along short distances, e.g., one-grain diameter.

Type 3: residual stresses (σ_3) are restricted to distances much less than the grain size, i.e., to grain boundaries, dislocations and small foreign particles [33].

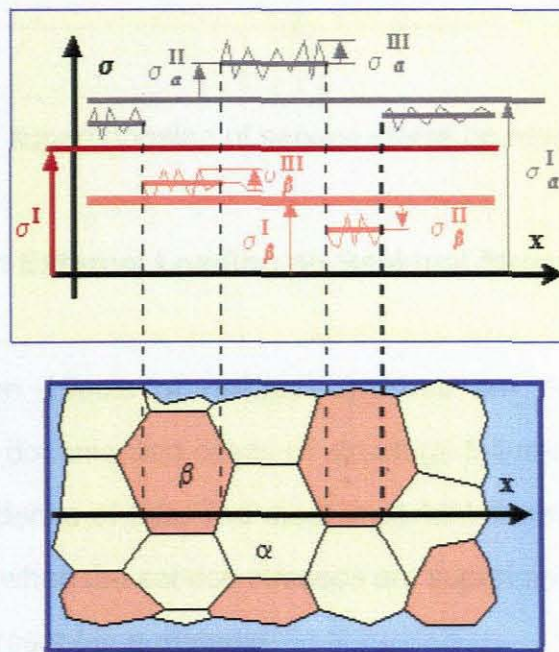


Figure 3.2: A schematic representation of grains on a microscopic scale[33].

The figure 3.3 below depicts a material, which has been subjected to elastic residual stress and represented as σ_R . Superimposed on these stresses are services stresses represented as σ_S . The real stress would then be $\sigma_R + \sigma_S$ as seen below. If service stresses and residual (tensile) stresses are combined,

the material is overloaded locally. If on the other hand an appropriate finishing process is applied to introduce compressive residual stresses, then the material will be released of some of its load locally and in so doing an increase in mechanical performance of the material is experienced [42].

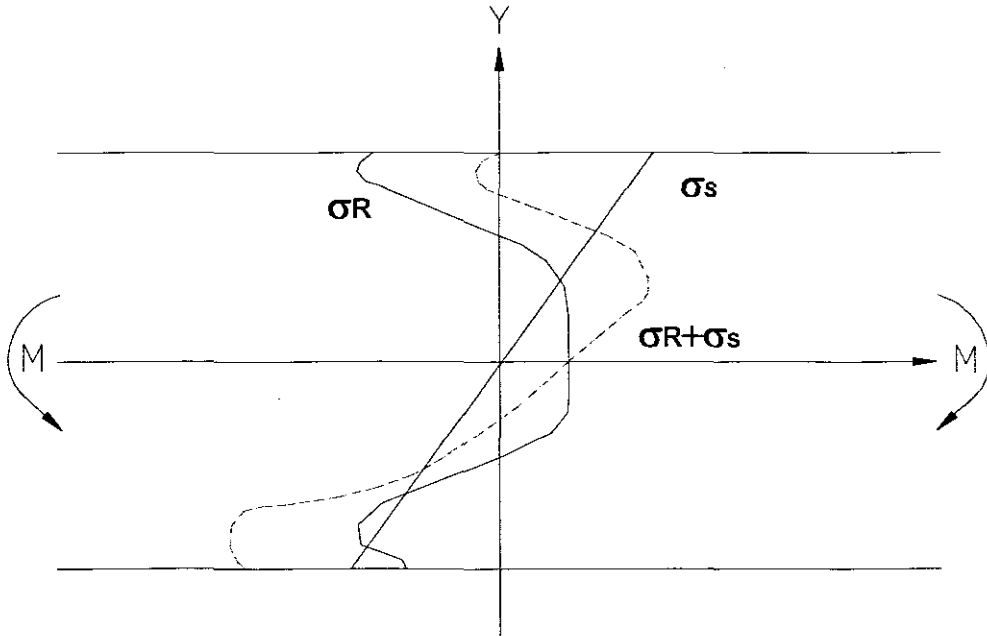


Figure 3:3 The superimposing of service stress on residual stress [42].

3.3 The Effects of External Loading on Residual Stress

The most common effects of residual stresses are detrimental, and the existence of many documented cases of structural failures in ships, buildings, bridges, etc. is evidence of this. The most important contributor to fatigue and structural failure is when the service stresses are superimposed on the residual stresses already present in a material.

Engineers are particularly cautious when confronted with this dangerous aspect of residual stress and is a major concern since its presence generally goes *unrecognised until after failure occurs*. Residual stresses in a weld region are usually tensile and very close to the yield stress due to the weld material shrinking during the cooling process. These stresses also cause immense

distortion in the welded material as well as brittleness around the heat-affected zone.

If the residual stresses are of opposite sign to the service stresses then part of the service load goes to reduce the residual stress to zero before the combined stress can again rise towards any likely failure value; such residual stresses are thus extremely beneficial to the strength of the component and significantly higher fatigue strengths can result [15].

The presence of residual stress in engineering components can significantly influence their fatigue and fracture behaviour. These stresses, when superimposed with applied stresses generally affect the mean level of the fatigue cycle and the duration to failure.

The effects of residual stress may either be beneficial or detrimental to the parent metal and is solely dependent on the magnitude, the sign, and the distribution of the stress with respect to the load-induced stresses. When residual stresses are in tension, the fatigue strength of the material is decreased. The fatigue strength of a component depends not only on the resulting stresses but also on the distribution of stresses across the section [40].

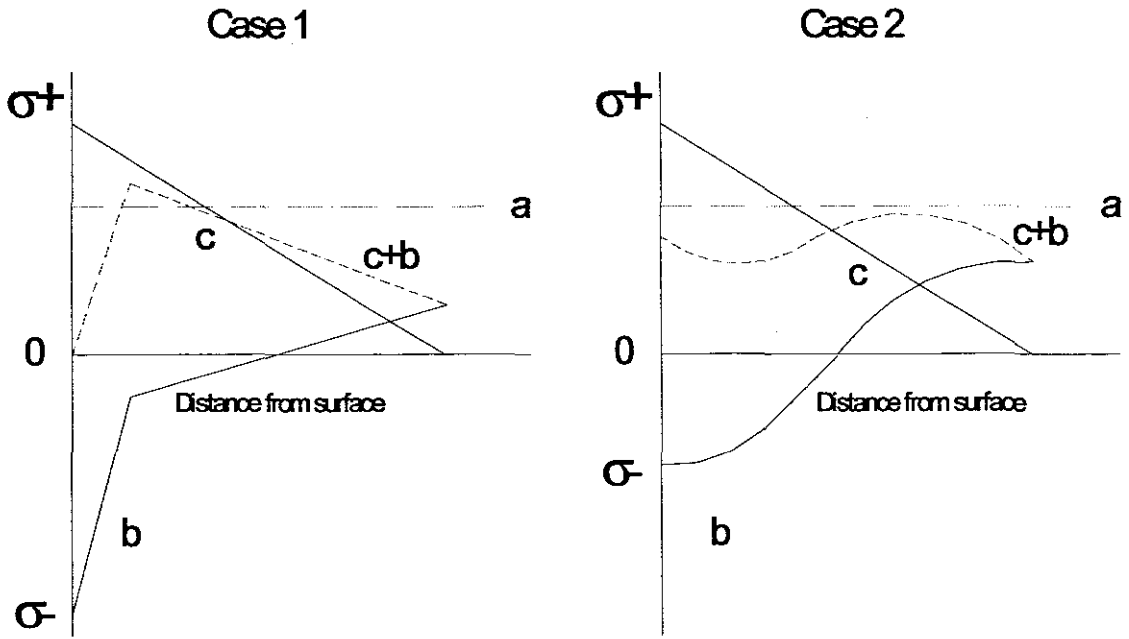


Figure 3.4: A schematic representation of a superimposed external load on residual stress in a fatigue test [42].

In the two diagrams above, the same external stresses (straight line c) and the same local fatigue strength (straight line a) are shown. The only difference is evident in the distribution of the residual stresses (curve b). In case 1 a compressive residual stress on the surface rapidly decreases below the surface. In case 2, even though the residual stresses are lower at the surface, it decreases more slowly below the surface.

The component can withstand the applied load only when the curve $c + b$, which represents the sum of external and internal stresses does not intersect the fatigue strength (straight line a) [42]. Although the compressive residual stresses are higher at the surface in the first case, the sum of the external and residual stresses is higher than the fatigue strength at a distance below the surface. At this point a crack can be expected to form.

In the second case the compressive residual stress is lower at the surface, yet its distribution below the surface is more favourable and the sum of the external and residual stresses does not intersect the fatigue strength curve at any point.

3.4 Methods of Residual Stress Formation

Very many residual stress-producing methods exist, but the two following aims to highlight the most common factors and influences in industry today as pertaining to this research.

3.4.1 Residual Stress Formation During Welding

Welded joints are very common in the manufacturing industry, including shipbuilding, boilers, vehicles, pipelines, etc. Residual stresses in welds evolve due to incompatible thermal strains caused by heating and cooling cycles and is explained in fig 3.6. These stresses are responsible for the reduction of fatigue life of the welded material and the tensile stresses of the yield magnitude at the toe area is of utmost importance to engineers.

During the welding process the weld arc generates heat locally. The distribution of the temperature in the weld is not uniform and changes rapidly as the welding progresses coupled with associated thermal strains and localised plastic deformation. Plastic deformation occurs when the material is deformed, so that the stresses exceed the elastic limit of the material. The material will not return to its original shape after the applied load is released.

Residual stresses resulting from welds present problems of its own and becomes evident in the form of fracture and strength deterioration. In the case of multi-pass welding, the solid phase transformation occurs in the base metal and possibly in the weld metal and is due to the heat generated from the welding process.

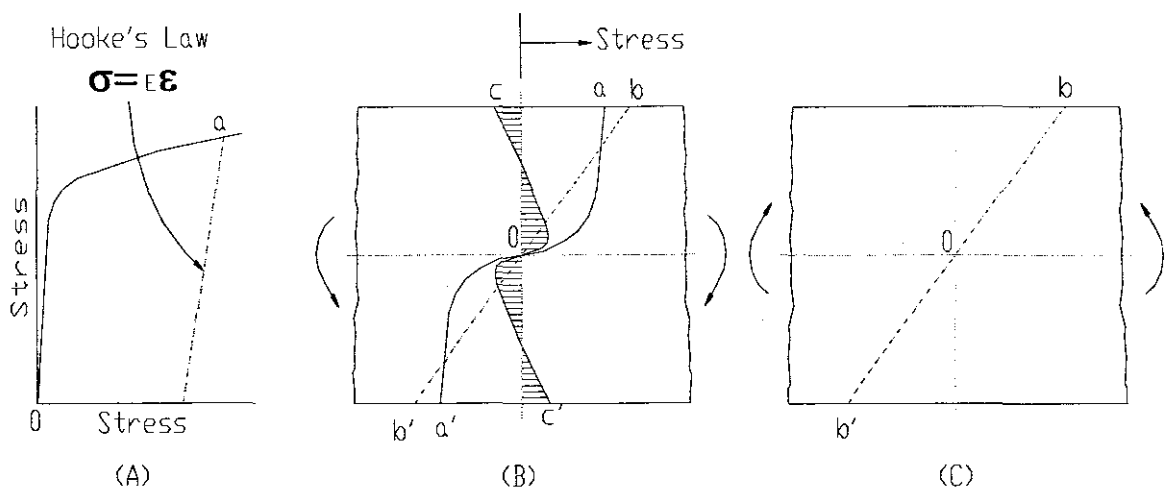


Figure 3.5: Residual Stress in bending. (A) Stress-strain diagram. (B) Composite diagram. (C) Unloading diagram [1].

This unloading stress distribution is evident in figure 3.5 (C) and as superimposed in the material in figure 3.5(B).

The figure 3.6 attempts to explain schematically the changes in temperature, the complex strains and the transient thermal stresses, which are experienced during the welding cycle. A weld-bead is being produced on a plate and in the direction of the 'X' axis. The weld arc progresses at a speed (v) and is currently at position 'O'. The temperature change in figure 3.6B is evident at the various sections when the weld arc is positioned at 'O' only at that specific time.

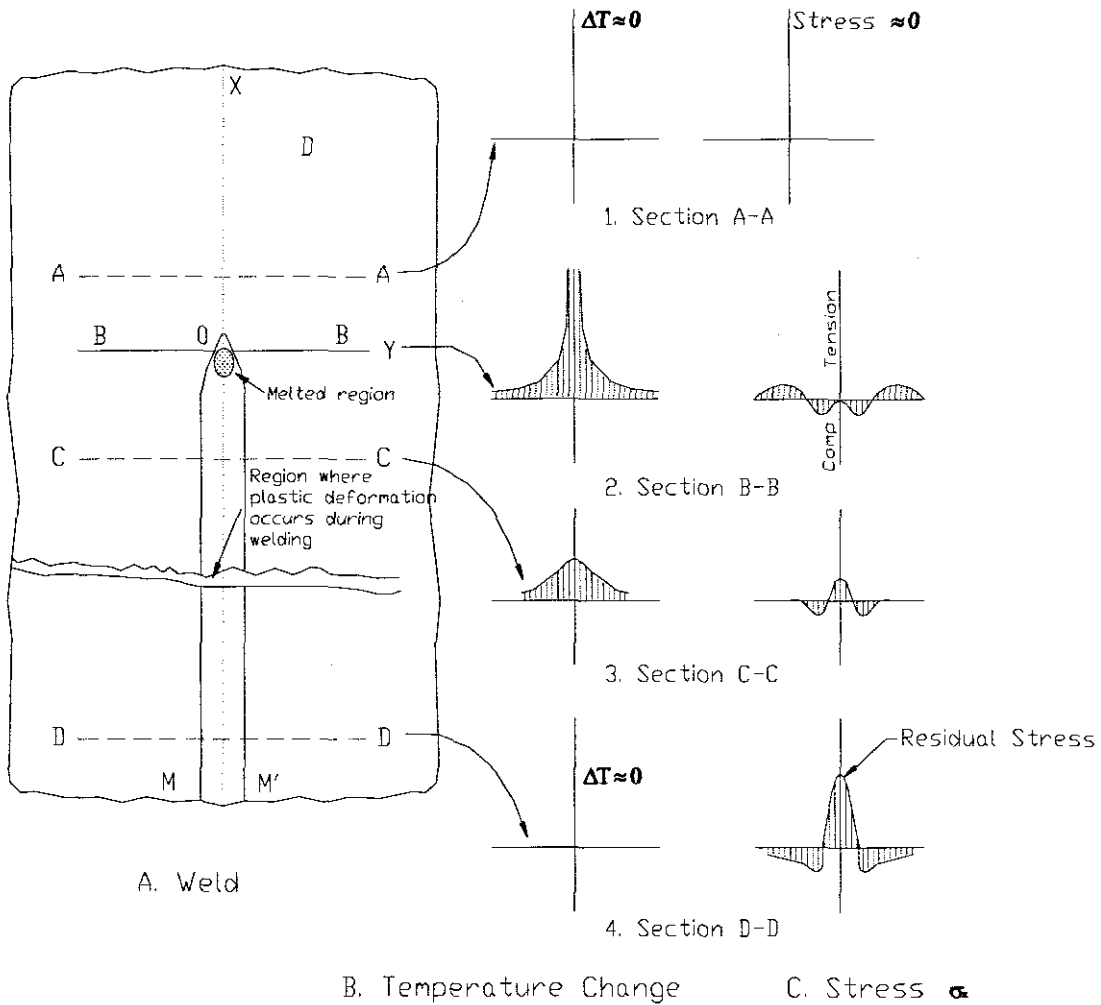


Figure 3.6: Change in temperature and related stresses during welding [24].

Because the cross-section A-A is ahead of the weld bead, very little temperature change is recorded and hence the stresses are not affected. At the cross-section B-B, the temperature change and heat distribution is excessively rapid and uneven, but since the molten weld pool cannot support a load, the stress underneath the weld arc is practically zero [28]. Stresses are compressive in areas at short distances from the weld. This is so due to expansion being restrained by the surrounding metal with lower temperatures. Since the temperature in these areas (section B-B) is significantly high with low material yield strength, the stresses are as high as the yield strength of the material at corresponding temperatures. The magnitude of compressive stress passes through a maximum increasing distance from the weld or with

decreasing temperature. However, stresses in areas away from the weld are tensile and balance with compressive stresses in areas near the weld. This means that,

$$\int \sigma_x dy = 0 \quad [1]$$

across section B-B. The effects of stresses σ_x and τ_{xy} are neglected on equilibrium conditions.

Along cross-section C-C, the weld and base metal near the weld have cooled moderately and contract and cause tensile stresses in the regions close to the weld. With an increase in distance from the weld, the stresses change from compressive to tensile. Cross-section D-D, which is some distance from the weld reflects a temperature, which is reduced to almost zero with high tensile stresses being produced in the weld regions and compressive stresses are produced some distance from the weld region (see also figure 3.7). This is the usual stress distribution that remains after welding is completed. The crosshatched area M-M' depicts the area where plastic deformation takes place during the weld cycle and the remaining area outside of this section remains elastic [28].

Figure 3.7-3.9 below shows how welding causes shrinkage and has a direct effect on residual stresses. This shrinkage occurs when heating and cooling takes place in areas adjacent to one another. The basic principle is when heated volumes shrink during the cooling process according to their coefficient of thermal expansion and the existing temperature difference. The assumption is made that no forces are exerted on the surrounding areas by the melted weld volumes. Weld seams and surrounding areas that have not been melted during the welding process display different thermal and residual stresses [42].

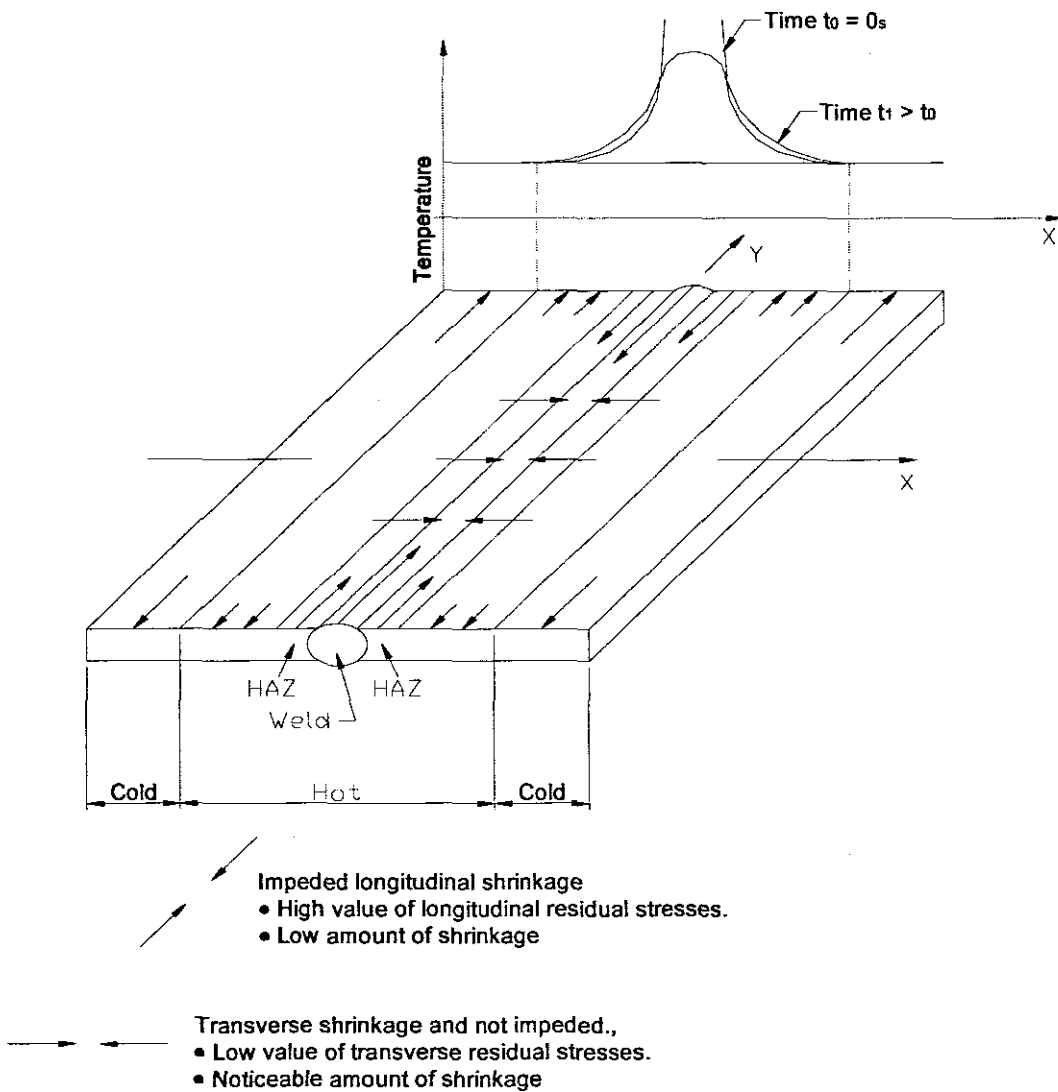


Figure 3.7: Shrinkage as a consequence of fluctuating inhomogeneous temperature distributions during the welding process [42].

If no shrinking takes place then no residual stress will be present after the material has cooled to room temperature.

Distortion is a result of excess residual stress and in turn, complicated effects are experienced and can be very harmful to the material or structure.

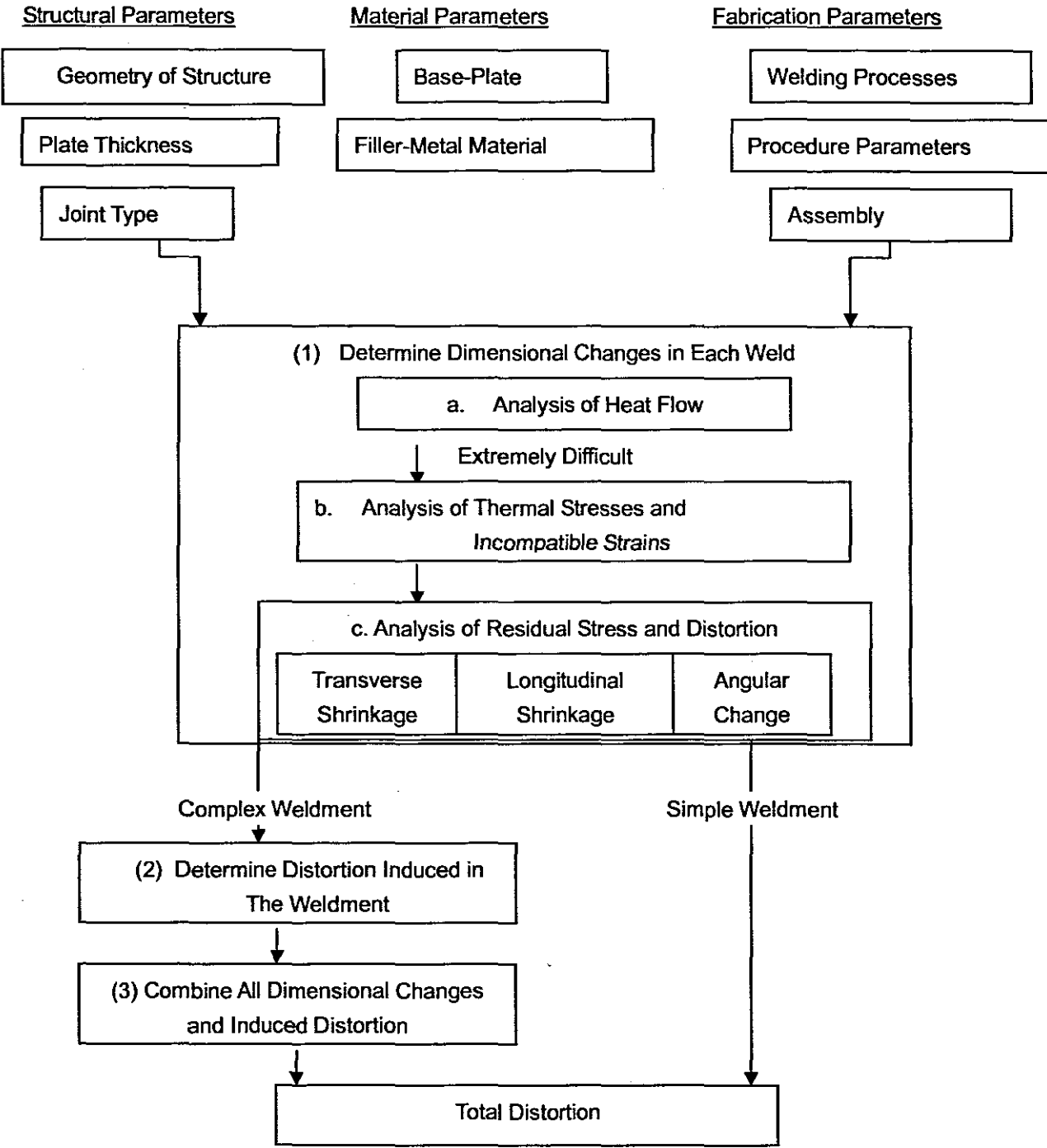
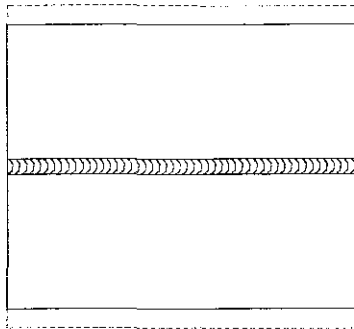


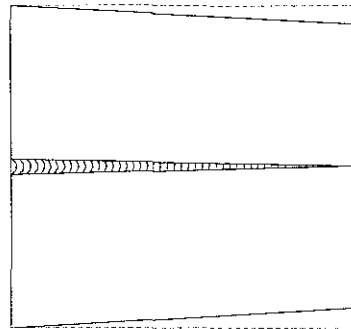
Figure 3.8: Factors that contribute to weld distortion [28]

There are three basic dimensional changes that occur during the welding process that cause distortion in materials or structures and are [28]:

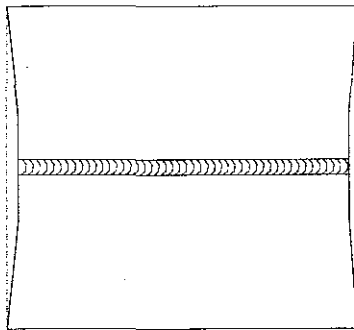
- Transverse shrinkage (perpendicular to the weld).
- Longitudinal shrinkage (parallel to the weld).
- Angular distortion (rotational around the weld).



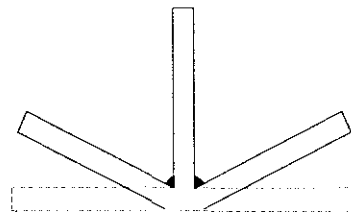
A) Transverse Shrinkage



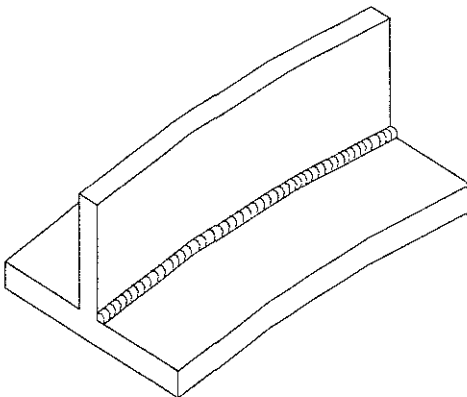
B) Rotational Distortion



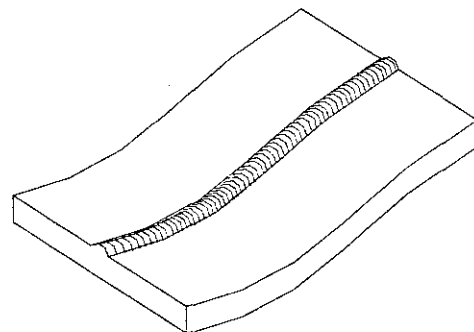
C) Longitudinal Shrinkage



D) Angular Distortion



E) Longitudinal Bending Distortion



F) Buckling Distortion

Figure 3.9: Different types of weld distortion [28]

Figure 3.9 clearly depicts the results of distortion after welding, with buckling occurring due to thermal stresses being the cause of instability in thin plate. Rotational distortion is more apparent when plates are prepared with a gap for deep root penetration in butt welds. As the weld progresses in length, the solidified weld contracts and draw the plates closer together, thus reducing the root gap. Depending on the length of the plate, the root gap may become non-existent in rigid material.

Angular distortion is prevalent when a weld is performed on one side of a material only, causing excessive contraction on one side of the material. Very often this is evident in fillet joints.

Three approaches to solving the problem of distortion exist and are:

- Welding process development and manufacturing procedures to minimise distortion.
- The advancement of correct techniques to remove distortion.
- Establishing acceptable standards for distortion limits [28]

The first and best approach would be to minimise distortion. Various standard codes of practice for manufacturing exist and is used primarily to assist and guide employees in attaining a good weld with a sound structure with limited and accepted distortion. Also minimum distortion can easily be achieved by preparing jigs and fixtures for welding. In the case of a V-butt weld with a 2mm weld gap, it would be advisable to weld a run-off plate one each end of the plate. These run-off plates in figure 3.10 serve as a means to start and end an uninterrupted weld with minimal porosity inclusion as well as to keep the plates to be welded in a stationary position. In this case the weld gap is maintained and a weld of even proportions is achieved.

Welding procedures to minimise distortion of the weld material would include reducing the heat input of the weld. Staggering the weld in cases of fillet welds is a sure way to minimise distortion. All these procedures reduce weld distortion but would not completely eliminate it. By combining preventative measures such as weld sequences, weld joint preparation, jig and fixture restraints, preheating of material, weld bead temperature, etc. would be an effective way to contribute to the reduction of distortion.

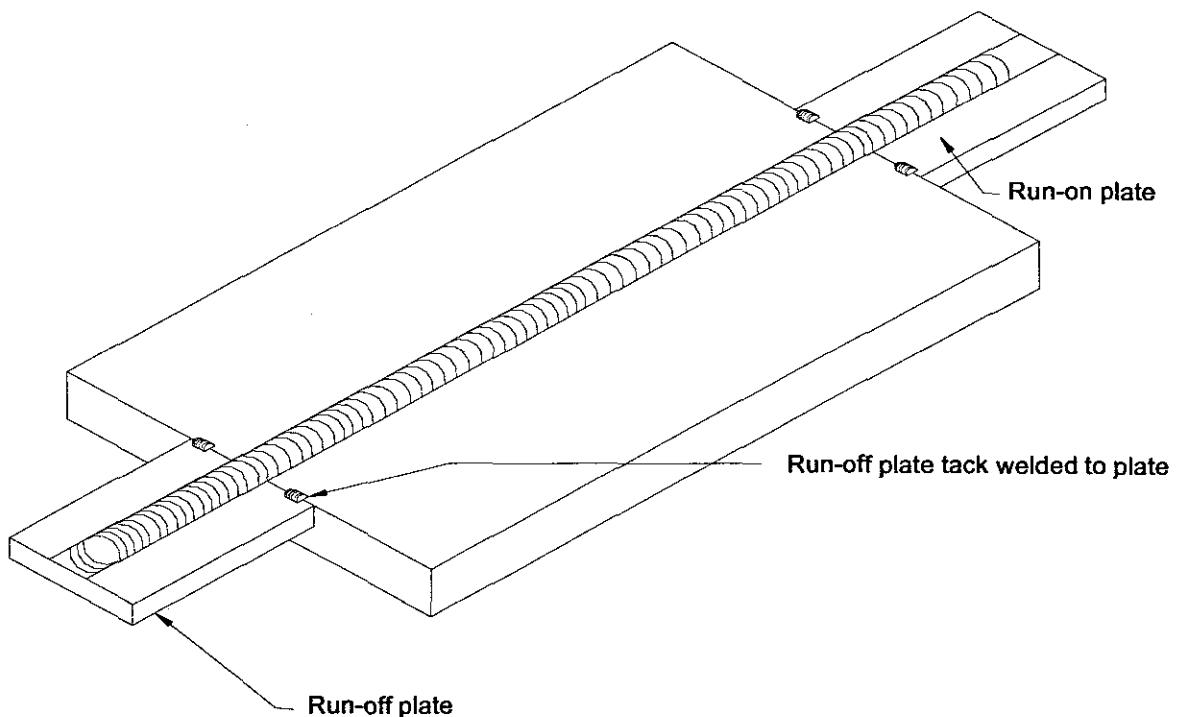


Figure 3.10: Run-on and run-off plates present for an uninterrupted weld.

3.4.2 Residual Stress Formation During Machining

Machining, as pertains to this chapter is a manufacturing process used to remove unwanted or excess material by means of chip formation. This machining is done in order to transform the material into the desired shape, size and finish as specified to by the design requirements. This holds true especially for experimental analysis. Although the application of machining is widely used in industries today, very little thought is given to residual stress formation during

this process. Various processes exist for the chip formation and are:

- Milling
- Turning (facing, boring, threading. Chamfering, etc.)
- Sawing
- Drilling (reaming, tapping, countersinking, etc.)
- Broaching (internal and surface)
- Abrasives (grinding, honing)
- Shaping (planning)

Some of these processes can be combined into machine centers to expedite the machining process.

The basic principle of chip formation is when the edge of the cutting tool is pressed against the material. Either the material or the tool could be rotating. As pressure is increased cutting or chipping is taking place. Since compression between the tool and the material is effected, a shear deformation is being applied to remove the material.

Although most machining methods are oblique (having three component forces), models of orthogonal (having two forces) machining of metals are useful in order to understand the basic mechanics of machining and can be extended for modelling of the production processes [11].

Thin zone mechanics was developed for materials that produce chips constantly and with a planar shear process together with the following assumptions:

- The tip is sharp and no rubbing occurs between the tool and the material.
- Plain strain conditions prevail (no side spread occurs).
- The stresses on the shear plane are uniformly distributed.
- The resulted force, R , on the chip is equal, opposite and collinear to the

force R' at the tool/chip interface.

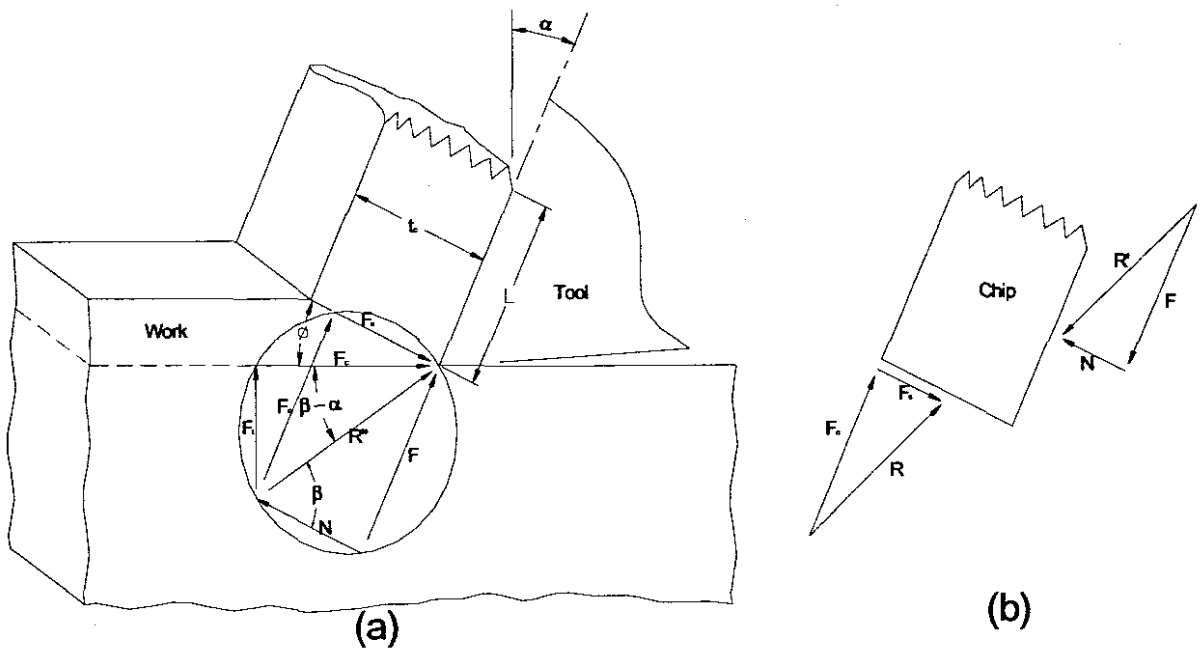


Figure 3.11: Material geometry (a) and forces (b) in orthogonal cutting [11].

Where:

F_c = cutting force

t_c = chip thickness

F_t = tangential (vertical) force

α = back rake angle

F_s = shear force

ϕ = shear angle

F_n = normal force

From the diagram in figure 3.11 and given the required forces, which can be measured by using a dynamometer, calculations can be done to ascertain the stresses produced during the machining process. Exceptionally high shear strain rates are evident and is caused primarily due to excessive force of the tool [10]. It must be understood that during this machining process the material is plastically deformed at the surface and the stress concentrations depend on a number of input variables as can be seen in figure 12.

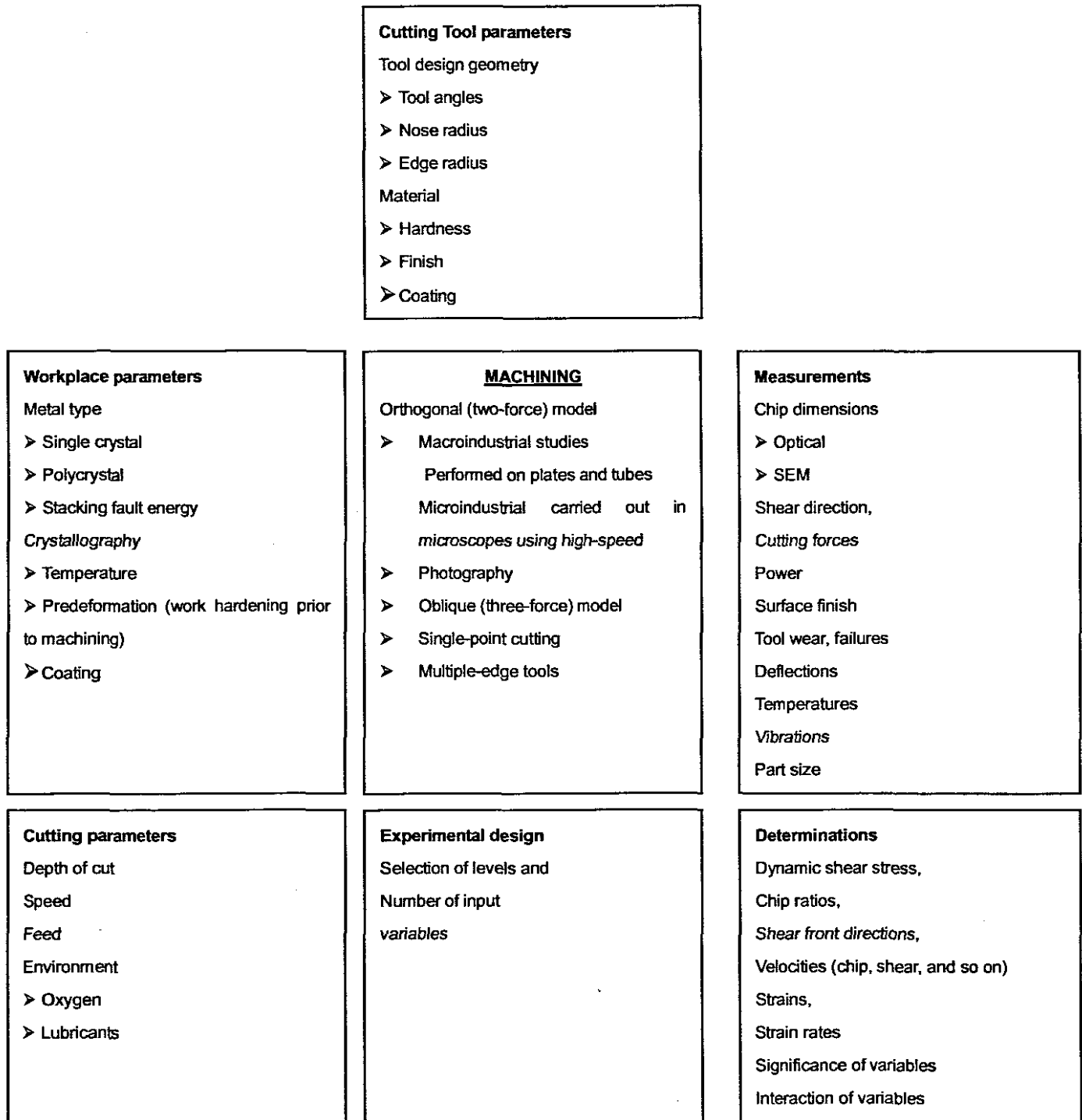


Figure 3.12: The input & output association during the machining process [11].

Since the experiments for this research closely emulates industrial conditions, residual stress formation analysis during machining will not be performed.

Chapter 4

Stress & Strain Measurement

4.1 Introduction

In order for failures to be prevented, various test methods were developed and were categorised either by their destructive or non-destructive nature. It is so aptly named because destructive tests included destroying part of the test piece, whereas non-destructive tests were more suited because of the obvious benefits of inspection without impairing the future functions of the material. The primary purpose of a non-destructive inspection is to determine the existing state or quality of a material, with a view to acceptance or rejection [27].

Furthermore, the different non-destructive methods can generally be reclassified in two sub-categories and that being active and passive tests. The active techniques require that something be introduced into or onto a specimen and a response is expected. Magnetics, ultrasonics and radiography are labelled as active techniques. Passive techniques on the other hand monitor or observe a typical load environment or a proof cycle in an attempt to determine the presence of a defect through some reaction of the specimen. Acoustic emissions, noise analysis, leak testing, visual examinations and some residual magnetic techniques are in this classification [7].

It made perfect sense to detect defects in mechanical designs, but in many cases these flaws propagated into fractures and detection was too late. Prevention and prediction of deficiencies seemed a more appropriate option and so the science of prevention and prediction was elevated to a somewhat higher level.

Recently safety of employees and passengers in public and private air transportation became a top priority and prevention of fatigue failures was imminent. Jet planes now operate at much higher speeds than they previously did and passenger plane engines are developing greater horsepower per unit weight. Pressure vessels and pipelines are also operating at higher pressures. As the engineering technology advances, the need for improved engineering materials becomes a constant demand. In order to sustain the continuous advances of technology and materials improvement, non-destructive test methods and especially ultrasonics have become a common practice not only in manufacturing and quality control but also in research [27].

4.2 The Basic Principle Of Ultrasonics

Mechanical vibrations can be propagated in solids, liquids and gases. When the particles of matter vibrate and if the mechanical movement of these particles has regular motion, then the vibrations can be assigned a frequency in cycles per seconds. These cycles are measured in hertz (Hz), where $1\text{ Hz} = 1$ cycle per second. If the frequency is within the range of $10 - 20\,000$ Hz, the sound is audible. If the frequency is above $20\,000\text{ Hz}$, the sound waves are referred to as ultrasound or ultrasonic [19]. The waves during ultrasonic inspection are usually in the range of $0.5\text{ MHz} - 20\text{ MHz}$.

Ultrasonic techniques have been employed in various fields and its importance has not gone unnoticed. These techniques emanate from simply detecting the sound differences in a body. Previously by striking an object and listening to the characteristic ringing sound was a common practice in detecting flaws. A cracked specimen, which has been struck, will emit a dull sound when compared to that of a sound specimen. This practice still exists today when artisans check for cracks in pedestal grinding wheels. Countless attempts have been made to improve this technique and to increase the sensitivity of this test.

An example of this would be electro-magnetically driven hammers, which were used to strike a specimen rapidly and with even blows. Stethoscopes, telephone receivers, microphones and electronic amplifiers were used to detect changes in audible sound emitted. A stethoscope was placed near the weld area and the weld was lightly struck with a hammer continuously. As the stethoscope was moved along the weld variations in the sound were evident and indicated irregularities in the weld [27]. A high-pitched reedy sound would indicate a lack of fusion and even badly cracked welds can be detected in this manner. Detection of such flaws depends entirely on the skill of a highly trained inspector and the results may even become questionable when complex shapes are tested.

Ultrasonics is also currently used in prevention and prediction strategies and for this purpose it is most commonly employed in residual stress measurement. Residual stresses are classified in groups according to the characteristic length of the stress distributions. When stresses are uniform over distances less than or equal to a grain size they are called micro-stresses and macro-stresses when they are uniform over several grain diameters [37].

The ultimate strength of a specimen is determined by the macro-stresses and the detection of these stresses prior to service is of utmost importance. Macro-stress measurement is commonly found in pressure vessel fabrication especially in the welded areas, where stress distributions are most likely to extend over several centimeters. This application is appropriately suited for ultrasonic measurement.

4.3 The Generation Of Ultrasound

There are numerous ways in which ultrasonic waves can be produced. However, most equipment used for non-destructive testing employs the

piezoelectric effect for both its transmitter and receiver probes. Certain crystalline material displays the piezoelectric effect. The piezoelectric effect is exhibited when crystals show strain if a voltage is induced across the crystal faces. Conversely, an electric field will be created if such a crystal is subjected to a mechanical strain with the voltage produced being proportional to the amount of strain [22].

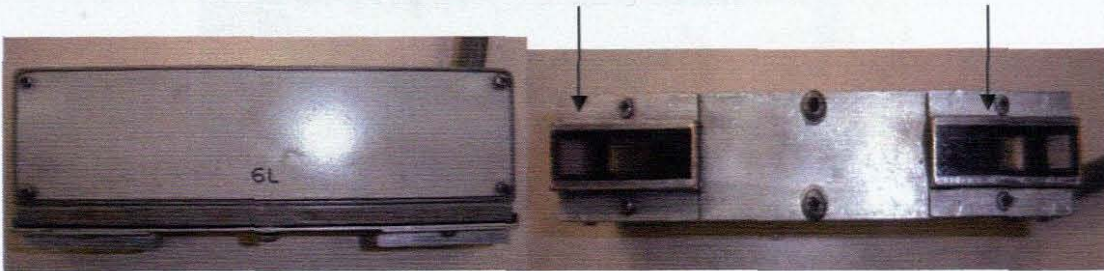


Figure 4.1: A typical ultrasonic probehead (6L150) with a transmitter and receiver made of piezoelectric material.

Natural quartz was originally used as a piezoelectric material and still is used today. Various other materials, which have been polarized to behave like piezoelectric material such as barium titanate, lead metaniobite and lead zirconate are also used with great success [19].

4.4 The Debro-3.0 Ultrasonic Stress Measuring Device

The Debro 3.0 ultrasonic stress-measuring device applies the principle of the acousto-elastic effect. Ultrasonic waves, which depend on the stress present in the material, are generated and penetrate the test-piece and record the subsurface stresses to a depth of two millimeters (2mm). The device includes a cathode-ray oscilloscope as well as interchangeable probe heads, which may be used in different applications.



Figure 4.2: The Debro-30 cathode-ray oscilloscope.

The 6L150 probe head, which is the primary probe head of concern, measures stress changes in the test-piece for a stress direction that is parallel to the longitudinal wave propagation direction. The probe-head also consists of six (6) transducers that emits and receives subsurface longitudinal waves [5].

The stresses are measured in a cycle of four steps. Since the measuring cycle is dependant on a reference time of flight, constants have to be programmed into the device. These constants are obtained by experimental methods and are different for various materials.

After a cycle of four steps a stress reading is recorded on the oscilloscope. Since the stresses are measured only to a depth of two millimeter (2mm) and across a distance of 150mm, it is advisable to take as many readings as possible in close proximity in order to obtain an accurate average measurement.

4.5 Strain Gauge Measurement.

The engineering industry relies heavily on the knowledge of the suitability of a material, which is about to be placed in service or that has been in operation for some time. A very common method of ascertaining this is by performing strength of material calculations, with strength being a fundamental property of the material. These calculations are easily accomplished provided the knowledge of all loads both qualitatively and quantitatively are forthcoming. The knowledge of loads is not always possible, especially when very complex geometry in a material or structure is prevalent.

Design engineers have previously compensated for strength by adding a safety factor to the design, hence increasing the dimensions of the material somewhat. With new technology being introduced especially in aeronautics, lighter material has become more of a necessity than a demand. Since lighter material has now become imperative and not impeding on the safety of the material, material stresses must be determined to maintain the same design effect. Also these material stresses are to be determined while in service.

Since stresses cause distortion (strain), a relationship between the two are notable and the latter measurable. Various devices known as strain gauges are readily available for different applications of stress analysis. The strain gauge measurement technique has been in existence for some time now and its use has been successful in determining the material's state.

4.6 Strain Gauge Measurement For Residual Stress Determination.

A strain gauge is a measuring device that converts force, pressure, tension, etc., into an electrical signal and is the most commonly used measuring device for electrical measurement of mechanical quantities.

A strain/resistance relationship exists in electrically conductive materials. This relationship is known as the ratio of relative electrical resistance change of the conductor to the relative change in its length. The strain sensitivity (gauge factor) is a function of the dimensional changes, which takes place when the conductor is deformed plastically as well as any change in resistivity of the material with strain [47].

When such a material is stretched, the conductors become longer and narrower, which causes an increase in resistance. A Wheatstone bridge then converts this change in resistance to an absolute voltage. The resulting value is linearly related to strain by a constant called the gauge factor.

Assuming that a welded plate is to be tested for its condition of residual stresses. In this case the direction of the principle stresses will be unknown and a biaxial stress will be observed. A strain gauge rosette is selected and bonded to the welded material at the location where the stresses are of concern. It is important to bond the rosette, with its gauges aligned to a reference point of the material being tested. The grids on the rosette should be connected to a strain indicator, which should be set to read zero. A hole may then be drilled through the center of the rosette and into the plate in order to remove some material. Since the drilled part of the material acts as an interruption of the flow of forces imposed on it from the surrounding areas, a natural unstressed state is achieved. Measurements taken will show a difference in strain.

4.7 The Rosettes Strain Gauge Hole Drilling Method

In order for strain measurements to be accurately recorded from strain gauges, it is of utmost importance that the gauges be aligned and spaced accurately about the centre to be drilled. Failure to do so will eventually result in large errors in strain being recorded from small errors in alignment and location. The

rosette strain gauge has been designed and manufactured so that semi-skilled operators may use them. Three strain gauges are required to determine the strains in various directions and are clearly numbered.

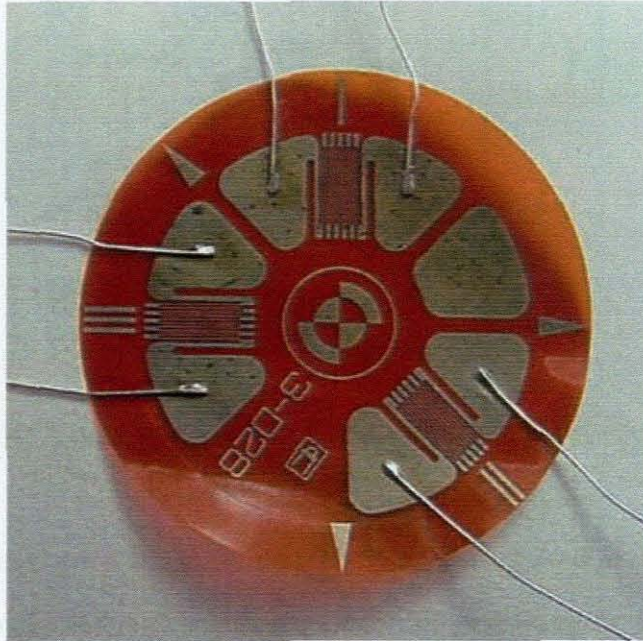


Figure 4.3: A Typical Rosette strain gauge used to determine stress states.

The rosette strain gauge is manufactured with three gauges set at $0^\circ/45^\circ/90^\circ$ or $0^\circ/60^\circ/120^\circ$. The strain measuring grids are aligned round about a centre, which is marked for centring the drilling tool. Placing the drilling tool centrally is accomplished with the use of a microscope. Drilling accuracy is very important and according to Vishay Company Measuring Systems, accuracy of 3% or less must be maintained in the case of drilling an offset of 0.025mm from the centre.

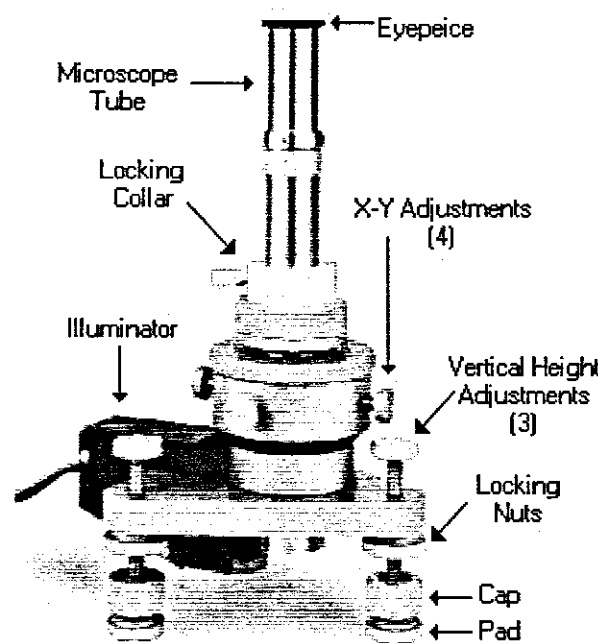


Figure 4.4: A typical drilling guide depicting a microscope [46].

The figure above shows an eyepiece fitted to visually align the drilling guide above the centre of the rosette with considerable accuracy and is achieved with the aid of four adjustment bolts. After alignment, the microscope is removed and replaced with the drilling device.

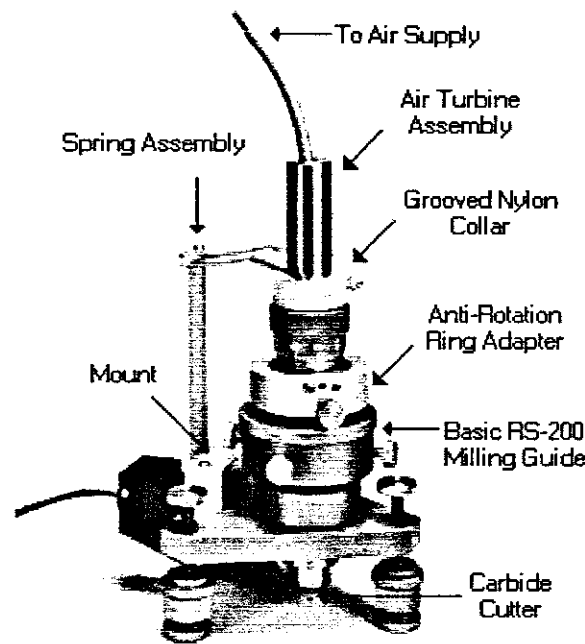


Figure 4.5: A typical drilling guide depicting a drill [46].

Figure 4.4 shows a drilling guide with three pads. These pads are bonded to the material to be tested. The guide is also fitted with a micrometer in order to accurately drill the required depth into the specimen. A strain indicator and a switch balance is utilised to record strain measurement after drilling.

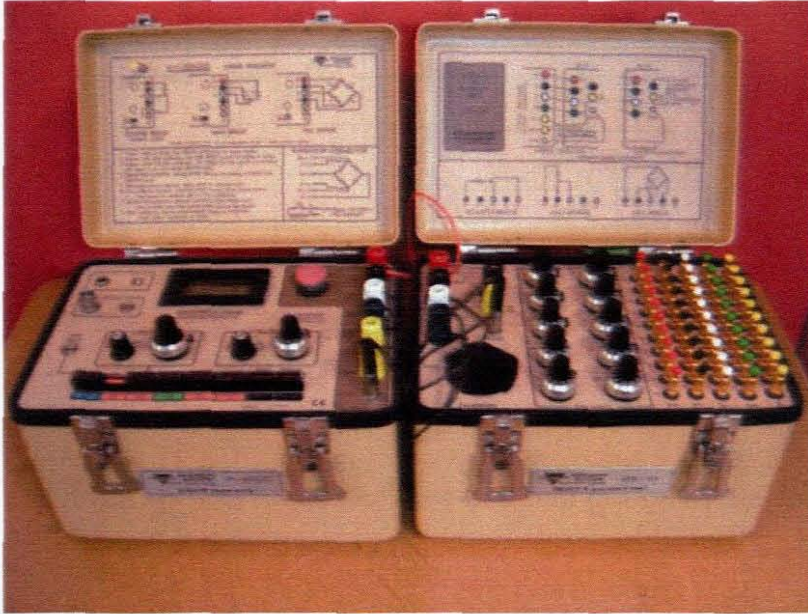


Figure 4.6: Switch and balance unit used to record strain measurement.

4.8 Calculating The Stress From The Strain Measurements

The most common method of measuring the relieved strains is to bond a rosette strain gauge in the vicinity of the hole to be drilled for strain measurement.

According to Vishay, for any given initial state of residual stress and a fixed hole diameter, the relieved strains usually increases at a decreasing rate as the hole depth increases. Thus in order for the strain readings to be maximised, the hole is drilled to a depth of at least $Z/D = 0.4$.

Where:

D = the outside diameter of the strain gauge.

Z = the depth of the drilled hole.

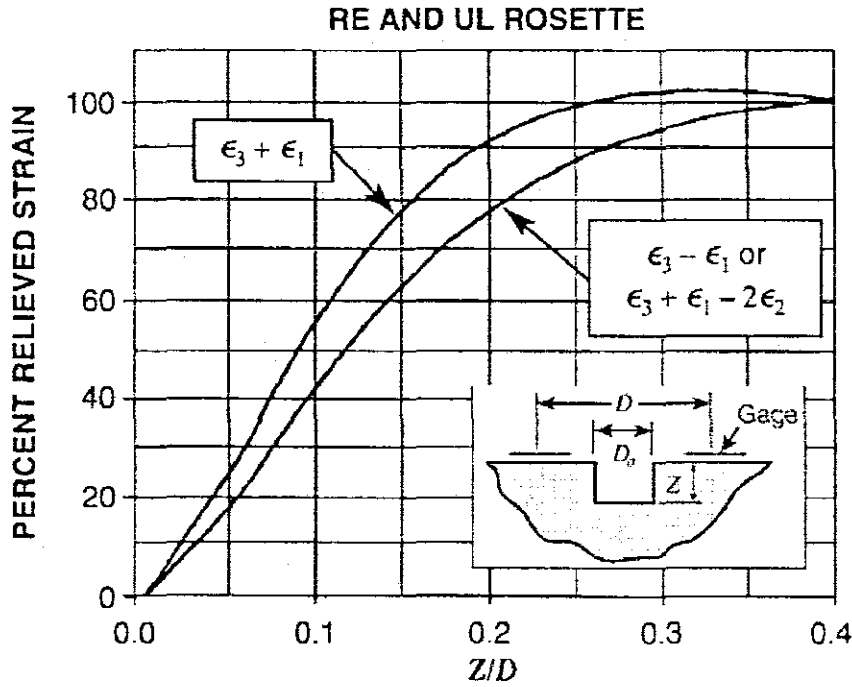


Figure 4.7: Relieved strains vs ratio of hole depth to gauge circle diameter [46].

When using a strain gauge with $\varnothing 15\text{mm}$, the maximum strain reading will be found at a depth of:

$$\frac{Z}{D} = 0.4 \quad \therefore Z = 15 \times 0.4 = 6\text{mm} \quad [4.1]$$

The maximum and minimum principle stresses and their directions are found by:

$$\sigma_{\max} = \frac{\epsilon_1 + \epsilon_3}{4A} - \frac{1}{4B} \sqrt{(\epsilon_3 - \epsilon_1)^2 + (\epsilon_3 + \epsilon_1 - 2\epsilon_2)^2} \quad [4.2]$$

$$\sigma_{\min} = \frac{\epsilon_1 + \epsilon_3}{4A} + \frac{1}{4B} \sqrt{(\epsilon_3 - \epsilon_1)^2 + (\epsilon_3 + \epsilon_1 - 2\epsilon_2)^2} \quad [4.3]$$

$$\tan 2\alpha = \frac{\epsilon_1 - 2\epsilon_2 + \epsilon_3}{\epsilon_1 - \epsilon_3} \quad [4.4]$$

Where:

α = angle from the nearer principle axis to gauge no. 1

ϵ = strain measurements recorded

A & B = coefficients

Coefficients A and B are determined by experimental calibration and the procedure automatically accounts for the mechanical properties of the material tested. It is also the most accurate method for determining the coefficients if performed accurately [46].

The calibration procedure must be performed on a test piece of similar material as that to be measured for strains and must be uniaxially stressed. The strain grid no. 1 should be aligned in the loading direction and grid no. 3 in the transverse direction. It is important to note that the stresses should be uniform over the cross-section and that bending stress is negligible. The specimen width should be at least ten times that of the hole diameter and the length between the loading grips should be at least five times the width. The specimen thickness should be at least five times the hole diameter and the maximum applied stress should not exceed half of the proportional stress limit for the test piece.

The calibration procedure is as follows:

- Zero-balance the strain gauge circuits
- Apply a tensile load to the test piece to produce a stress
- Measure the strains ϵ_1' and ϵ_3'
- Drill the into the rosette strain gauge as described previously
- Refit the specimen to the test rig, zero-balance the circuits and reapply the same load
- Measure the strains ϵ_1'' and ϵ_3''

The calibration strains for the measured load:

$$\epsilon_{c1} = \epsilon''_1 - \epsilon'_1 \quad [4.5]$$

$$\epsilon_{c3} = \epsilon''_3 - \epsilon'_3 \quad [4.6]$$

Solving for A and B:

$$A = \frac{\epsilon_{c1} + \epsilon_{c3}}{2\sigma_c} \quad [4.7]$$

$$B = \frac{\epsilon_{c1} - \epsilon_{c3}}{2\sigma_c} \quad [4.8]$$

A and B are substituted into [4.2] and [4.3] to determine the principal stresses in the material [46].

Chapter 5

Analysis Of Microstructure In Welds

5.1 Introduction

Materials science in general and with particular reference to metallurgy, concerns the understanding of both the structure of useful materials as well as the relationship between the structure and the properties of the material. Using this approach along with empirical development, drastic improvements in useful properties have been achieved, especially in the changes in the microstructure of the material [26].

The term microstructure relates to structural features, which ranges in size from 0.3nm up to the external shape of the specimen, which could be of the scale of millimetres or metres. It is these structural features that include the crystal structure, composition, grain size and distribution of additional phases. The structural features are controlled by methods of alloying, fabrication and heat treatment [26].

5.2 Phase Transformation Characteristics Of Steel During Welding

A phase is referred to as a separate and identifiable state of matter in which a given substance may exist. When referring to a phase in the structure of a material, it implies a region, which comprises of a large number of atoms with the existence of a bounding surface to separate it from the contiguous phases. Phase transformation is the result of a free energy difference between two phases and pressure and temperature has a direct influence on this free energy [32].

The iron-carbon phase diagram is the foundation for understanding the microstructures of the ferrous alloys commonly termed steels and cast iron. Three allotropes of pure iron are α -Fe (bcc), γ -Fe (fcc), and δ -Fe (bcc). Very small carbon atoms dissolve interstitially in these allotropes and form three primary solid solutions, which are α -phase (ferrite), γ -phase (austenite) and the δ -phase.

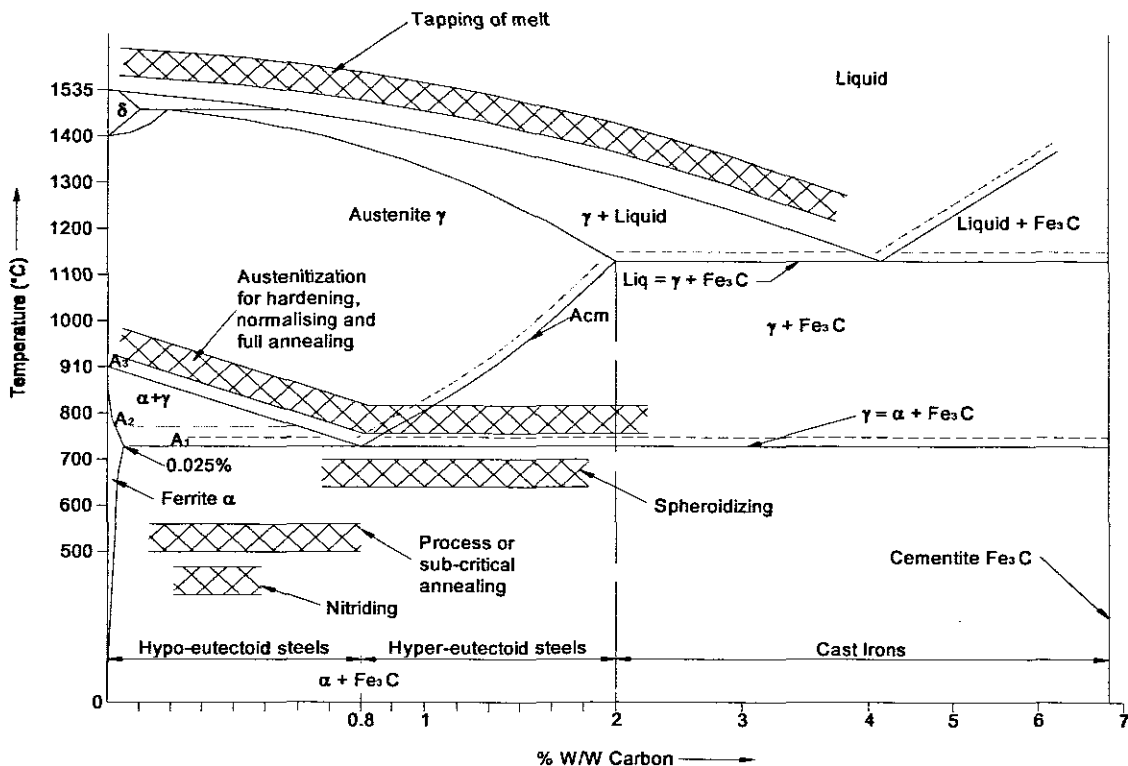


Figure 5.1: The phase diagram for Fe – C system [39].

In order to study the constitution and structure of all steels and iron one must first start with the iron-carbon equilibrium diagram. The most basic of these features has an influence on the behaviour of the most complex steels [21].

An important aspect of phase transformations is the sequence in which iron changes from $\alpha \rightarrow \beta \rightarrow \gamma \rightarrow \delta$ during the heating process. The atomic structure of α - iron is depicted in the figure 5.2 (a). The single cell displays the atoms at each corner of the cube as well as in the center, termed the body-centered

cubic structure. This structure is evident at room temperature. The temperature at A_1 is the eutectoid temperature of 723°C and is the boundary between ferrite-cementite and austenite-ferrite or austenite-cementite. As the temperature is increased to 790°C , the iron then changes to the β phase. The β phase has the same lattice as the α - iron. At this stage the only difference between the two is that α - iron is ferromagnetic and β - iron is paramagnetic. Even though there is a distinction in magnetism, it by no means implies a phase change. In fact, the crystal structures are the same and α - iron includes β - iron [32].

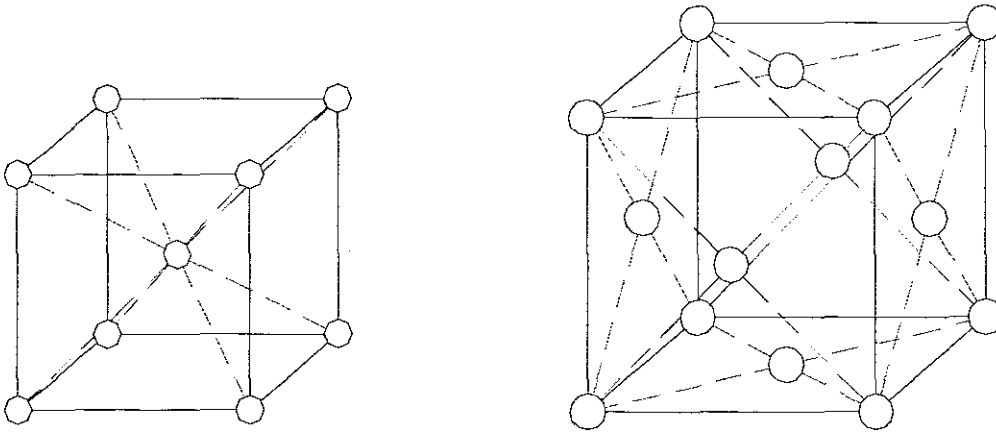


Figure 5.2: (a)Body-centered cubic lattice (α -iron). (b)Face-centered cubic lattice (γ - iron) [32].

At 910°C , which is the A_3 temperature and represents a boundary between the ferrite-austenite and austenite fields. The γ - iron phase transformation is reached and a face-centered cubic structure is evident. In a single cell the atoms are situated at the corners and on each face center of the cube. The next transformation is the δ phase, which is reached at 1400°C and has the same lattice as that of α -iron. During the cooling process the transformation from γ to α is closely related to the martensitic transformation [32].

The following formulae below determine the critical temperatures, has been

developed from experimental data [38].

For 0.08 ~ 1.4% C steel:

$$Ac_1(^{\circ}C) = 723 - 10.7Mn - 16.9Ni + 29.1Si + 16.9Cr + 290As + 6.38W \quad [5.1]$$

For 0.3 ~ 0.6% C low-alloy steel:

$$Ac_1(^{\circ}C) = 723 - 13.9Mn - 14.4Ni + 22.2Si + 23.3Cr \quad [5.2]$$

For 0.25 ~ 0.45% C low-alloy steel:

$$Ac_1(^{\circ}C) = 755 - 32.3C - 17.8Mn + 23.3Si + 17.1Cr + 4.5Mo + 15.6V \quad [5.3]$$

For 0.1 ~ 0.55% C low-alloy steel:

$$Ac_1(^{\circ}C) = 751 - 16.3C - 27.5Mn - 5.5Cu - 15.9Ni + 34.9Si + 12.7Cr + 3.4Mo \quad [5.4]$$

For 0.07 ~ 0.22% C low-alloy steel:

$$Ac_1(^{\circ}C) = 751 - 26.6C - 11.1Mn - 22.9Cu - 23Ni + 17.6Si + 24.1Cr + 22.5Mo - 39.7V + 223Nb - 169Al - 895B \quad [5.5]$$

For 0.08 ~ 1.4% C steel:

$$Ac_3(^{\circ}C) = 910 - 203\sqrt{C} - 30Mn - 20Cu - 15.2Ni - 11Cr - 700P + 44.7Si + 31.5Mo + 104V + 460Al + 13.1W + 120As \quad [5.6]$$

For 0.3 ~ 0.6% C low-alloy steel:

$$Ac_3(^{\circ}C) = 854 - 179C - 13.9Mn - 17.8Cu - 1.7Ni + 44.4Si \quad [5.7]$$

For 0.25 ~ 0.45% C low-alloy steel:

$$Ac_3(^{\circ}C) = 930 - 395C - 14.4Mn + 55Si + 5.8Ni + 24.5Cr + 83.4Mo \quad [5.8]$$

For 0.10 ~ 0.55% C low-alloy steel:

$$Ac_3(^{\circ}C) = 881 - 206C - 15Mn - 26.5Cu - 20.1Ni - 0.7Cr + 53.1Si + 41.1V \quad [5.9]$$

For 0.07 ~ 0.22% C low-alloy steel:

$$Ac_3(^{\circ}C) = 937 - 476C - 19.7Mn - 16.3Cu - 26.6Ni - 4.9Cr + 56Si + 38.1Mo + 12.5V - 19Nb + 198Al + 3315B \quad [5.10]$$

The differences in the thermal processes in welding and heat treatment of steels vary largely. During the welding process temperatures in excess of 1500°C are reached rapidly near the fusion boundary and these temperatures are retained only for a brief moment and drops very quickly. With the heat treatment process, temperatures only reach about 950°C over an extended period of time and the high temperatures are retained for a much longer period.

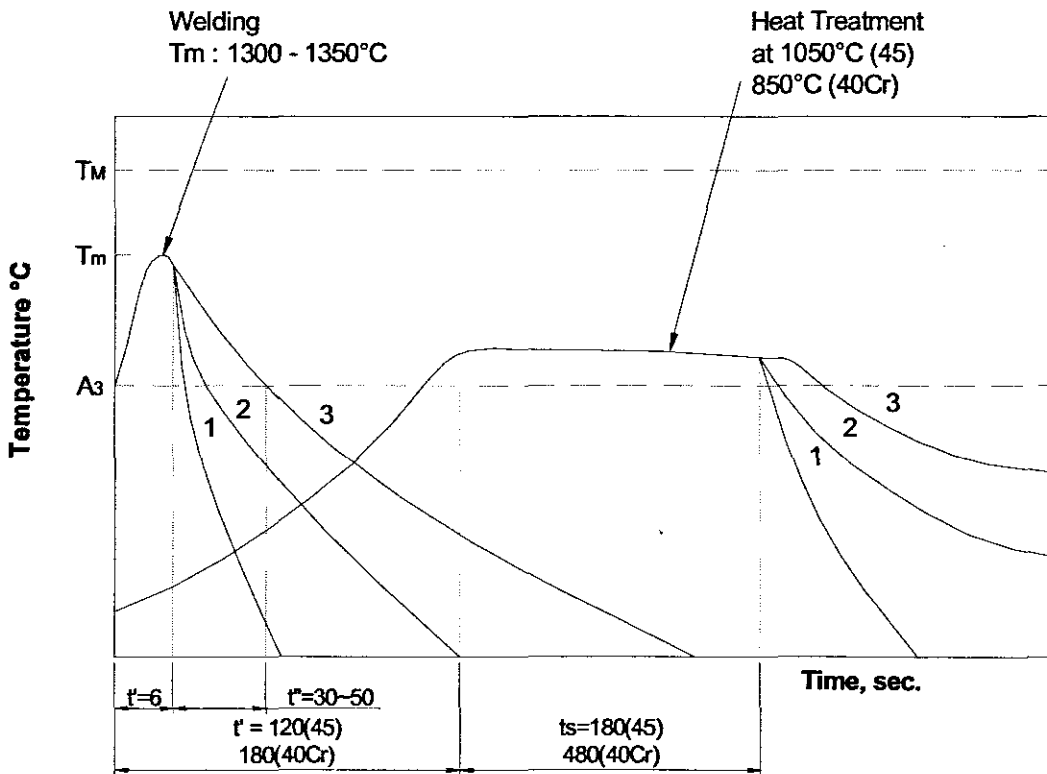


Figure 5.3: Temperature-time relationships for the welding and heat treatment processes of 1045 (45) steel and a Cr alloy steel with 0.4% C (40 Cr) [24].

The figure above compares the two thermal processes. Due to the excessive heating rate during welding, the diffusional transformation process from ferrite + pearlite to austenite becomes difficult. A consequence being that the effective

transformation temperatures, such as the lower critical temperature A_{c1} as well as the upper critical temperature A_{c3} is inclined to increase with an increasing heating rate during welding [24]. Very evident is the rapid heating and cooling rate of the welding process compared to the heat treatment process and the final material phase is dependent on these thermal rates.

The effect of the heating rate becomes more identifiable for steels containing larger amounts of carbide forming elements such as V, W, Cr, Ti, and Mo. This happens because the diffusion rate of these elements is lower than that of carbon. These elements also hinder the diffusion of carbon [24].

The formation of non-homogeneous austenite is the result of a rapid heating rate and high temperature retention during welding. With rapid cooling though, localized high carbon martensite may form causing the micro-hardness of the HAZ to scatter over a wide region. When high temperatures are reached, grain growth can take place close to the fusion boundary. During the cooling process grain growth may occur as well. With temperatures reaching below 1100° no significant grain growth is observed [24].

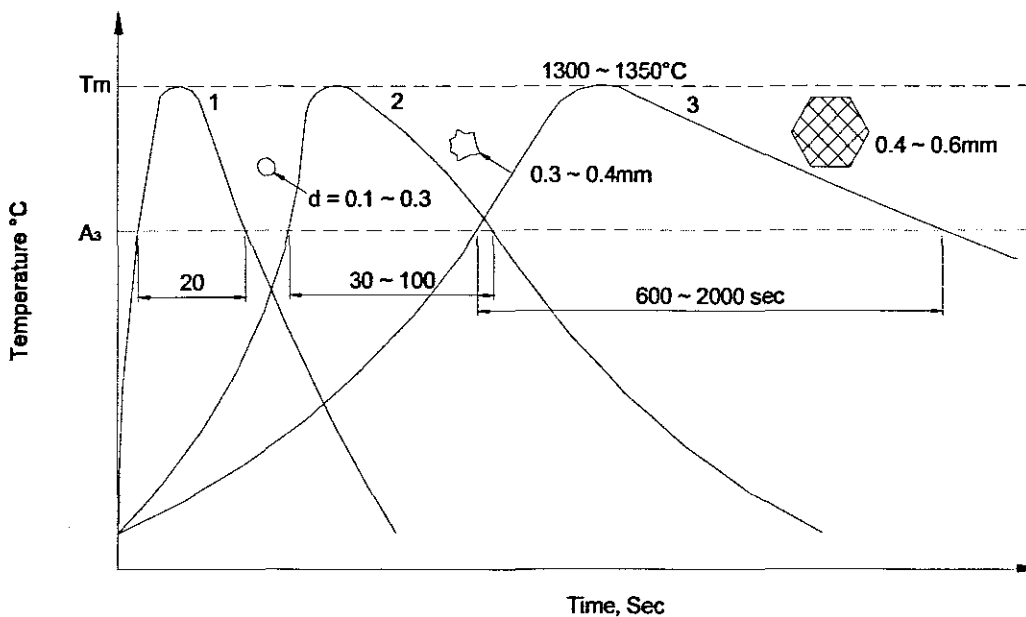


Figure 5.4: The effect of welding temperature on grain growth [24].

The figure above depicts shielded metal arc welding in the first instance with a thickness of less than 10mm. In the second case a submerged arc weld with plate 10-25mm thick. The third case represents electroslog welding with plate thickness of 100-300mm.

Evident is the fact that during welding and with high heat input, severe grain growth is produced and grain growth increases when high temperatures are retained. A coarse grain microstructure in a weld increased the fatigue crack growth resistance near the threshold growth region [45].

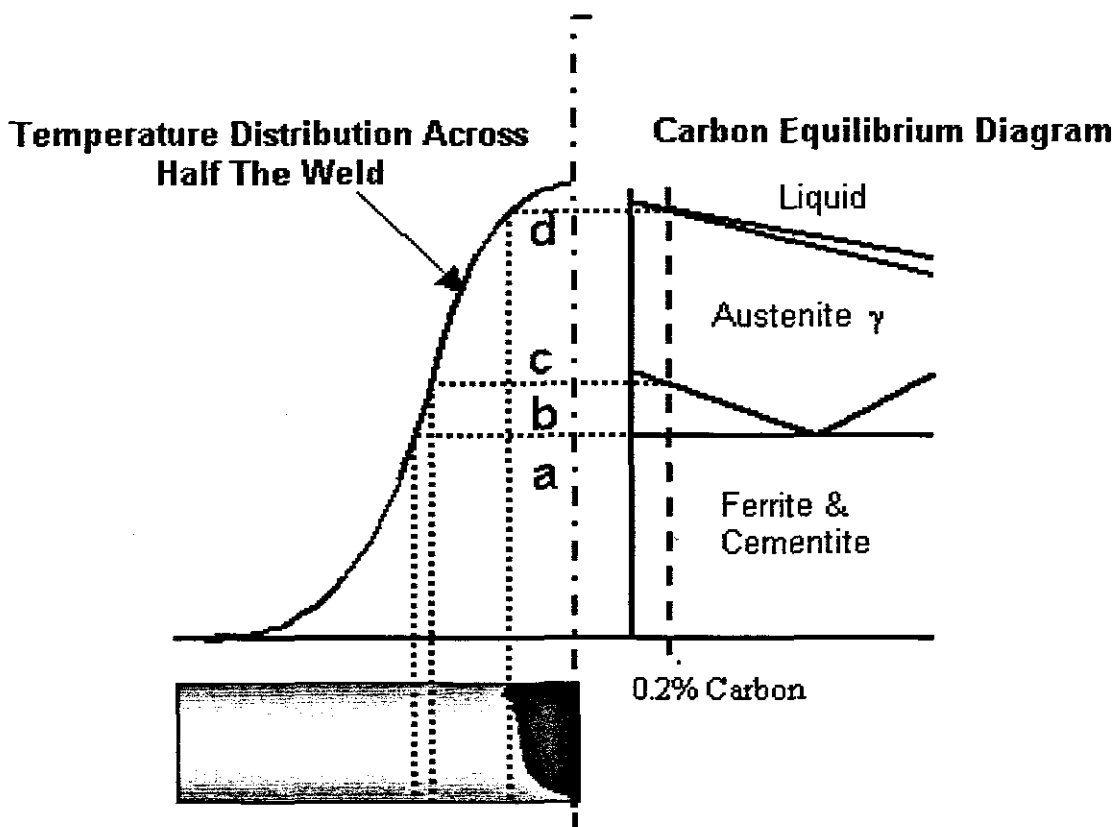


Figure 5.5: Temperature distribution curve depicting the phases in a weld [30]

The diagram above shows how the various phases are formed with respect to the temperature, time and the Carbon content in the steel. At point (a), with the temperature at A_1 , a mixture of ferrite and pearlite grains are visible. At this

temperature the microstructure has no significant change. At point (b), pearlite transforms to austenite, yet not all ferrite transforms to austenite due to the temperature not exceeding the A_3 line. At point (c), the temperature exceeds the A_3 line and full austenisation takes place. On cooling all the grains will be normalized. At point (d), The temperature significantly exceeds the A_3 line and grain growth is permitted [30].

5.3 The Mechanical Properties and Microstructure Relationship

An important aspect of phase transformation is that different types of phases are associated with different physical attributes. The strength and toughness of a material are the most important properties a material can possess in the engineering field, since the safe use of structures are dependent on these components.

A common practice in industry would be to use a weld metal with a tensile strength that is higher than that of the base metal. The most important constituents for a weld is;

- A fine grain size (acicular ferrite).
 - Solid solution hardening elements (manganese, nickel, etc.)
 - Dislocation hardening (acicular ferrite is essentially a bainitic structure)
- [41]

5.3.1 Mechanical Properties of The Heat Affected Zone (HAZ)

In structural steel welds, using typical arc energies, the HAZ is a mere 3 – 4mm wide. This band houses various micro-structural phases and properties with the critical region of importance being only about 1mm wide.

5.3.1.1 Strength

The heat-affected zone is the area closest to the weld and where the heat input during the welding process changes the microstructure without melting the steel.

The size of the HAZ in a typical weld is usually too small to perform a tensile test to determine the strength and ductility. Alternatively a hardness test can be done to determine some measure of the strength. The strength of the HAZ is very closely related to the volume of martensite in the microstructure [41]. Akselsen et al investigated the relationship between the HAZ and the strength and ductility of a welded material. The material for the purpose of this investigation was specimens of medium-strength steel with a low carbon content welded to high-strength steel.

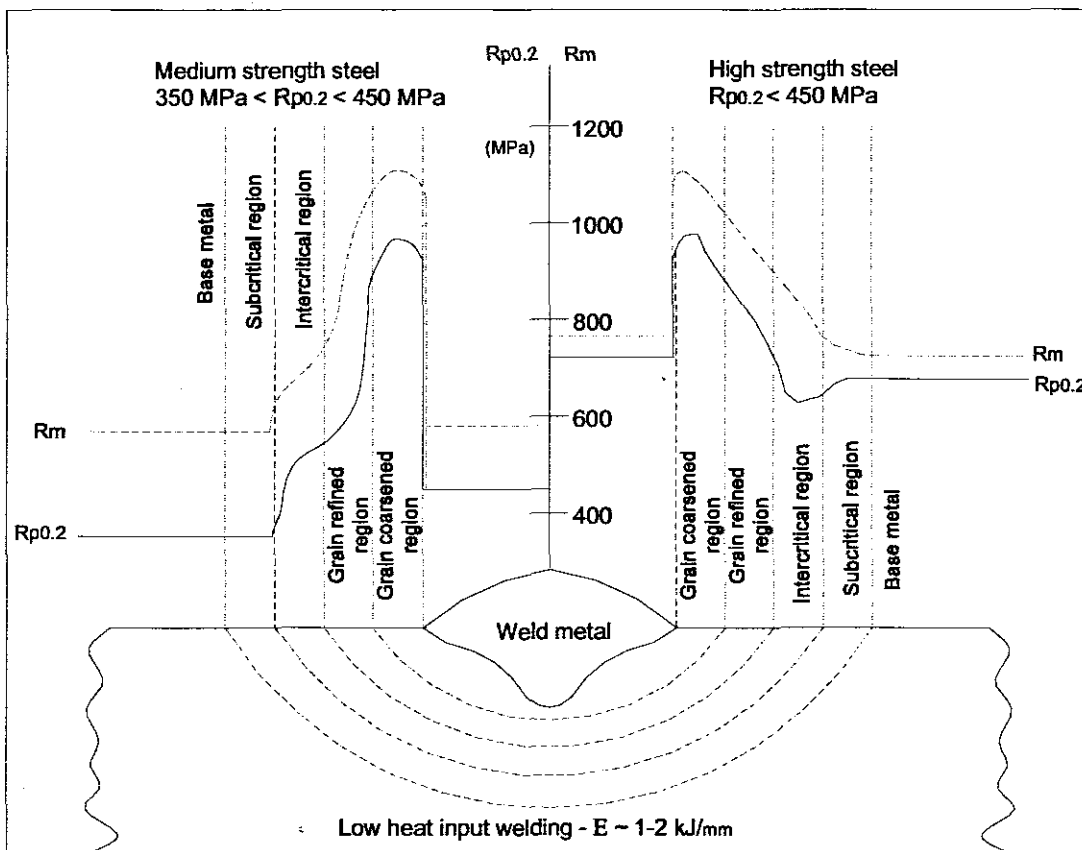


Figure 5.6: Variations in yield strength across the weld joint with low heat [41].

In the figure 5.6 and 5.7, the strength varies considerably over the HAZ. In the first diagram the weld material is the same strength as that of the high strength steel. It is evident that a low heat input results in a higher yield strength and hardness in the coarse-grained region than that in the weld and base metal. This is due to the presence of bainite and martensite [41].

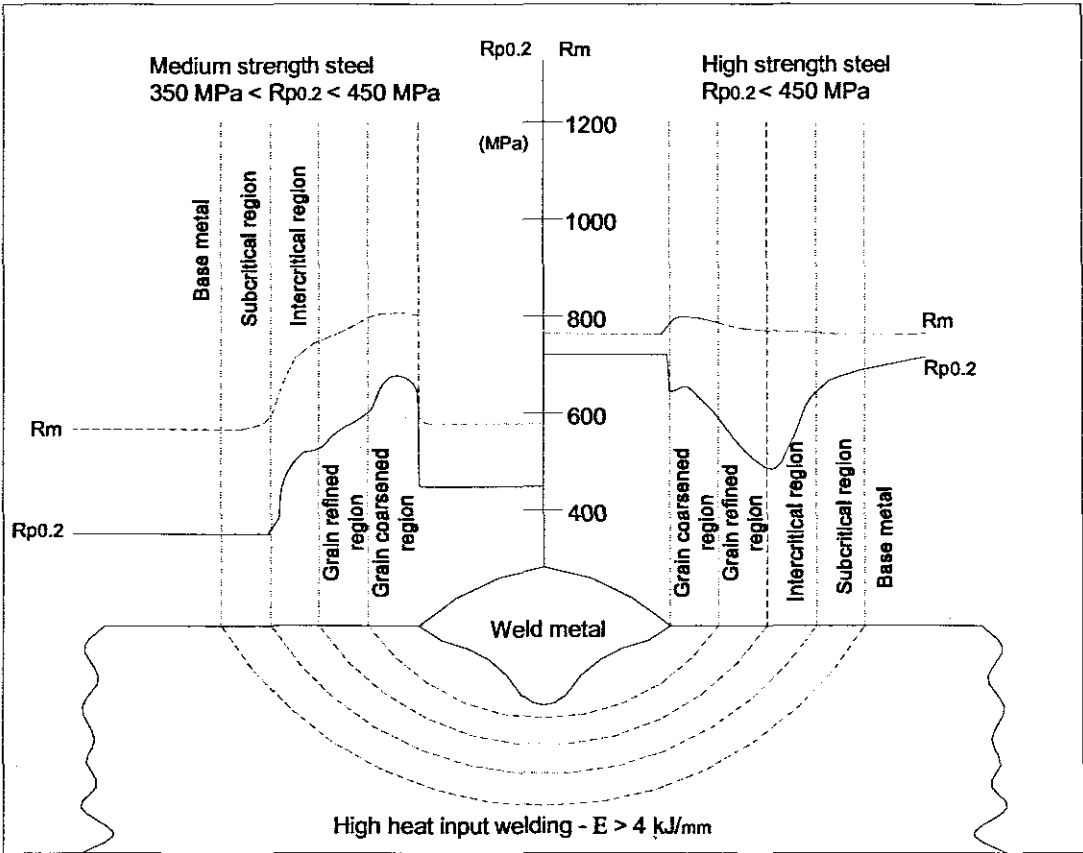


Figure 5.7: Variations in yield strength across the weld joint with high heat [41].

The figure above clearly indicates that the strength in the coarse-grained region in the HAZ is much lower than that of the weld and base metal. Even though the yield strength is higher in the HAZ than in the weld and base material in the medium strength steel, the high heat input results in less martensite formation and a softer material in the high strength steel. Equally evident is the fact that martensite influences the strength of the material immensely. Also the combination of fine grain size and carbon in solid solution determines the

strength of matensite.

5.3.1.2 Toughness

In the HAZ, toughness is considered to be a much more critical property than strength. Also since the strength of the material in the HAZ is higher than that of the base material, a sound structure can be expected from a design point of view. Yet the toughness of a material is closely related to the ability to withstand cracking and fracture and is thus more difficult to predict and design against. There are basically two zones within the HAZ, which is of primary concern and is the coarse-grained zone and the intercritically-heated zone.

Most particles from micro-alloying elements are dissolved in the coarse-grained zone resulting in re-precipitation during the austenite to ferrite transformation as the material cools. At this point in time the particles usually precipitate as an interphase reaction and results in a substantial increase in strength. Lower strength from precipitates can be expected in the refined-grain zone because the particles do not dissolve fully [41].

The matter becomes further involved due to the weld consisting of multiple passes, resulting in complex patterns of zones that have been reheated with every pass to varied temperatures. A low toughness in ferritic steel is normally related to fracture by cleavage. According to Svensson, if a material with a defect of length $2a$ is considered, the crack will propagate if the total energy of the system decreases during propagation. With an increase in crack growth, stored energy in the system decreases, yet instead the surface energy per unit area (γ) will increase. The condition for crack propagation is;

$$\sigma_F = [2 E \gamma / \pi a (1 - \nu)]^{1/2} \quad [5.11]$$

Where: σ_F is the fracture stress

E is Young's Modulus

ν is Poisson's ratio.

This equation though is for a plane strain condition [41].

In a ductile material, a large amount of energy is utilized for plastic flow around the crack tip. This energy (γ_p) is substantially larger than the surface energy per unit area. For the most common engineering materials the fracture stress;

$$\sigma_F = [E (2\gamma + \gamma_p) / \pi a (1 - \nu)]^{1/2} \quad [5.12]$$

Cleavage fracture is a result of tensile stress rather than shear stress. This suggests that the nucleation of a cleavage crack occurs easily, with propagation has to be controlled. It is assumed that a small crack nucleates in for example; a grain boundary carbide of thickness. It becomes critical when this crack propagates into the surrounding ferritic matrix [1]. With the fracture stress expressed as;

$$\sigma_F = [4 E \gamma_p / \pi (1 - \nu^2) l]^{1/2} \quad [5.13]$$

Even though grain size is a strong contributor in preventing cleavage fracture, it is important to note that fracture stress is independent of grain size. This is true due to the smaller grain size resulting in more grain boundary area, which reduces the size of the carbides, which eventually initiate fracture [41].

When the yield stress is higher than the fracture stress, the fracture occurs without plastic deformation and will thus be brittle. If the fracture stress is higher than the yield stress, then the fracture will be ductile. Increased yield strength will yield a brittle fracture at higher temperatures. Similar results are displayed if

the deformation rate is increased [41].

The figure 5.8 shows how the yield stress increases with a decrease in temperature, yet the fracture stress is independent of temperature. It is thus evident that an increase in strength leads to a decrease in toughness. This is true in the most common cases with some exceptions. A smaller grain size might increase both the yield and fracture stress to give an increased toughness. Various ways of increasing the strength such as solid solution hardening or precipitation leads to decreased toughness [41].

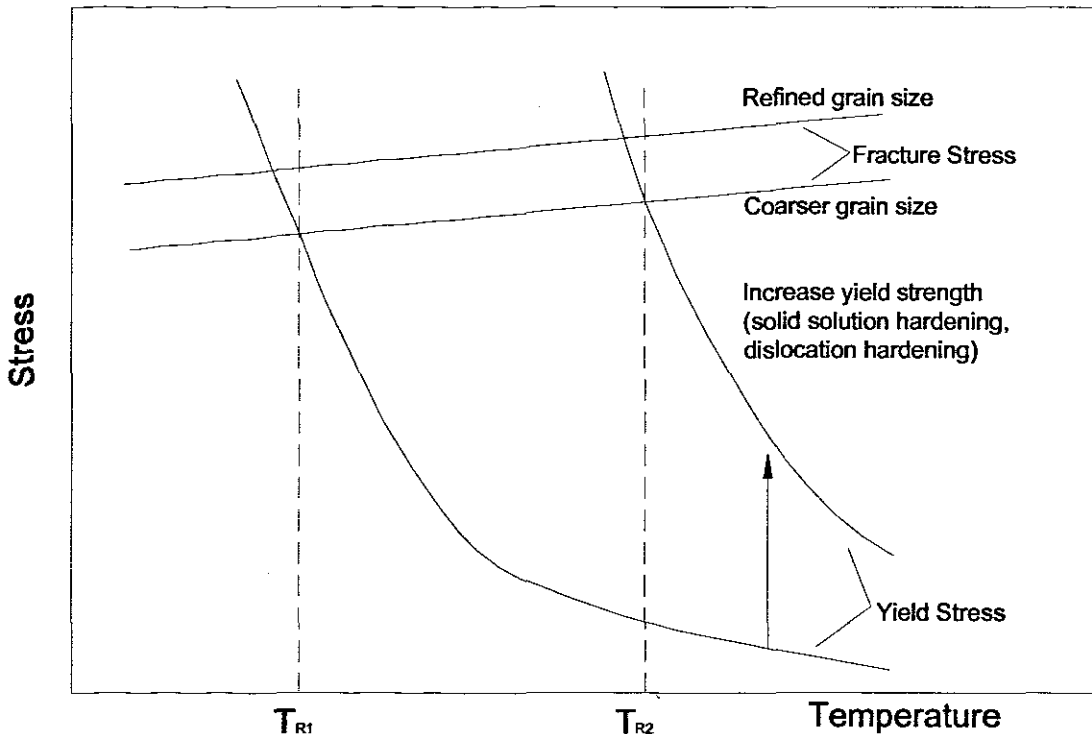


Figure 5.8: A diagram depicting the relationship between yield strength, fracture stress and mode of fracture [41].

From the above it is clear that various alloying elements play a huge role in the influence of the microstructure. Elements that assist to refine the grain size have a positive influence on the toughness. Manganese, molybdenum, copper, nickel, vanadium and chromium when used in controlled quantities have a positive bearing on the austenite to ferrite transformation resulting in a refined grain structure. A reduction in carbon also tends to increase toughness at

constant strength due to a reduced amount of carbides micro-phases. A martensitic microstructure with low carbon content will exhibit good toughness while a high carbon content will be brittle [41].

5.4 The Martensitic Phase Structure

The martensite phase structure, so aptly named after the German metallurgist Adolf Martens, is a classification of hard minerals, which occurs as lath or plate-shaped crystals. When this microstructure is observed through its cross-section, the crystals appear acicular (needle-shaped). The rapid cooling of austenite during quenching results in crystals that are displayed in a body-centred tetragonal (BCT) form of iron and carbon and may be seen as an α lattice with one cubic axis elongated. This phase is called the martensitic phase and produces the hardest and most brittle steel of all the phases. From the figure 5.9 it can be seen that during the slow cooling process the γ phase is decomposed into α phase and cementite [32].

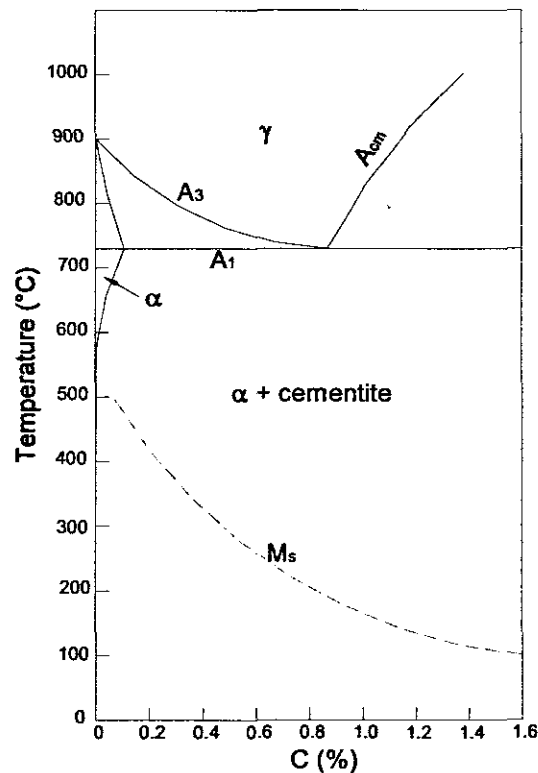


Figure 5.9: The Fe – C phase diagram showing the M_s temperature[32].

The start of the martensitic phase (M_s) is dependent on steel composition and can be determined by:

$$M_s(^{\circ}C) = 539 - 423C - 30.1Mn + 17.7Ni + 12.1Cr + 7.5Mo \quad [5.14]$$

5.5 Welding Procedure and its Effect on Grain Structure

The welding parameters have a profound effect on the grain structure and should be carefully selected so as to achieve the best results for the specified application.

Welding speed is deemed to play a significant role in the welding parameters. With a high welding speed, the weld pool is shaped like a teardrop. With a low welding speed the pool is more elliptical. A teardrop shaped weld pool has a trailing boundary that is basically straight. Similarly columnar grains are straight, in order to grow perpendicularly to the weld pool boundary. This is so because the crystal growth follow the steepest temperature gradients and the effect of changing the weld speed is to alter the solidification behaviour [34].

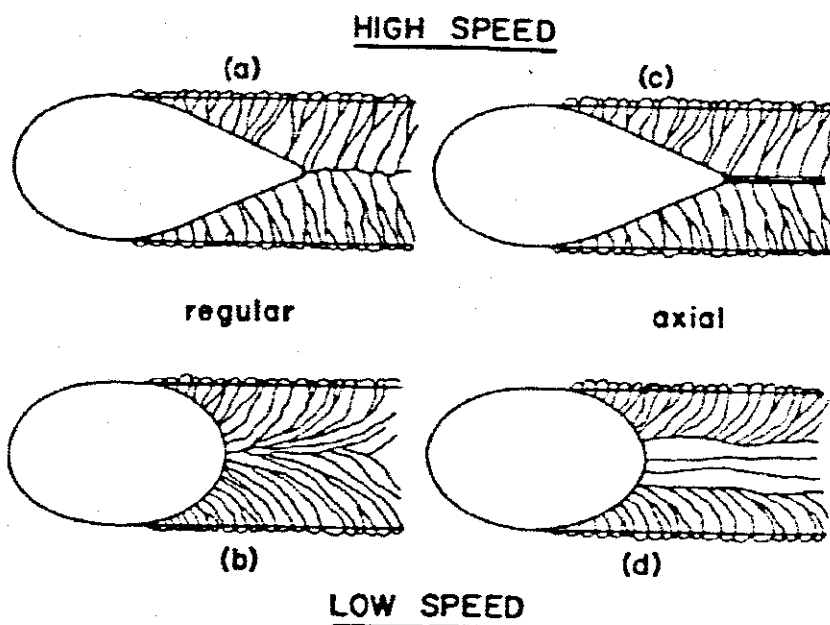


Figure 5.10: Variance in weld pool due to weld speed [24].

In the figure above, the welds (a & b) have a regular columnar grain structure, whereas in (c) displays a columnar grain structure with axial grains. The structure in (d) displays nucleation taking place in the bulk weld metal.

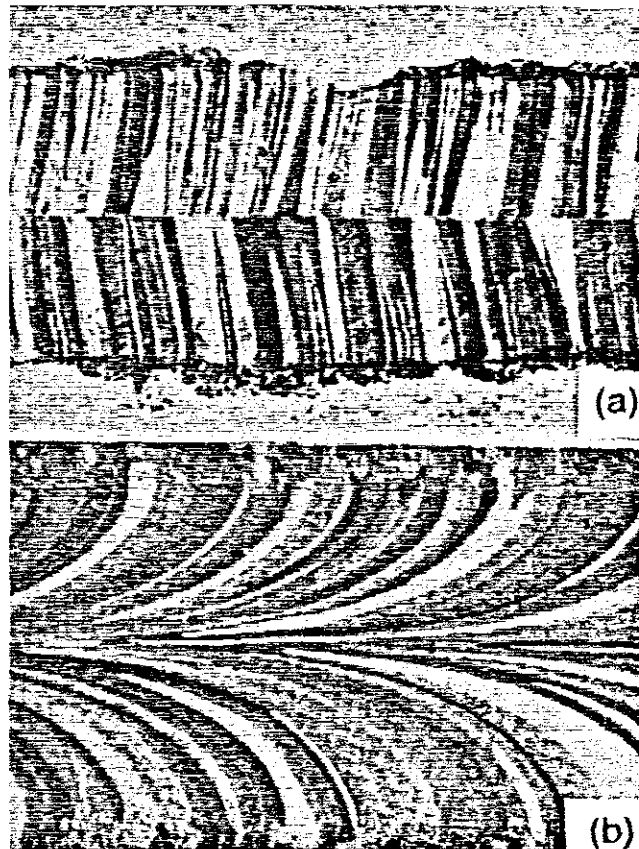


Figure 5.11: GTA welds at speeds (a) 1000mm/min and (b) 250mm/min [24].

The figure above depicts a gas tungsten arc weld at a speed of 1000mm/min where the straight columnar grains are pointed toward the centre line. At a speed of 250mm/min the curved columnar grains point in the direction of the weld.

5.6 Alloying Elements

Manganese:

It increases the strength and hardness; it forms carbide, it increases harden-ability and it lowers the transformation temperature range. When used in sufficient quantities, it produces austenitic steel and is always present in steel to some extent because it is used as a deoxidiser [30].

Silicon:

It strengthens ferrite, raises the transformation temperature and has a strong graphitising tendency. It is always present to some extent, because it is used as a deoxidiser together with manganese [30].

Chromium:

It increases strength and hardness and forms hard and stable carbides. The transformation temperature is raised significantly when its content exceeds 12%. It also increases hardenability and amounts in excess of 12%, results in stainless steel. It produces good creep strength at high temperatures [30].

Nickel:

It strengthens steel, it lowers its transformation temperature range, it increases hardenability and improves the resistance to fatigue. It also has strong graphite forming tendencies and stabilises austenite when in sufficient quantity. Fine grains and good toughness are present [30].

Nickel and Chromium:

When used together for austenitic stainless steels, each element counteracts disadvantages of the other[30] .

Tungsten:

It forms hard and stable carbides, it raises the transformation temperature range and tempering temperatures [30].

Molybdenum:

It is a strong carbide forming element and also improves high temperature creep resistance and reduces temper-brittleness in Ni-Cr steels. It also improves corrosion resistance and temper brittleness[30] .

Vanadium:

It is a strong carbide-forming element, has a scavenging action and produces clean, inclusion free steels. It can cause re-heat cracking when added to chrome moly steels[30] .

Titanium:

It is a strong carbide-forming element. It is not used on its own, but added as a carbide stabiliser to some austenitic stainless steels [30] .

Phosphorus:

It increases strength and hardenability and reduces ductility and toughness. It increases machineability and corrosion resistance [30].

Sulphur:

Reduces toughness and strength and also weld-ability [30].

5.7 Cooling Rate and Temperature Gradient of Weld.

The ratio EI/V determines the heat input per unit length of the weld [6].

$$T - T_0 = \frac{Q}{2\pi kx} \quad [5.15]$$

Thus the temperature gradient is

$$\left(\frac{\partial T}{\partial x} \right)_t = \frac{Q-1}{2\pi kx^2} = -2\pi k \frac{(T - T_0)^2}{Q} \quad [5.16]$$

From the above equation and

$$\left(\frac{\partial x}{\partial t} \right)_t = V \quad [5.17]$$

The cooling rate is:

$$\left(\frac{\partial T}{\partial t}\right)_x = \left(\frac{\partial T}{\partial x}\right)_t \left(\frac{\partial x}{\partial t}\right)_T = -2\pi kV \frac{(T-T_0)^2}{Q} \quad [5.18]$$

Chapter 6

Fatigue Fracture and Failure Analysis of Welds

6.1 Introduction

Fatigue failure is defined as the process of progressive localised permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations [4].

Failure analysis in turn is an engineering procedure to establish exactly how and why fatigue failure has occurred in equipment or components. The failure analysis process is complex and involves various different disciplines and includes observation, inspection and laboratory techniques and equipment.

Very often the study of metallurgical engineering is a necessity in determining failures, whether equipment fails during production processing, manufacturing, or in service. Equally important in fatigue failure are the aspects of failure prevention and the improvement of equipment or components.

6.2 Fatigue Crack Initiation

Metal fatigue cracks initiate and propagate in regions where the strain is most severe in relation to the material strength and is an effect of three simultaneous activities taking place, which are cyclic stress, tensile stress and plastic strain. Fatigue failure is dependent on all three activities and develops from plastic strain being caused by cyclic stresses, which result in crack initiation. Crack growth is then propagated by tensile stresses. Usually these critical regions are

high stress concentrations, which include a sudden change in physical geometry of a component or part. Even poor surface finish or local weakness such as scratches or structural defect may cause nucleation. Very often micro-cracks are a consequence of the welding process and propagate under loading conditions.

The process of fatigue consists of five stages [36]:

- Cyclic plastic deformation
- Crack initiation
- Propagation of micro-cracks to form macro-cracks
- Progressive growth of macro-cracks
- Final sudden fracture

High-Cycle Fatigue (HCF) occurs at a relatively large number of cycles and at high frequency. The cycles to fracture usually exceeds 10 000 cycles. Whereas Low-Cycle Fatigue occurs at less than 10 000 cycles. In HCF the strain imposed during cyclic loading is elastic, whereas in LCF the strain imposed is plastic. It is important to note that if high cyclic stresses or strains have been imposed on a material, the proportion of the cyclic life spent on initiating the crack will be substantially small and is typically of the order of 10% or less and equates to about 50 000 cycles. For considerably low stresses and strains though, the proportion of life cycle involved in crack initiation, may be 90% or more of the total life with the number of cycles equating to 1000 000. It is thus evident that absolute stress or strain amplitude has a direct bearing on the formation of fatigue cracks [12].

It is well known that fatigue cracks initiates along slip bands, in grain boundaries, in inclusions, in second-phase particles and second-phase interfaces with the matrix phase. The manner by which the fatigue crack will

initiate is dependent on the mode, which occurs more readily. Even though grain boundaries influence crack initiation, slip bands discontinue to propagate across these boundaries [36].

6.3 Fatigue Crack Propagation

It is rather a complex task to determine exactly when cracks initiate. The precise time of evolution of these micro-cracks must be established and micro-measurements in the order of less than $0.1\mu\text{m}$ are experienced at this point. Micro-cracks propagate or coalesce into macro-cracks as a result of cyclic stress or plastic strain exceeding the fatigue limit. The growth of these cracks is dependent essentially on the cyclic stress or strain amplitude, material characteristics, material geometry and environmental conditions. Macro-cracks are measured over a few grains whereas micro-cracks are limited to single grains.

High amplitudes influence micro-cracks and coalescence across grain boundaries. Very often propagation is due to plastic deformation brought about by these high amplitudes. Also important to note is the fact that grain boundaries resist propagation because plastic deformation is discontinuous across boundaries [36].

If a macro-crack has developed into a few millimetres or more, the stress intensity range, ΔK , of linear fracture mechanics, determine the propagation rate on condition that small scale yielding occurs at the crack tip. At this point Δ

K is $\Delta\sigma\sqrt{af(g)}$, Where: $\Delta\sigma = \sigma_{\text{max}} - \sigma_{\text{min}}$

a = crack length

$f(g)$ = specimen geometry function, ratio of crack length/specimen width, a/w .

6.4 Fatigue-Life Variables

A life cycle of a material, which is loaded with a constant-amplitude loading cycle, is defined by the minimum and maximum stresses applied during the loading cycle as seen in figure 6.1 with the mean stress σ_m and the alternating stress σ_a being defined as:

$$\sigma_m = \frac{(\sigma_{\max} + \sigma_{\min})}{2} \quad [6.1]$$

$$\sigma_a = \frac{(\sigma_{\max} - \sigma_{\min})}{2} \quad [6.2]$$

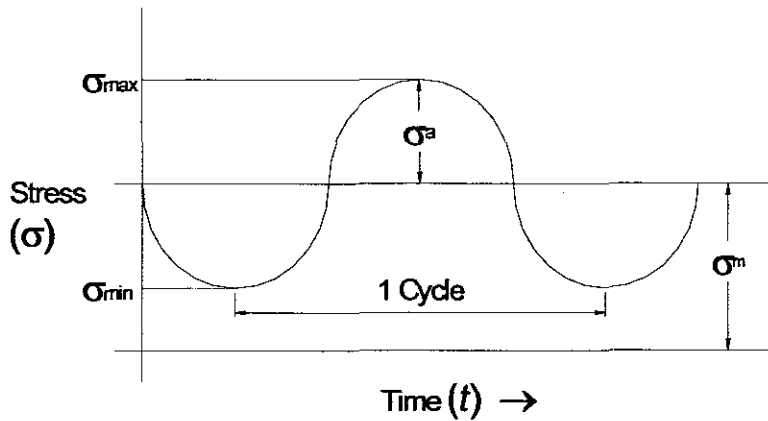


Figure 6.1: Constant amplitude loading cycle [4]

Also another parameter that characterises the type of loading is the R -ratio:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \quad [6.3]$$

A negative R -ratio suggests a tension-compression loading cycle. Thus for an R -ratio of -1 , loading is entirely reversed and as a result of this, the mean stress is zero (0). An S - N curve can be plotted for the results of a fatigue test at $R = -1$ in order to establish an endurance limit for the material. When considering low

strength steels, the endurance limit is determined by the part of the $S-N$ curve that becomes asymptotic as the number of cycles increase. Stress levels that do not reach the endurance limit are deemed to be non-damaging. The limit for low-strength steel is usually in the region of 50% of the ultimate tensile strength. In the case of high strength steels, the asymptote is not clearly established and the endurance limit is characterised as the alternating stress levels, which occurs at 10^7 cycles [4].

Constant amplitude loading is beneficial in determining material properties and comparing fatigue test data, yet variable amplitude loading is experienced more often in industry. However, this research will only focus on constant amplitude loading.

6.5 Fatigue Concentrations in Welded Joints

It is common knowledge that a welded joint subjected to a cyclic load will display a reduced life cycle when compared to that of a plain component. When a weld is joined to a load-carrying member, the fatigue strength and fatigue limit is reduced substantially. The design stress of a cyclically loaded welded joint is thus limited by the fatigue strength of that joint.

Factors that effect the reduction of fatigue strength are:

- Stress concentration due to weld geometry and shape.
- Stress concentration due to weld imperfections.
- Welding residual stresses.

In order to effectively design against fatigue in welded joints, the above factors and their influence on the performance of the weld must be understood to some degree [36].

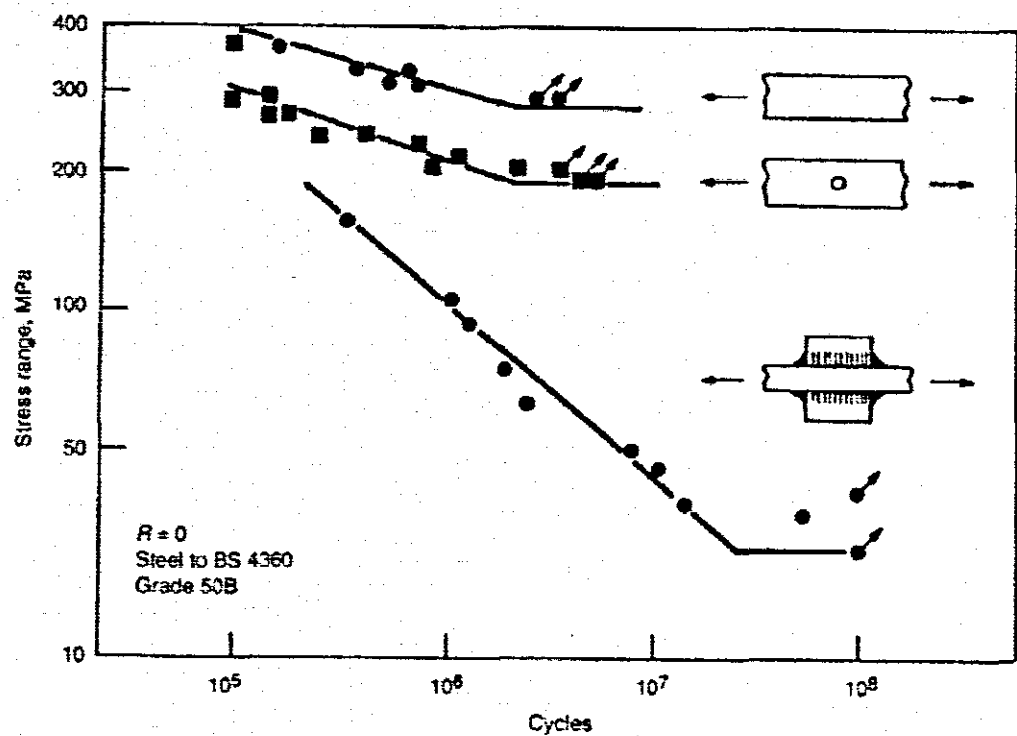


Figure 6.2: Comparison of fatigue performance of weld and parent metal [36].

6.5.1 Stress Concentration Due To Weld Geometry

A welded joint will display a cross-sectional area that has either increased or decreased in dimension at the point where the parent metal meets the weld. Changes in cross-sectional area automatically results in stress concentrations. The stress concentration is dependent on the direction of loading and the weld joint.

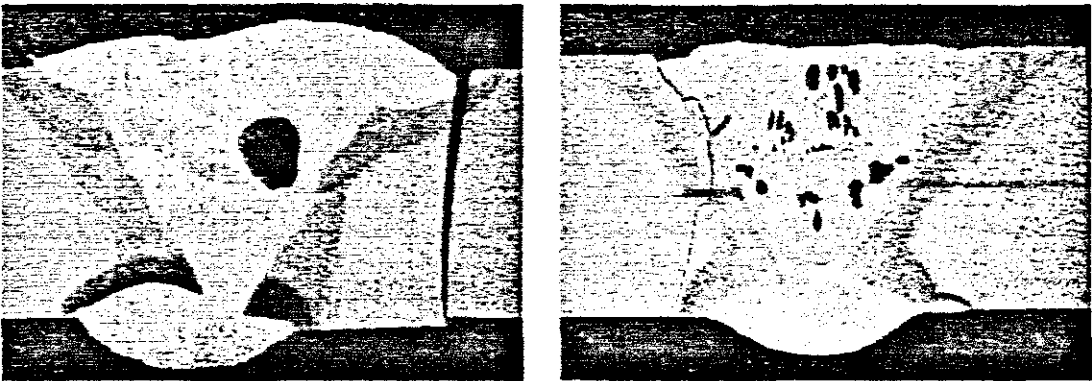


Figure 6.3: Volumetric imperfections and slag inclusion in a butt weld [36].

The figure 6.3 depicts a weld that is not load bearing, yet stress concentrations are evident and toe cracking inevitable. Usually when a weld has deep penetration, the toe is the most likely place for fatigue cracking to commence. Also, a joint with a poor weld penetration, coupled with an excessive root gap, results in cracks, which initiates from the root of the weld and propagated throughout the weld. From experimental results it has been proven that welding processes have a significant influence on fatigue crack initiation [3].

The geometry parameters that influences fatigue in welded joints by affecting the stress concentrations are:

- Plate thickness (T)
- Attachment toe-to-toe length (L)
- Attachment thickness (t)
- Weld toe radius (r)
- Weld angle (θ)
- Weld profile (concave / convex) [36]

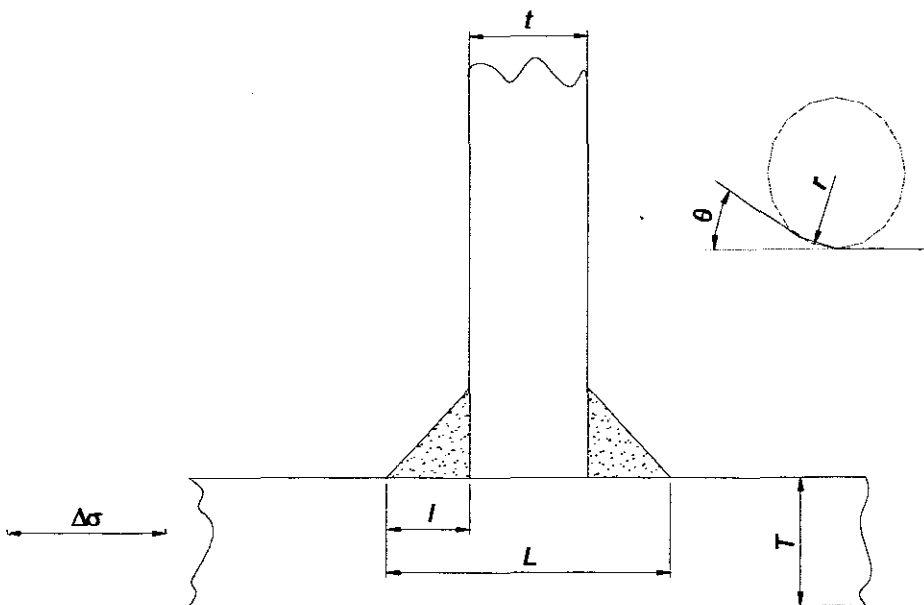


Figure 6.4: Geometry parameters that influence stress concentration [36].

As the attachment length of the weld joint increases, the fatigue strength

decreases. Misalignment of base plates of a welded joint also has a significant effect on the fatigue behaviour. As the misalignment increases, the fatigue strength decreases.

6.6 The Influence of Material Properties

Material properties do not influence the fatigue strength of the welded joint since crack propagation governs the fatigue life as seen in figure 6.5. Hence using a material with increased strength will not improve the fatigue life of the joint.

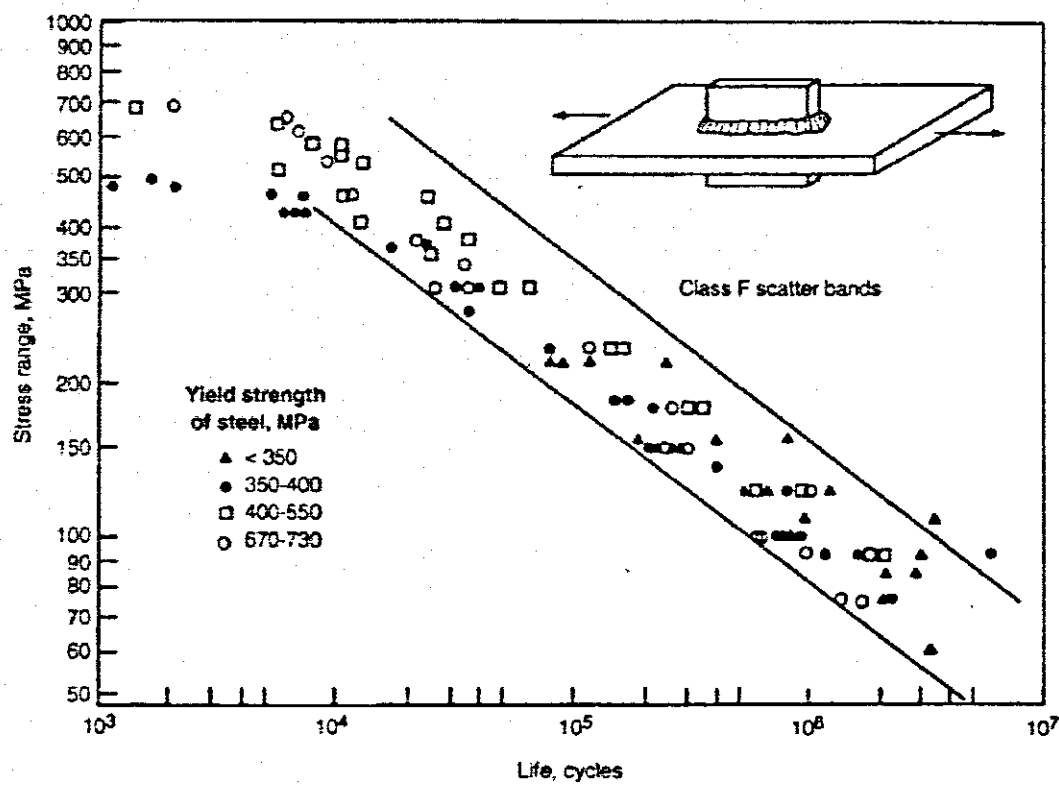


Figure 6.5: Fatigue tests of fillet welds using varied materials strengths [36].

A crack that initiates at the weld toe will generally propagate into the HAZ and eventually into the parent metal as seen in figure 6.3. As the crack propagates, it passes various microstructures, yet the growth rate is not retarded or influenced at all by the hardness in the HAZ, the toughness of the material or

the parent metal. The toughness of the material does have some effect in that it accommodates a bigger fatigue crack before fracture takes place [36].

6.7 Control of Fracture in Welds

Failures of welds may be categorised as those welds that are rejected after inspection and mechanical testing and those failures that occur in service due to wear, corrosion or deformation.

To some extent, all welds are subject to imperfections (discontinuities) with the joint being a major discontinuity in the structure. Planar, volumetric and geometrical imperfections are three categories of weld deficiencies that promote crack propagation.

The ***planar imperfections*** resemble sharp crack-like characteristics and may impede the fatigue strength of the welded joint and even initiate brittle fractures. Causes of these deficiencies vary and include hydrogen cracks, lack of fusion, solidification cracks, lamellar tears, etc. Characteristics such as these are the fundamental reason why weld fatigue is dominated by crack propagation [4].

Volumetric imperfections include porosity and slag inclusions. Since these imperfections are near spherical, their notch effect is of little or no consequence to the fatigue life of the welded joint. The reduction in the load bearing area is evident though and results in a reduced static strength.

Geometrical imperfections includes stop/starts, undercuts, weld ripples, misalignments, etc. Geometrical imperfections raises the stress levels somewhat above the stress concentration and is due to the welded joint geometry [4].

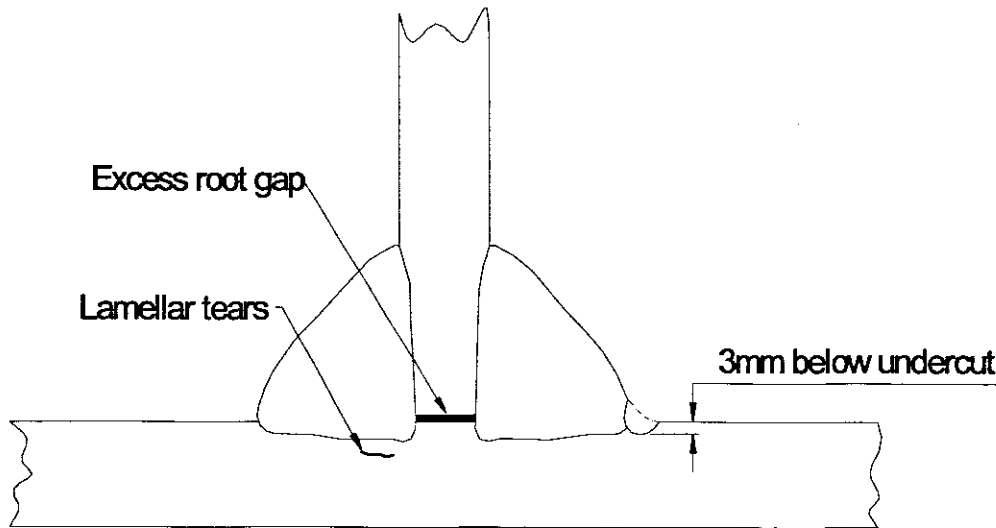


Figure 6.6: Typical examples of weld imperfections, which may initiate cracks.

Above are typical examples of imperfections that cause fracture in structures. The root gap in this case is excessively large, yet very little weld penetration is evident. Undercutting at the toe of the weld is caused by too much heat input and is a typical example where failure will occur. Lamellar tears are base metal cold cracking and occur parallel to the parent metal surface and adjacent to the weld. These tears occur due to tensile strains that result from thermal contraction of the weld area.

It is important to note that prevention is better than cure. Thus the first step in fatigue control is to avoid fatigue crack initiation. The next step is to avoid crack growth and the final step is to design to prevent unstable fracture with the assumption that fatigue crack initiation will occur. Fatigue crack initiation is very seldom experienced on in-service welded joints, but existing weld impediments are sure targets for crack propagation [36]. When designing for crack initiation prevention, machined joints should be carefully analysed, as this could be a major cause of fracture as well.

6.8 Stress Intensity and Fracture Toughness Factor

The stress intensity factor concerns the stress distribution at a crack tip. Given a thin flat plate subject to a uniform tensile stress and with a small edge crack, the stress intensity factor is determined from:

$$K_I = \sigma \sqrt{\pi a} \quad [6.4]$$

where: K_I = stress intensity factor

σ = applied stress

a = crack length

The subscript for the intensity factor refers to the mode of loading for crack initiation. There are basically three modes loading. For mode **I** loading, a tensile loading on the edge of a flat thin plate opens the gap between the opposing crack surfaces. For mode **II** loading, a shear load causes the two opposing crack surfaces slide relative to each other and in the plane of the plate. For mode **III** loading, a shear load causes the two opposing crack surfaces slide relative to each other perpendicular the plane of the plate [4].

Even though mode **I** loading is a typical loading mode, stress intensity factors can be determine for all three modes of crack loading. A crack in a flat loaded plate has a critical length (a_c) that will result in fracture. The length of the crack is dependent on the applied stress as well as the fracture toughness (K_c), of the plate:

$$K_c = \sigma \sqrt{\pi a_c} \quad [6.5]$$

Fracture toughness is therefore a measure of the critical stress intensity factor a plate can withstand before ultimate fracture [4].

In thin plate the prevalent stress state is plane stress. As the plate material increase, the stress state transforms to plane strain conditions and fracture toughness is represented by K_{Ic} . The stress intensity factor has an notable effect on the growth of cracks and is directly related to the elastic energy release rate (G), which is a measure of the amount of available energy for crack growth [4]:

$$G_I = \frac{K_I^2}{E} \text{ for plane stress conditions } (\sigma_{zz} = 0) \quad [6.6]$$

$$G_I = \frac{(1-\nu^2)K_I^2}{E} \text{ for plane strain conditions } (\varepsilon_{zz} = 0) \quad [6.7]$$

where: E = modulus of elasticity

ν = Poisson's ratio

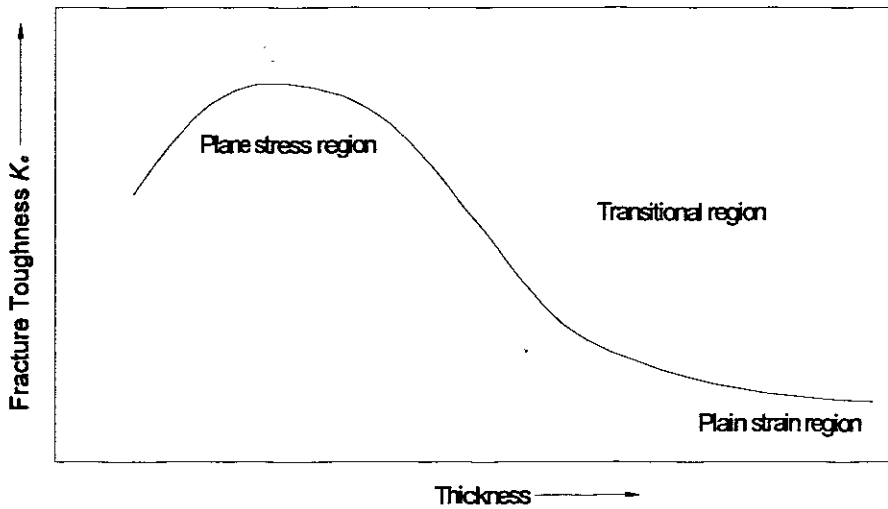


Figure 6.7: The effect of thickness on fracture toughness [4].

In a ductile material the cracks undergo stable crack growth and the energy released during the extension of the crack, is absorbed to establish a plastic zone around the crack tip. If not enough energy is present to create a new plastic zone, the crack will cease to grow.

The crack formation equation for regions I & III is:

$$\frac{da}{dN} = \frac{C\Delta K^n}{(1-R)K_c - \Delta K} \quad [6.8]$$

where: R = ratio of minimum to maximum stress
 ΔK = stress intensity range ($K_{max} - K_{min}$)
 C & n = material-dependant coefficients

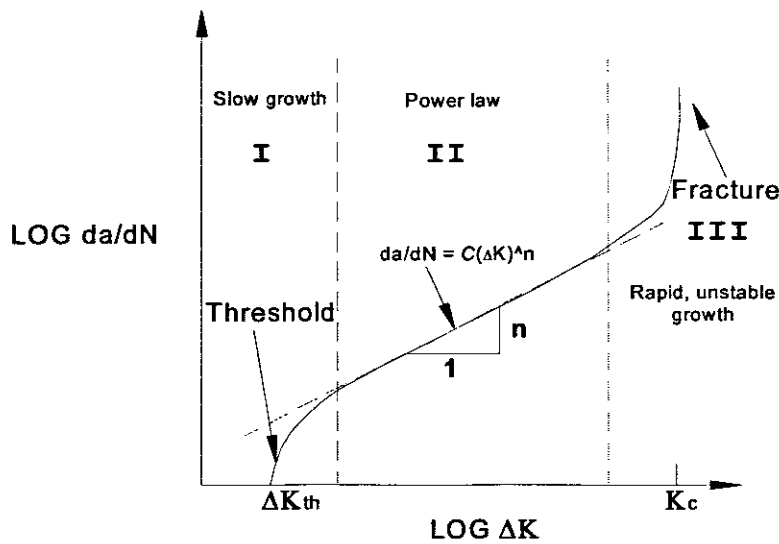


Figure 6.8: Typical fatigue crack growth behaviour in metals [2].

da/dN represents the change in crack length per stress cycle, also known as the growth rate and each stress cycle consists of a minimum and a maximum stress. The material-dependant coefficients C & n are calculated from the slope of crack growth rate data curves, which plot da/dN versus ΔK . The data for these curves are determined from tests that are run for a particular R -ratio and may display several regions with different slopes. It is therefore important to determine the material coefficients from that portion of the curve corresponding to the expected stress intensity factor range. If in the event that ΔK falls below the stress intensity threshold (ΔK_{th}), very little crack growth will prevail. It is assumed that in practice that ΔK is greater than ΔK_{th} . An approximate value for

ΔK_{th} can be found from the indicated ΔK for the minimum data point on the crack growth rate data curve [2] [4].

To determine the fatigue loading scope, it is important to know the anticipated use of the material. For a complete fatigue analysis, a spectrum must be provided as a series of whole cycles where a cycle consists of a maximum stress, minimum stress and maximum stress. Thus the spectrum consists of a constant mean stress cycle to be used in the crack growth analysis [4].

Chapter 7

Experimental Procedure

7.1 Introduction

The objectives of the experiments were to analyse crack initiation and the ultimate failure of both the base metal and the welded metal under cyclic loading. These failures had also to be related to the existing microstructures in the welds and the residual stresses. Also an attempt was made to find a correlation between the hardness of the weld metal, the strength as well as the metallurgical phase present. Stress measurements were made to reveal the residual stresses present in the fatigue specimens.

Tests were also done post fatigue to see if the hardness changed to see if it could be used to categorise the state of the fatigue in the material. The objectives were to be achieved using metallography, stress measurement and fatigue testing as experimental methods. The stress patterns associated with the evolution of the specimens subjected to cyclic loading were analysed using stress measurement techniques (with application of the Debro-30 ultrasonic stress measuring device and rosette strain gauges).

Low-carbon steel, which is commonly used in the engineering industry and which is of weldable quality, has been used for these experiments. This material is often used in welded constructions such as huge container tanks, certain pressure vessels, structural construction, etc.

7.2 Experimental Procedure

7.2.1 MIG Welding Specimens

The MIG welding procedure carefully simulated industrial conditions. This was done in order for the experimental results to reflect true and close correlation between this research and the engineering workshops. The welded specimens consisted of 2 off 300mm x 100mm x 12mm thick carbon steel plates, V-butt welded together using the MIG welding process.

Grade :	Commercial Low Carbon Steel						
Chem	C	Si	S	P	Mn	V	Al
wt%	0.19%	0.29%	0.01%	0.01%	0.23	0.01%	0.00%

Table 7.1: Chemical composition of welded specimens (wt%).



Figure 7.1: A MIG-welded test specimen.

Ten (10) of these welded specimens were prepared from 300WA carbon steel plates. Six (6) of these specimens that displayed the least weld imperfections to the naked eye, were selected for experimental analysis.

7.2.2 The Mig-Welding Procedure

The weld joint selected for this experiment is a 60° V-butt joint with a 3mm root gap and a 2mm landing. The weld joint was cleaned of all foreign particles with the aid of an angle grinder.

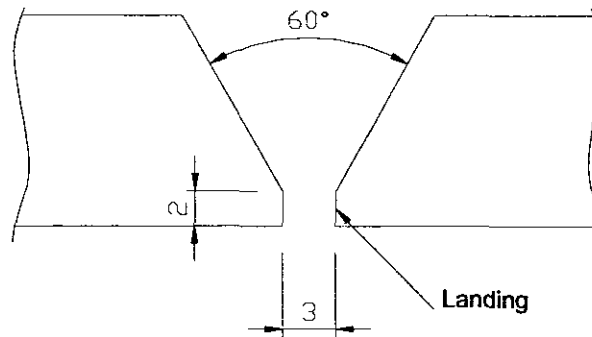


Figure 7.2: Schematic view of a weld joint used for the experiments.

The weld specimens were placed side by side as per figure 7.2. Run-on and run-off plates were then tack-welded to the test pieces. These run-on and run-off plates serve two purposes. Firstly, it prevents the weld root-gap between the plates from closing as the weld progressed. Secondly, a continuous uninterrupted weld can be maintained from one end of the plate to the other, thus minimising porosity and foreign inclusions. The weld specimens were not constrained by any other means. Welding commenced with a full penetration root run and progressed with a number of passes as seen in figure 7.6. The completed welded specimens were allowed to cool to room temperature in air.

Multi-pass welding produces bead tempering and due to this re-heating process, residual stresses are induced. During the multi-pass welding process, the temperature is raised to well above the A_3 line where grain growth and re-austenisation is permitted. Since the weld is then cooled in still air, normalising takes place. Multi-pass welds require less heat input than that of single-pass welds. According to [41], a low heat input results in a higher yield strength. Shrinkage in single-pass welds is essentially influenced by the temperature gradient, which develops in a transverse direction to the weld. In

multi-pass welds, the residual stress develops across the section, due to the temperature gradient between weld beads [48]. In multi-pass welds it is advisable to use inter-pass temperature control to minimise both the heat influence on the weld HAZ and oxidation potential.

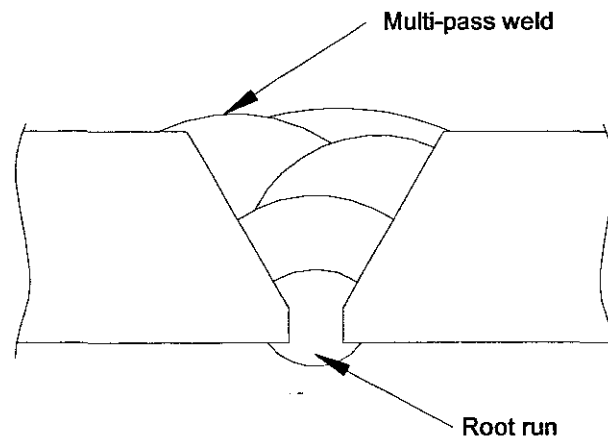


Figure 7.3: Depicts the typical multi-pass weld used for the specimens.

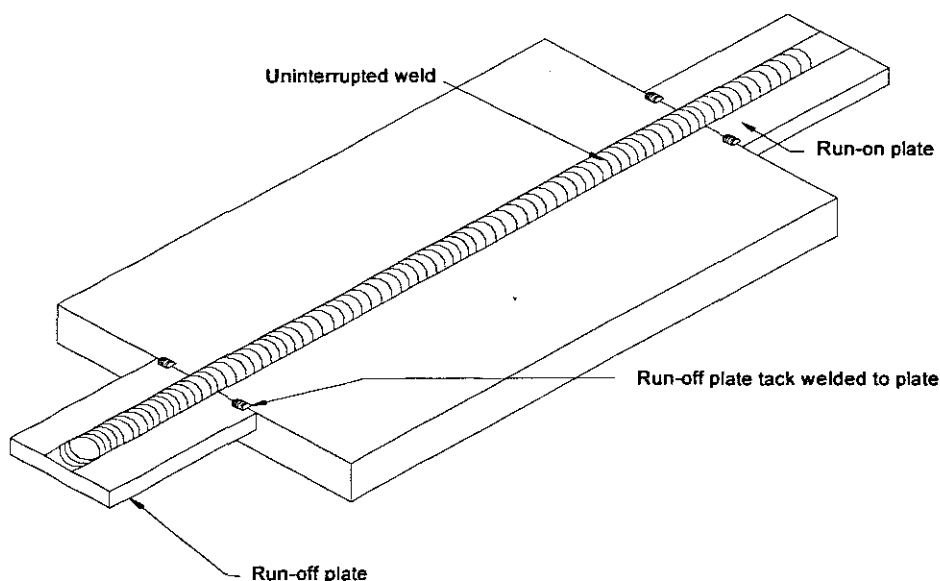


Figure 7.4: Weld specimens depicting run-off plates on the sides.

The Mig-welds were performed using a Kemppi welding machine with a 1mm welding electrode. With the weld specimen being stationary, the welding gun travelled automatically across the plate to perform the weld. The welding speed

was set at 150mm/min, the feed rate for 3mm plate and a gas flow rate of 15ml/min.



Figure 7.5: A semi-automatic Kemppi welding machine of the type used for the welds [23].

The gas selected for the procedure is Argon and Carbon Dioxide. An automated gas mixer was used to maintain a mixture of 97.5% Argon and 2.5% Carbon Dioxide. This gas mixture seemed the most appropriate and was decided upon because of prior welding experiments with various gas mixtures.



Figure 7.6: Depicts the automatic gas mixer used for the welds.

7.2.3 Residual Stress Measurement

Two methods were applied to determine the residual stresses present within the test specimens. The first technique was achieved with the aid of the

Debro-30 ultrasonic stress-measuring device followed by the Rosette strain gauge hole-drilling method.

7.2.3.1 The Debro-30 Residual Stress Measuring Technique

When employing the Debro-30 device, calibration of the probe head is essential to the stress measuring process and is the first step before ultimately measuring the specimen. The 6L150 probe head was used for these experiments. This probe head measures stress changes in a specimen with a stress direction parallel to the longitudinal wave propagation direction.

The probe head, which is 150mm long, consists of six transducers for emitting and receiving subsurface waves to a depth of 2mm. The probe head is equipped with a temperature sensor that detects temperature differences between the specimen and the probe head. This is important since ultrasonic pulses are temperature dependant. Thus when times of flight are displayed, temperature correction has already been accounted for.



Figure 7.7: The 6L150 probe head used to measure subsurface stress.

The calibration process commenced with a measuring cycle that was performed on a stress free specimen. This specimen is of a similar material as that of the welded specimen. The times of flight were recorded at least three

times and an average time was determined for accuracy. This reference time of flight was then stored in the memory of the measuring device. A tensile load was then applied to the stress free specimen and times of flight were recorded for the stressed material. From the recorded times of flight, an acousto-elastic constant was determined and stored in the device for stress measurements to be performed.

$$\beta_L = \frac{(T_L^0 - T_L^\sigma)}{\sigma_K} \quad [7.1]$$

where:

T_L^0 = time of flight of a longitudinal wave for a stress which equals zero (0)

T_L^σ = time of flight of a longitudinal wave for a stress which equals σ_K

β_L = accousto-elastic constant

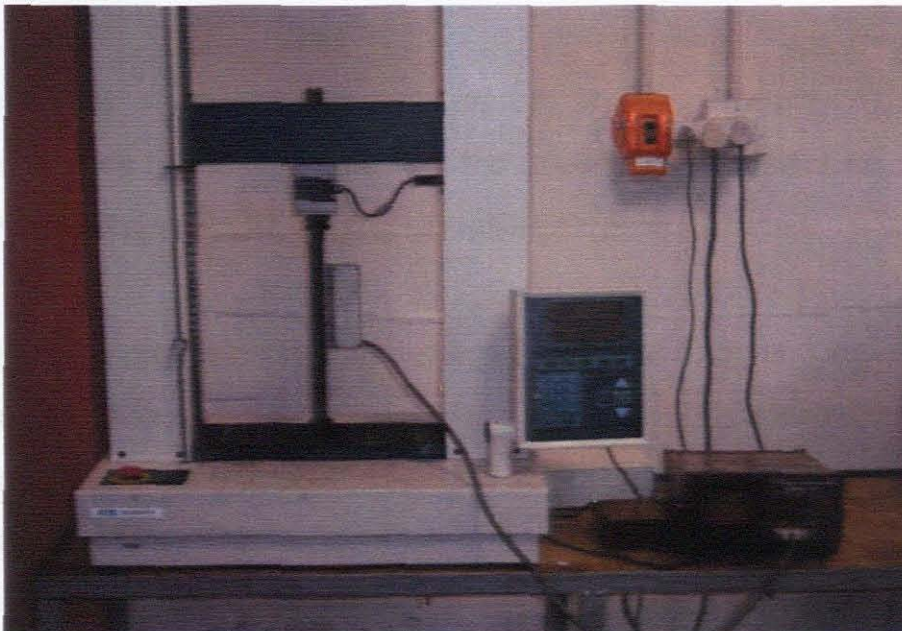


Figure 7.8: A tensile load applied to a stress free specimen during calibration.

Special attention had to be given during the stress measuring cycle since a high degree of accuracy and skill is required for this purpose.

Stresses were recorded parallel to and furthest away from the weld and

progressed toward the weld. After each stress measurement the probe head was moved in increments ten millimetres (10mm) along the same parallel path and an average was calculated for that distance from the weld. The probe head was then moved five millimetres (5mm) closer to the weld where the same procedure was applied. This continued until stresses were recorded closest to the weld.

As the distance from the weld increased, the stresses decreased. The stresses then increased again until the edge of the plate was reached. The residual stress distribution in a welded plate is unique and this characteristic was evident in the measurements shown in figure 7.9. This entire process was repeated for the other side of the weld. Each plate was subjected to one hundred and twelve (112) stress measurements in order to accurately determine stresses along the paths parallel to the weld

The ultrasonic stress measurement results were significantly high when measured close to the weld and with the highest measurement recorded at 217MPa (see Appendix E). The result was higher than expected.

The calibration process was repeated again at a later stage and with a similar specimen of equal grade as that of the weld specimen. This time the calibration process yielded a different reference time of flight. Ultrasonic Stress measurements were then recorded from a test specimen with a load applied and compared to strain measurements taken and converted to stresses from the same specimen but by using strain gauges.

The measurements recorded from the strain gauge technique were very similar to the new ultrasonic stress measurements. These strain measurements were converted to stresses and were in the region of 32MPa in the parent metal and about 52MPa in the weld. Unfortunately by the time this information was

revealed, it was too late to repeat all the ultrasonic stress measurements since all welded specimens were cut into fatigue test specimens.

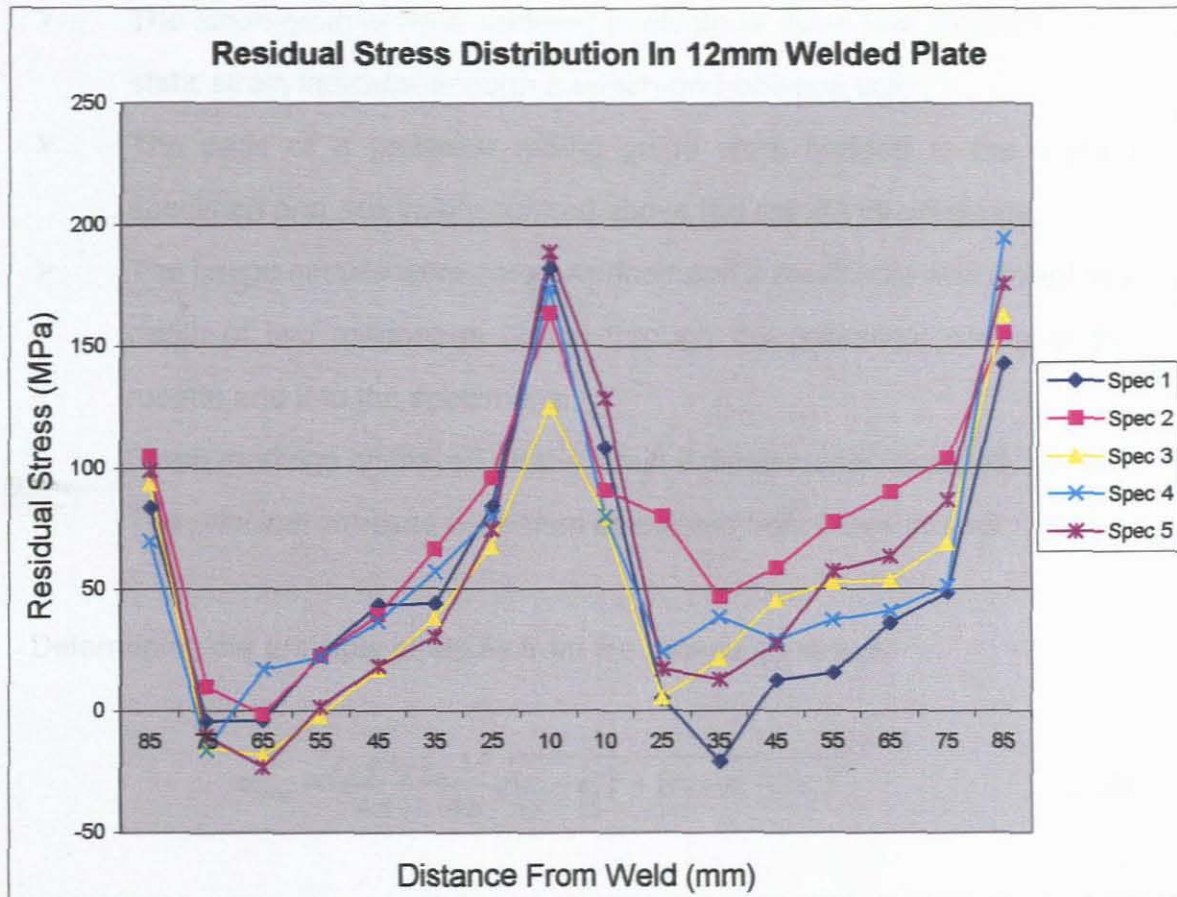


Figure 7.9: The graph above depicts the residual stress distribution across the five (5) of the welded specimens. Note the weld at "0mm".

A clear pattern exists between the five specimens in that they all display the characteristics of residual stress distribution of a welded specimen as shown in figure 3.6.

7.2.3.2 The Rosette Strain Gauge Hole-Drilling Technique

The rosette strain gauge method is a technique used for accurately determining the strain of a material and this strain is then converted into a stress. The strain gauge measurement procedure involved six (6) basic steps:

- Special three element strain gauge rosettes were bonded to the welded specimens at the points where the residual stresses were to be determined.
- The strain gauges were soldered to electrical wires and connected to a static strain indicator through a switch-and-balance unit.
- The pads of a precision milling guide were bonded to the welded specimen and accurately centred above the rosette strain gauge.
- The gauge circuits were zero-balanced and a small hole was drilled to a depth of two millimetres (2mm) through the geometric centre of the rosette and into the specimens.
- Strain readings displayed on the strain indicator were recorded.
- The principal stresses were then calculated from these strains.

Determining the principle stresses from the measured strains:

$$\sigma_{\max} = \frac{\varepsilon_1 + \varepsilon_3}{4A} - \frac{1}{4B} \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \quad [7.2]$$

$$\sigma_{\min} = \frac{\varepsilon_1 + \varepsilon_3}{4A} + \frac{1}{4B} \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \quad [7.3]$$

$$\tan 2\alpha = \frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_1 - \varepsilon_3} \quad [7.4]$$

Coefficients A & B were determined by experimental calibration. This calibration procedure included measuring the rosettes strains under the same applied load σ_c .

The calibration procedure is as follows:

- Zero-balance the strain gauge circuits
- Apply a tensile load to the test piece to produce a stress
- Measure the strains ε_1' and ε_3'
- Drill the into the rosette strain gauge as described previously

- Refit the specimen to the test rig, zero-balance the circuits and reapply the same load
- Measure the strains ε_1'' and ε_3''

The calibration strains for the measured load of:

Load: 30kN

Test specimen cross-sectional area: 12mm x 25mm = 0.0003m²

$\sigma = 100 \text{ MPa}$

$$\varepsilon_{c1} = \varepsilon_1'' - \varepsilon_1' \therefore \varepsilon_{c1} = 480 - 407 \Rightarrow \varepsilon_{c1} = 73 \text{ E-6} \quad [7.5]$$

$$\varepsilon_{c3} = \varepsilon_3'' - \varepsilon_3' \therefore \varepsilon_{c3} = 141 - 125 \Rightarrow \varepsilon_{c3} = 16 \text{ E-6} \quad [7.6]$$

Solving for A and B:

$$A = \frac{\varepsilon_{c1} + \varepsilon_{c3}}{2\sigma_c} \therefore A = \frac{73\text{E-6} + 16\text{E-6}}{2 \times 100\text{E6}} \Rightarrow A = 4.45\text{E-13} \quad [7.7]$$

$$B = \frac{\varepsilon_{c1} - \varepsilon_{c3}}{2\sigma_c} \therefore B = \frac{73\text{E-6} - 16\text{E-6}}{2 \times 100\text{E6}} \Rightarrow B = 2.85\text{E-13} \quad [7.8]$$

A and B are substituted into [7.2] and [7.3] to determine the principle stresses in the material.

$$\sigma_{\max} = \frac{\varepsilon_1 + \varepsilon_3}{4A} - \frac{1}{4B} \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \quad [7.9]$$

$$\sigma_{\max} = \frac{(47\text{E-6}) + (47\text{E-6})}{4 \times 4.45\text{E-13}} - \frac{1}{4 \times 2.85\text{E-13}} \sqrt{((47\text{E-6}) - (47\text{E-6}))^2 + ((47\text{E-6}) + (47\text{E-6}) - (2 \times 47\text{E-6}))^2}$$

$$\sigma_{\max} = 52.8 \text{ MPa}$$

$$\sigma_{\min} = \frac{\varepsilon_1 + \varepsilon_3}{4A} + \frac{1}{4B} \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \quad [7.10]$$

$$\sigma_{\min} = \frac{(47E-6) + (47E-6)}{4 \times 4.45E-13} + \frac{1}{4 \times 2.85E-13} \sqrt{((47E-6) - (47E-6))^2 + ((47E-6) + (47E-6) - (2 \times 47E-6))^2}$$

$$\sigma_{\min} = 52.8 \text{ MPa}$$

$$\tan 2\alpha = \frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_1 - \varepsilon_3} \quad [7.11]$$

$$\tan 2\alpha = \frac{(47E-6) - (2 \times 47E-6) + (47E-6)}{(47E-6) - (47E-6)}$$

$$\tan 2\alpha = 0.5 \therefore \tan 2\alpha = \frac{\tan^{-1} 0.5}{2} = 0^\circ$$

Three rosettes were located in significant areas on each welded specimen as seen in figure 7.10. The strain gauges were located closest to the weld and then again furthest from the weld in order to determine the differences in stress concentrations. The rosettes were bonded to the specimen with gauge number one aligned parallel to the weld.

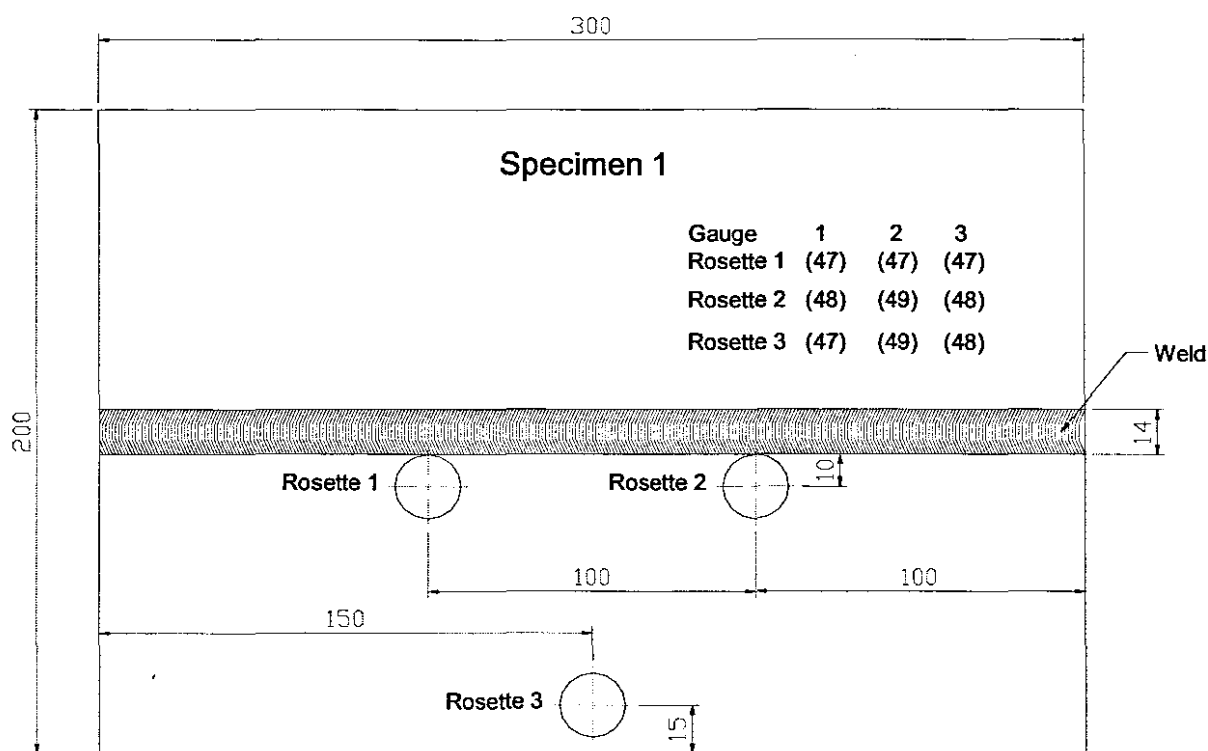


Figure 7.10: Welded specimen, depicting location of rosettes strain gauges.

Even though stresses can be recorded to a depth of six millimetres (6mm), only stress measurements up to a depth of two millimetres (2mm) were considered. The stresses recorded using the strain gauge technique was to be compared to that of the ultrasonic stress measuring technique and with this technique the sound waves only penetrate the specimen to a depth of two millimetres (2mm). See Appendix B for calculated stresses.

7.2.4 Tensile Test

The mechanical behaviour of a material is identified by its deformation and fracture characteristics when subjected to applied tensile, compressive or multi-axial stresses [1].

In order to determine the strength of a material, a standard tensile test is performed on a material specimen so as to determine their relative properties.

The specimen is prepared as per [2] as seen in figure 7.11. Three tensile tests were performed to determine the strength of the weld, the heat affected zone and the base plate.

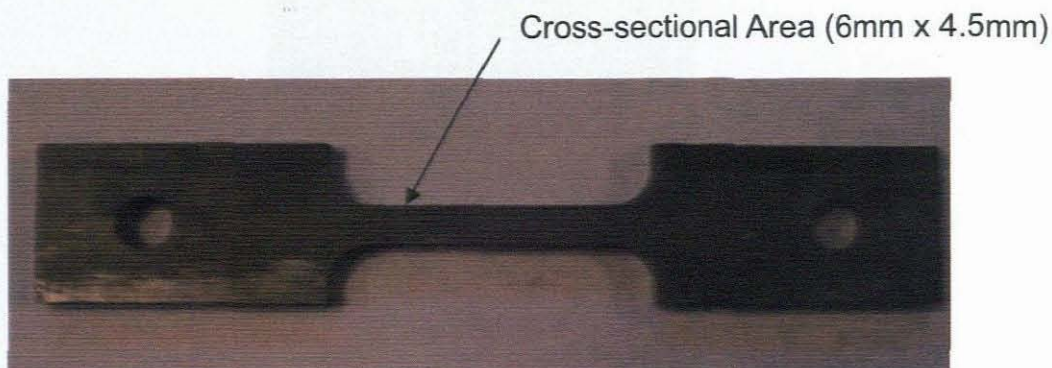


Figure 7.11: Typical tensile test specimen machined to standard.

The ultimate tensile stress (S_u) is the maximum load divided by the smallest cross-sectional area of the specimen.

$$S_u = \frac{P_{\max}}{A_0} \quad [7.12]$$

7.2.4.1 Tensile Test Results

The tensile test yielded results given the following parameters:

Tensile test specification

Tensile test speed : 3mm/s

Maximum Load Cell : 50 kN



Figure 7.12: Tensile test in progress.

Results of tensile test for weld specimen:

Yield stress	: 430MPa
Specimen strain at this point	: 0.0213
Ultimate tensile stress	: 548MPa
Specimen overall elongation	: 22.17% or 9.975mm

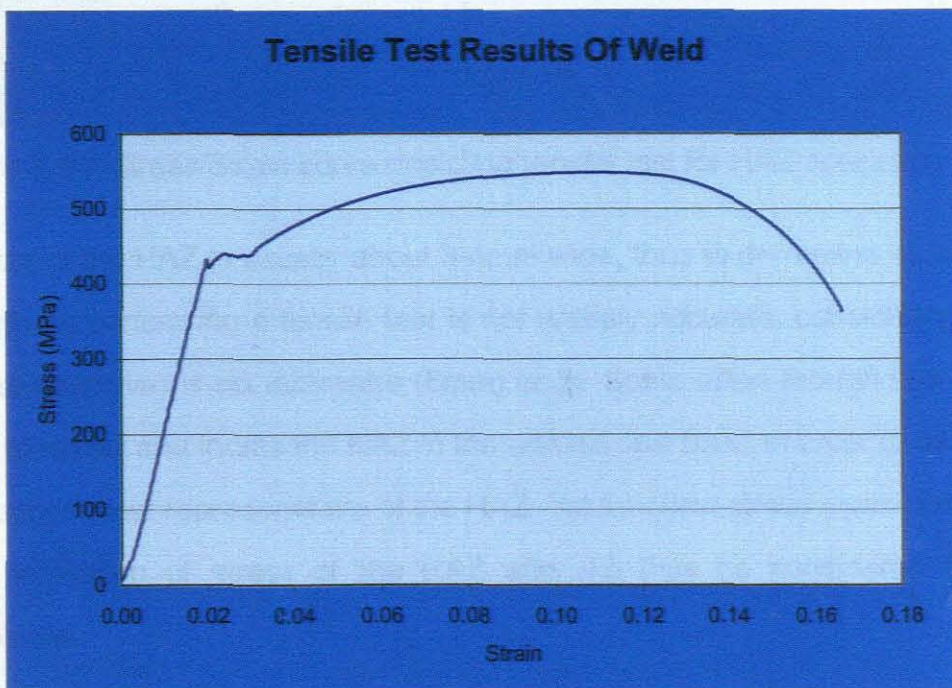


Figure 7.13: Stress/Strain curve depicting tensile test for weld specimen.

Results of tensile test for HAZ specimen:

Results of tensile test for HAZ specimen:

Yield stress	: 380MPa
Specimen strain at this point	: 0.0186
Ultimate tensile stress	: 501MPa
Specimen overall elongation	: 17.17% or 10.3mm

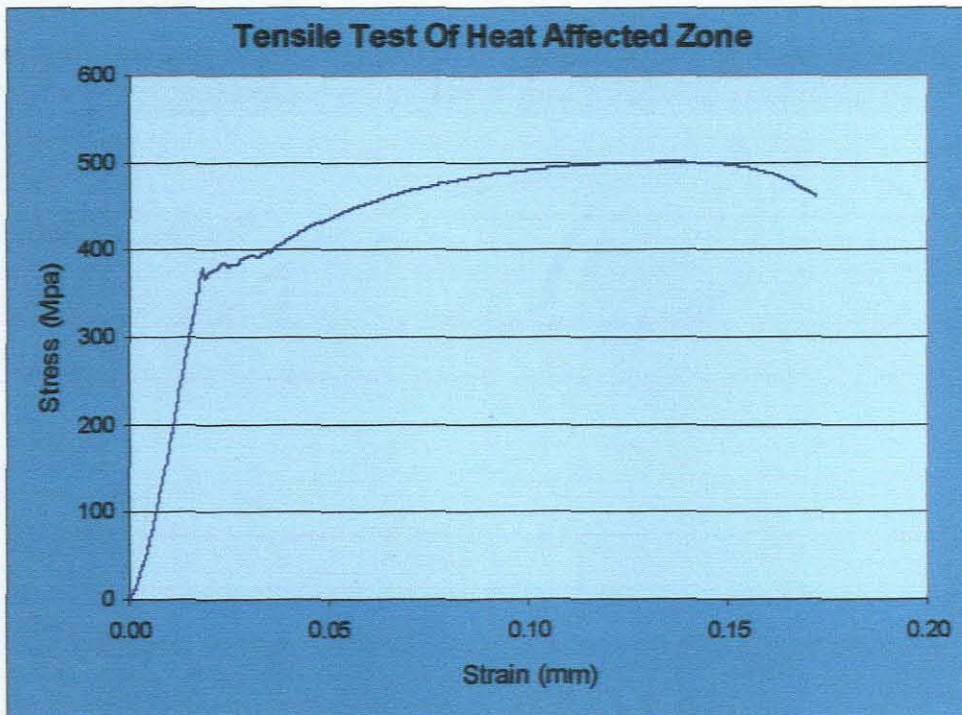


Figure 7.14: Stress/Strain curve depicting tensile test for HAZ specimen.

The size of the HAZ is usually about 3-4mm wide, thus to determine its tensile strength by performing a tensile test is not entirely accurate, considering that the test specimen is six millimetre (6mm) wide. Some effort though has been made to reveal and locate the HAZ in the welded specimen in order to extract a specimen most representative of the HAZ. Yet the yield stress given above is some indication of stress of the HAZ and will thus be considered to be acceptable.

Results of tensile test for base plate specimen:

- Yield stress : 282MPa
- Specimen strain at this point : 0.0137
- Ultimate tensile stress : 450MPa
- Specimen overall elongation : 25% or 15mm

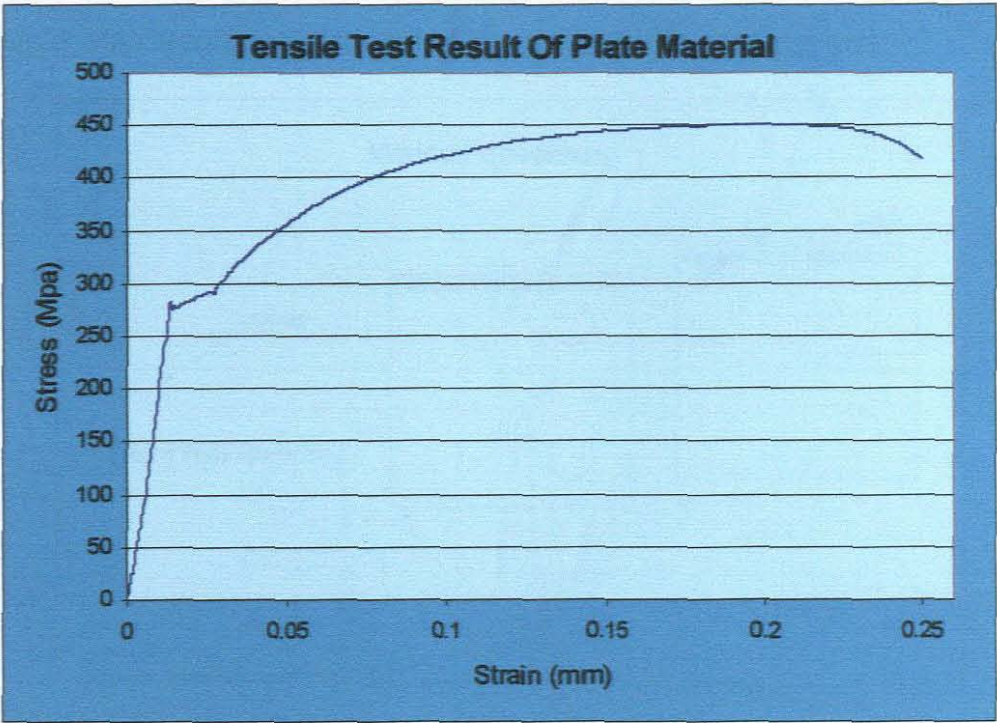


Figure 7.15: Stress/Strain curve depicting tensile test for weld specimen.

	Yield Stress (MPa)	Ultimate Tensile Stress (MPa)
Weld	430	548
Haz	380	501
Plate	282	450

Table 7.2: Comparison of stress of weld, HAZ & plate.

From the Table 7.2, it is clear that the ultimate tensile stress of the weld is higher than that of the HAZ and the plate, yet it is the yield stress that is of importance. Evidently it is the weld that has the highest yield stress when compared to the HAZ and the base plate. In this case the weld is 13% stronger than the stress of the HAZ and 52.5% stronger than the parent metal.

7.2.5 Fatigue Test Results

The aim of the fatigue test was to determine the life cycle of the welded specimen under specified conditions. The following procedure has been employed for the fatigue test experiment and all fatigue test specimens have been prepared as seen in figure 7.17 and as per ASTM E647. Specimens were machined from each welded specimen and were located as shown below, with the weld, HAZ and base plate being the subject of the fatigue test.

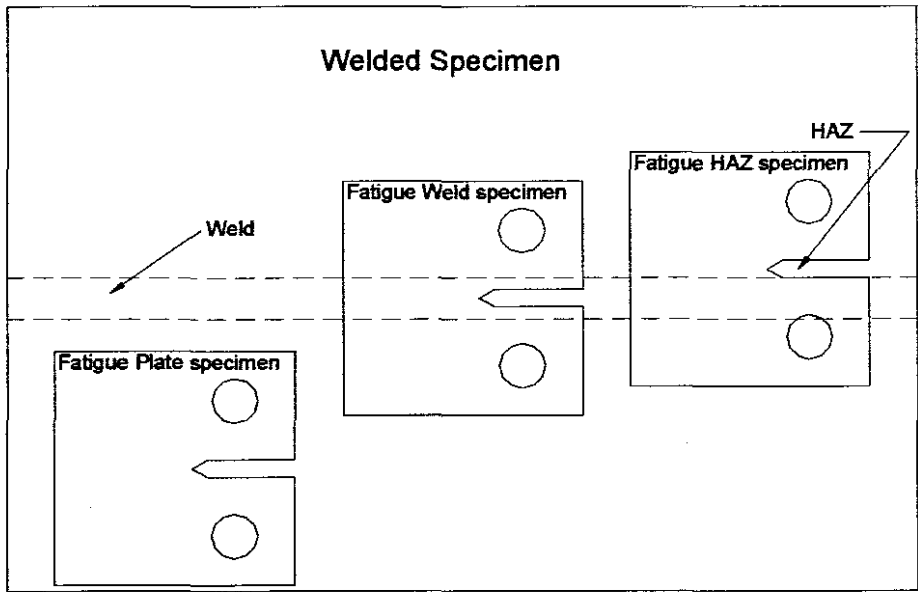


Figure 7.16: Depicts location of fatigue test specimens relative to weld.

The test specimens were machined to the dimensions as shown below.

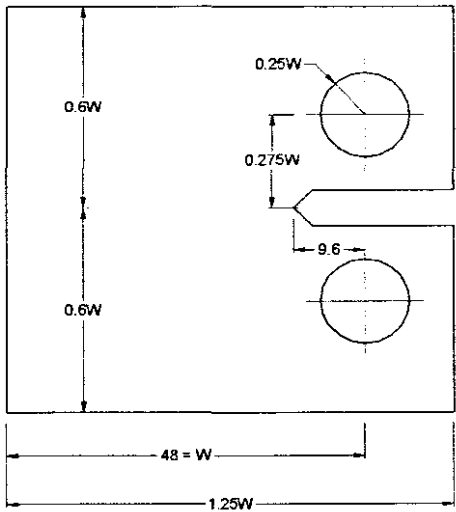


Figure 7.17: A typical fatigue test specimen as per ASTM E647 [43].

The fatigue fracture experiments were conducted using a pneumatic vertical pulsator with a load cell of 15kN capacity. The surfaces of the test specimens were adequately prepared so as to increase illumination in aid of crack growth detection.

The following fatigue test parameters were as follows:

- Control : Constant Amplitude Load
- Frequency : 10Hz
- Mean : 2.5kN 3.75kN 5kN
- Range : 5kN 7.5kN 10kN
- Ramp rate : 0.1kN/s



Figure 7.18: Fatigue testing machine used for the experiments.

The fatigue test was paused often in order to determine the approximate number of cycles when crack initiation occurred. Crack initiation was detected using a pocket microscope with measurement graduations of 0.2mm. The results of the fatigue test as seen in table 7.3 for the weld specimen at a 10kN load reflect an average of 11833 cycles before crack initiation is detected. At this point the cracks average between 0.8 – 1mm long. It is thus evident that the cracks initiated before the number of cycles mentioned above considering the length of the cracks on detection. The average number of cycles before fracture is 40133, with the lowest being 30000 cycles and the highest 56700 cycles.

(See note below on specimen elimination).

Fatigue Test Results			
	Load (kN)	Crack Initiation (Cycles)	Fracture (Cycles)
Weld	10	11500	36500
Weld	10	12800	35600
Weld	10	11000	34000
Weld	10	11900	36900
Weld	10	11000	38000
Weld	10	7000	13700
Weld	10	12000	44900
Weld	10	15500	56300
Weld	10	18000	34500
Weld	10	7300	56700
Weld	10	12000	30000
Weld	10	7000	18500
Weld	10	7000	35700
Weld	10	12000	42500
Weld	7.5	10500	642500
Weld	5.0	8900	915965
Plate	10.0	1750	12500
Plate	7.5	1800	239750
Plate	5.0	2000	452449
HAZ	10	2200	10686
HAZ	7.5	5580	20200
HAZ	5.0	10900	89500

Table 7.3: Depicting the number of cycles for crack initiation and fracture.

There is an apparent difference in the number of cycles between fatigue specimens 2.1 and 2.3. In the case of specimen 2.1 the crack initiated and propagated at the notch. Fracture then progressed from this point until it branched into the diffuse transition zone as seen in figure 7.21. Multi-pass welds with successive passes produce changes in the fusion and HAZ of previous passes and are termed reheat zones. The transformation behaviour of the reheated zones and HAZ are similar and results in microstructures that can be divided into four zones, extending from the fusion zone outward; the grain growth zone, the fine grain zone and the tempered zone [44].

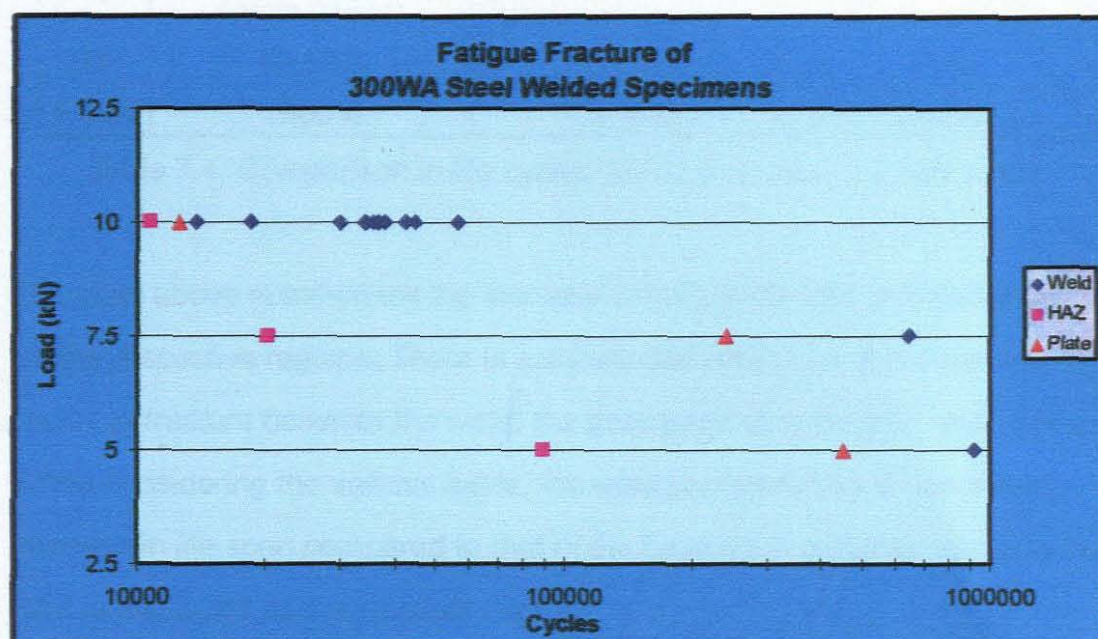


Figure 7.19: Depicting the number of cycles to fracture of 300WA steel welded specimens.

The graph above displays the results in Table 7.3 and illustrates the cycles to fracture for the weld, HAZ and plate specimens for the various loads. The graph displays a trend in the three different regions. There is a significant difference in life cycle for the various loads, i.e. as the load increase, the number of cycles tend to decrease.

The weld life cycle has increased by 1500% when the load was decreased from 10kN to 7.5kN. It then increased by 42.5% when the load was decreased by a further 2.5kN. In the case of the base plate, the life cycle increased by 1818% when the load was decreased from 10kN to 7.5kN. A further increase by 88.7% was noted when the load was decreased to 5kN. The life cycle for the HAZ has increase by 343% and then again 89% when the load was decreased to 7.5kN and 5kN respectively.

Load	Increase in Life Cycle (Weld)	Increase in Life Cycle (Plate)	Increase in Life Cycle (HAZ)
5kN	42.50%	88.70%	89%
7.5kN	1500%	1818%	343%

Table 7.4: Comparison in life cycles with a decrease in 2.5kN loads.

The table above summarises the increase in fatigue life with a decrease in load for the respective regions. There is a substantial difference in the number of cycles to fracture between the weld, the base plate and the HAZ specimens. When considering the various loads, the weld specimen has a noticeable increase in life span compared to that of the base plate material, whereas the HAZ is displayed as the weakest region.

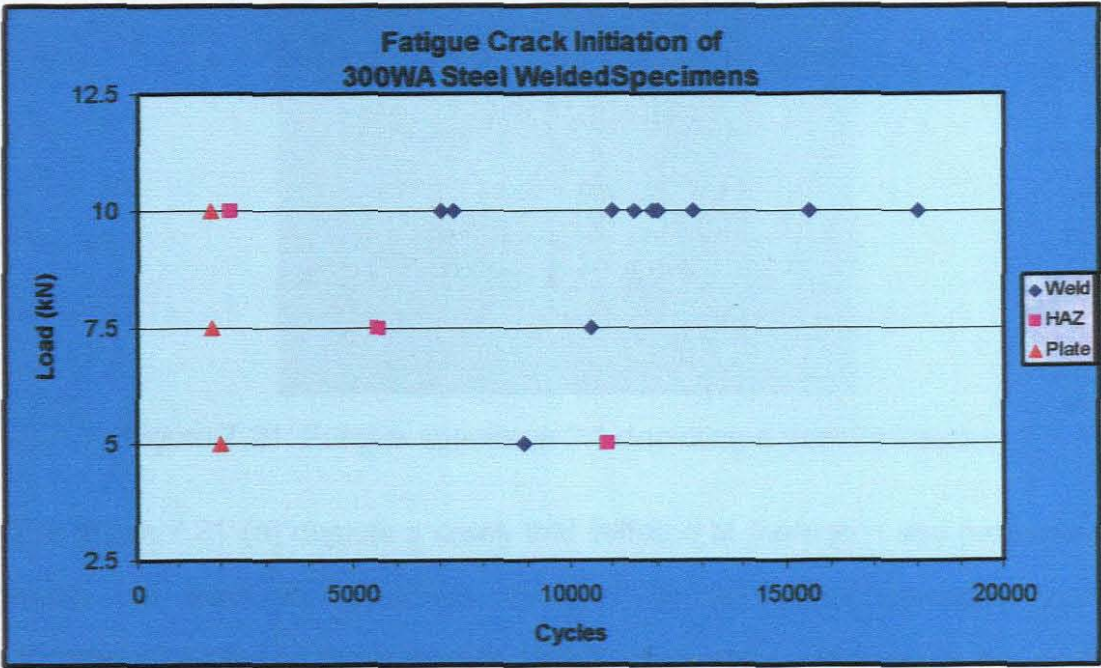


Figure 7.20: Depicting the number of cycles to crack initiation and fracture of 300WA steel welded specimens.

The graph in figure 7.20 portrays an irregular set of data for the weld at a 10kN load. The average recorded number of cycles to fatigue crack initiation for the weld is 11833 compared to 1750 for the HAZ and 2200 for the base plate for the 10kN load. The number of cycles to crack initiation tends to increase with a decrease in load for the welded specimen. The opposite is true for the base

plate and HAZ specimens, i.e. as the load decreases the number of cycles to crack initiation increases. For all three loads the base plate displayed the least resistance to crack initiation.

The graph in figure 7.20 displays the results in Table 7.3 and illustrates the approximate number cycles at crack initiation for the weld, HAZ and plate specimens for the various loads. The number of cycles at crack initiation for the various loads for the plate specimens was very similar.



Figure 7.21: Fatigue specimen 2.1 depicting a distinct fracture.

The figure 7.21 (a) depicts a crack that initiated at the notch and propagated along the weld and suddenly deviated to the diffuse transition zone, accompanied by a more pronounced plastic deformation of material around the crack. This would indicate that the initial crack in the transition zone encountered enough resistance as it propagated to deform the structure around it (see also figure 7.23). In the case of specimen 2.3, even though the crack initiated at the notch, one or more large influential crack initiators were present between the weld and the heat-affected zone. Alternatively, the diffuse transition zone was too close to the notch area and this sparked a sudden redirection in crack propagation.

This important observation was made in the early stages of crack initiation, where the crack was directed toward the diffuse transition zone.

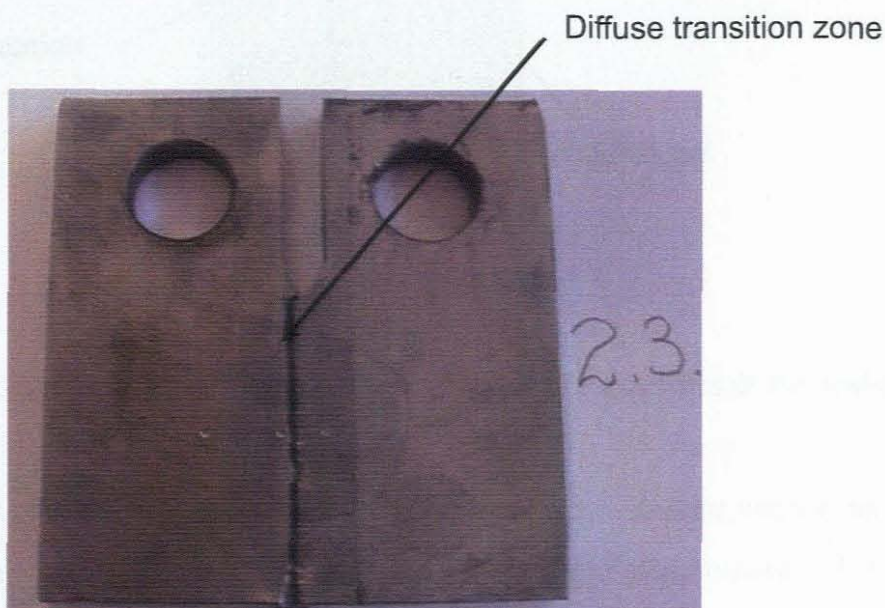


Figure 7.22: Specimen 2.3 displays immediate redirection of the fracture.

From table 7.3, fatigue specimen 4.3 fractured at 18500 cycles. Even though the fracture progressed along the centre of the weld as seen in figure 7.23, the cyclic fracture seems premature. Figure 7.24 explains why fracture occurred prematurely.



Figure 7.23: Specimen 4.3 depicts a fracture through the centre of the weld.

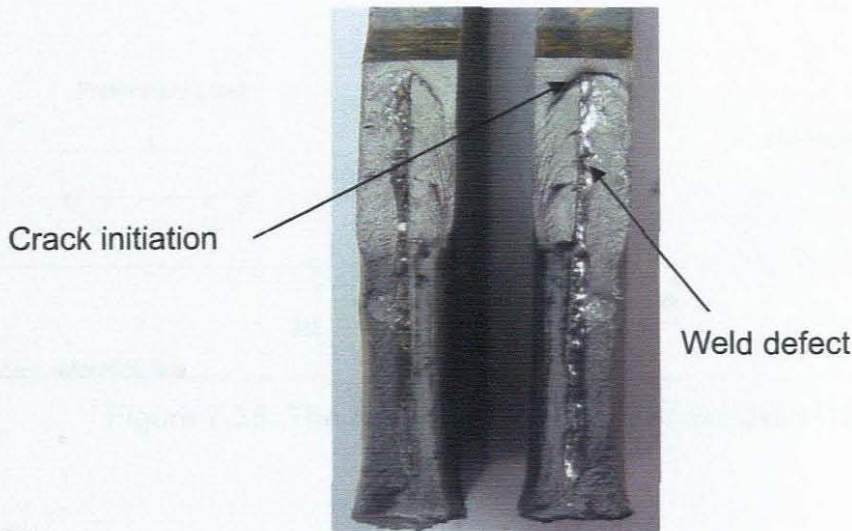


Figure 7.24: Specimen 4.3 depicts a fracture through the centre of the weld.

The presence of weld defects/incompatible bonding is an obvious reason as to the premature fracture and can be observed as the bright silver colour in figure 7.24. Also the crack initiated at the commencement of the weld defect and not at the notch provided resulting in an early failure. Fracture specimens 2.3 and 4.3 have thus been eliminated from the experiment.

7.2.6 Rockwell Hardness Testing

The Rockwell hardness test method involves indenting a test specimen with a hardened steel ball or a diamond cone indenter. The testing machine uses a preliminary load to force (about 10kgf) the indenter into the test specimen. When equilibrium is reached, an indicating device, which follows the displacement of the indenter, responds to variations in depth of penetration of the indenter is set to a datum position. With the applied preliminary load, an additional load is applied resulting in increased penetration. After equilibrium is reached again, the specimen is released of the additional load while the preliminary load is maintained. When the additional load is removed, the depth of indent is slightly reduced. The permanent depth of penetration after applying and removing the additional load is then used to calculate the Rockwell

hardness number [13].

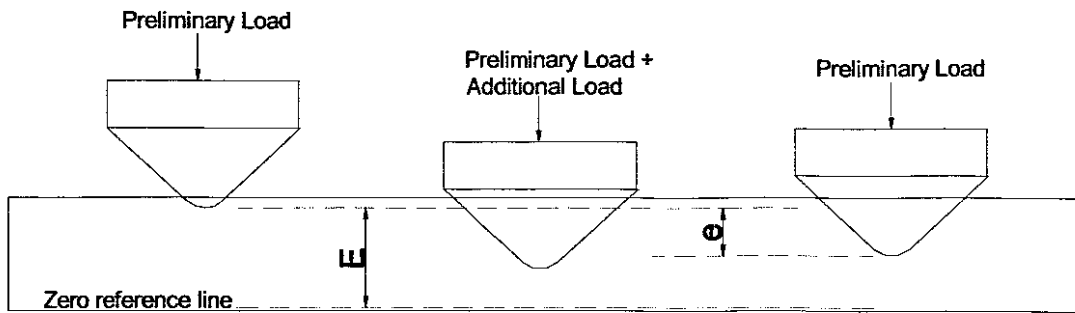


Figure 7.25: The Rockwell hardness test principle [13].

Where:

E = a constant depending on the form of indenter

e = permanent increase in depth measured in 0.002mm

thus: Rockwell hardness number (HR):

$$HR = E - e \quad [7.13]$$

Various Rockwell hardness scales exist (see Appendix C) and depend entirely on the test specimen material.

Hardness tests were performed on specimens prior to and after fatigue testing in order to determine any change in hardness. Each specimen was tested in the weld region, the HAZ as well as the base plate.



Figure 7.26: Digital Rockwell type Hardness tester.

Hardness testing proceeded with the above machine and in conjunction with a diameter 1/16" steel ball indenter, flat anvil and a test load of 100kgf. A mixture of ninety eight percent (98%) ethanol and two percent (2%) nitric acid (2% nital) was used to reveal the weld and HAZ boundaries. This made it easier to distinguish the different zones for hardness testing. Care was taken to perform the hardness tests, with specimens being in close proximity to each other before and after fatigue testing in order to achieve exact results.

From the results of the hardness tests (see Appendix D), it has been determined that the hardness of the weld, HAZ and the parent metal has not been affected by the fatigue fracture.

	Pre-Fatigue Test		Post-Fatigue Test	
	HRB	HV	HRB	HV
Average for Weld	89.2	183.1	88.5	180.2
Average for HAZ	85.5	168.8	85.6	167.8
Average for Plate	74.9	137.0	74.7	136.6

Table 7.5: Average hardness test results for prior to & post fatigue testing. Table 7.4 displays hardness values, which closely relate to strength values for the various regions as seen in figure 7.26. The weld region displays the highest hardness values and is confirmed by the highest strength values. Similarly the HAZ and base plate exhibits hardness values relative to their strength. Thus it is

clear that a relationship exists between the hardness and the strength of a material.

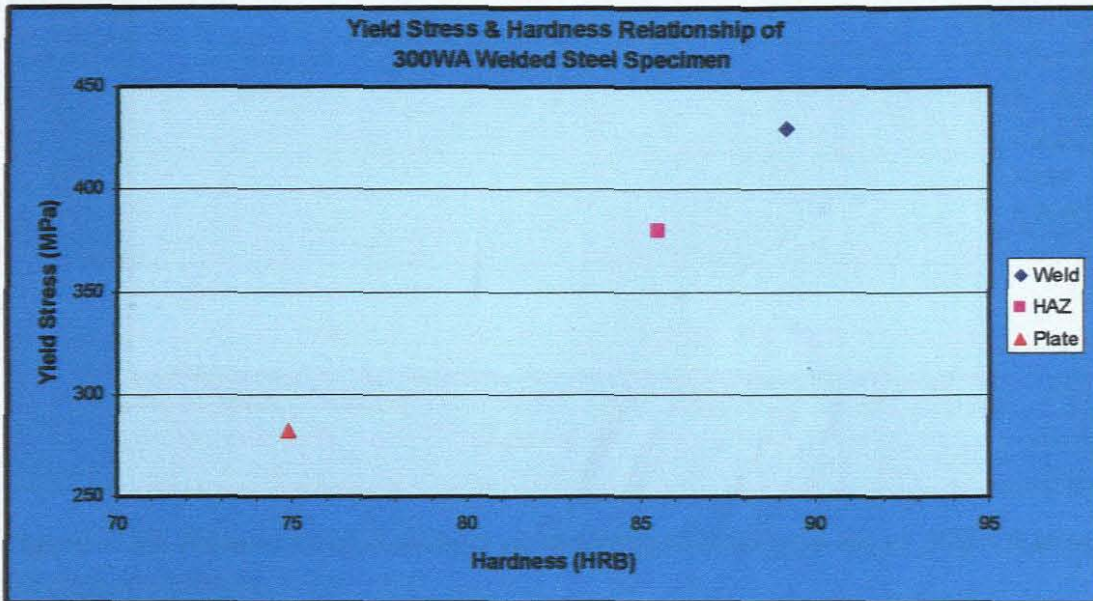


Figure 7.27: Relationship between hardness and yield stress of 300WA steel welded specimens.

A similar pattern exist between the data displayed in figure 7.28 and 7.29. In both graphs the base plate display lesser hardness and yield stress values than that of the HAZ, however it is the base plate that has a longer fatigue life. The HAZ is therefore evidence of a region of weakness. The base plate and weld metal is shown to have yield stress and hardness relative to its cycles. Thus it is clear that a relationship exists between the hardness and fatigue life and the yield stress and fatigue life.

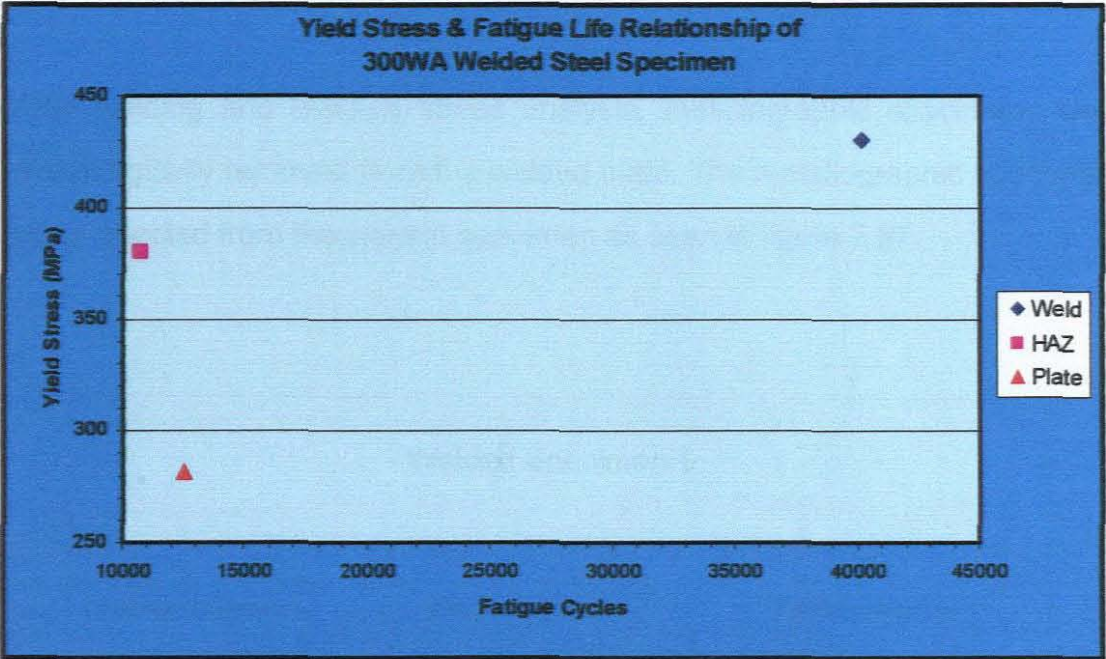


Figure 7.28: Relationship between yield stress and fatigue life of 300WA steel welded specimens.

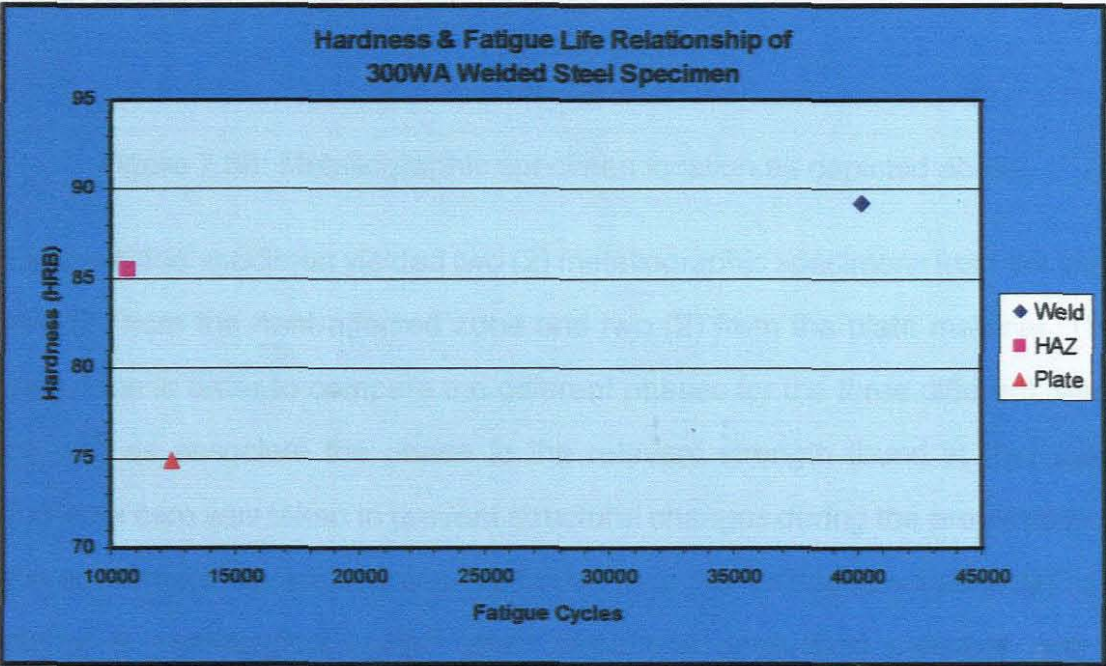


Figure 7.29: Relationship between hardness and fatigue life of 300WA steel welded specimens.

7.2.7 Micro structural Analysis

After welding and residual stress analysis, metallographic specimens were metallurgically removed from the welded plate. The metallographic specimens were selected from the welded specimen as seen in figure 7.27.

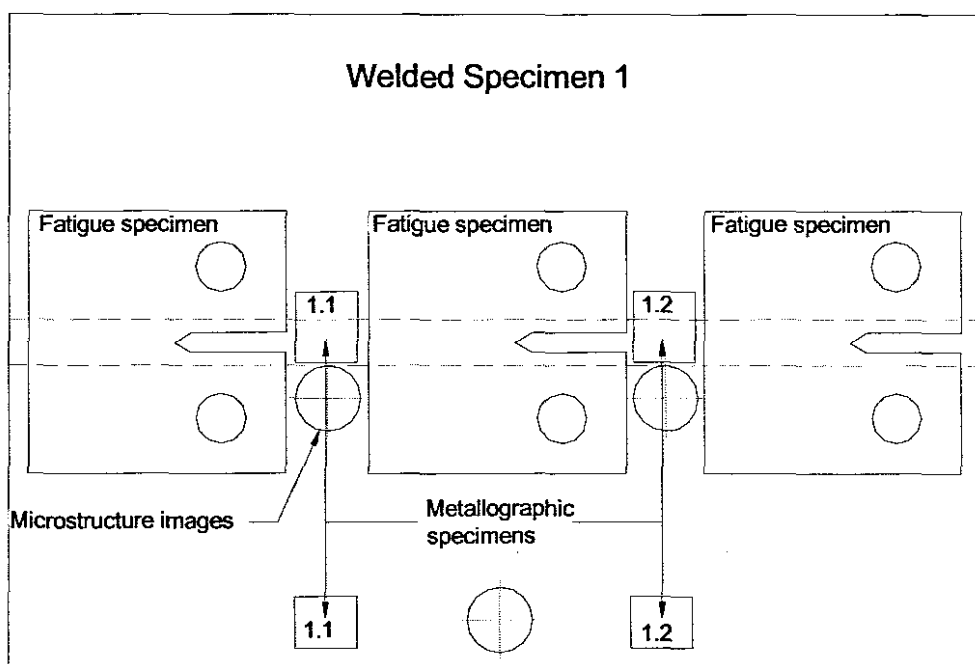


Figure 7.30: Metallographic specimen location as depicted above.

Each welded specimen yielded two (2) metallographic specimens from the weld, two (2) from the heat-affected zone and two (2) from the plate material. This was done in order to compare the different phases for the three different areas as well as associate the phase to the relevant strength found in that area. Extreme care was taken to prevent structural changes during the preparation of the specimens. Specimens were removed from the welded specimens with the aid of a metallurgical cut-off saw. Specimens were then mounted with a diameter of forty (40) millimetre, pressure of 30kN, temperature of 180°C with twelve (12) minutes for heating and twelve (12) minutes for cooling. The mounted specimens were then polished according to table 7.5.



Figure 7.31: Metallurgical cut-off saw used for metallographic preparation.



Figure 7.32: Mounting press used for metallographic preparation.



Figure 7.33: Polishing machine used for metallographic preparation.

Step	Abrasive	Suspension	Rotational Speed (Rpm)	Force (N)	Time (min)
1	MD Piano	Water	150	250	3
2	MD Largo	9µm Diamond Suspension	150	200	5
3	MD Plus	6µm Diamond Suspension	150	200	4
4	MD Plan	3µm Diamond Compound	150	250	6
5	MD Nap	1µm Diamond Compound	150	150	3

Table 7.6: Polishing procedure for metallographic specimens.

After polishing, the specimens were etched with two percent (2%) nital. Specimens were then stored in a desiccator cabinet for protection from the atmosphere. Optical analysis was made possible with the use of a microscope and camera to capture the microscopic images.

7.2.7.1 Results of Micro Structural Analysis

The microstructures of the weld, HAZ and the base plate has been analysed prior to and after fatigue testing. This was done in order to compare the microstructures and strength before and after fracture. Unfortunately only one microstructural weld specimen, one HAZ specimen and one plate specimen from each welded specimen could be analysed due to time constraints. The figures below represent the results of specimens prior to fatigue testing and fracture. All specimens were compared to specimens as per [44].

There is a prevailing presence of equiaxed ferrite with pearlite islands in the base plate and HAZ specimens prior to and after fatigue testing. The weld region displayed acicular ferrite in all specimens prior to and after fatigue testing as expected due to the fine grain structure it was not possible to detect changes in the grain sizes.

Following, is an approach to determine the grain size of each distribution. A line is drawn across the sample image and its length (l), is noted. The number of grain boundary intercepts is then counted (n) and the grain size (d), determined [44].

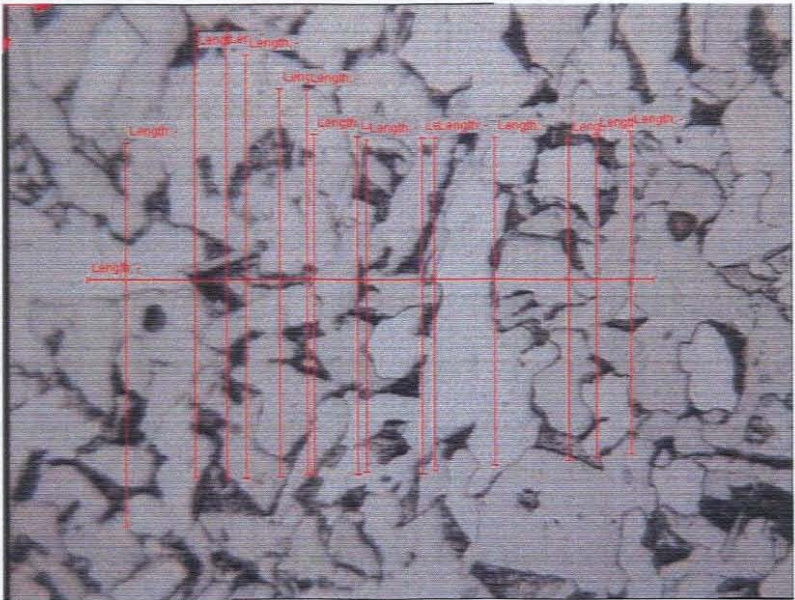


Figure 7.34: Depicts grain size measurement.

The grain size measurement is to be repeated with different line orientations on several fields of view.

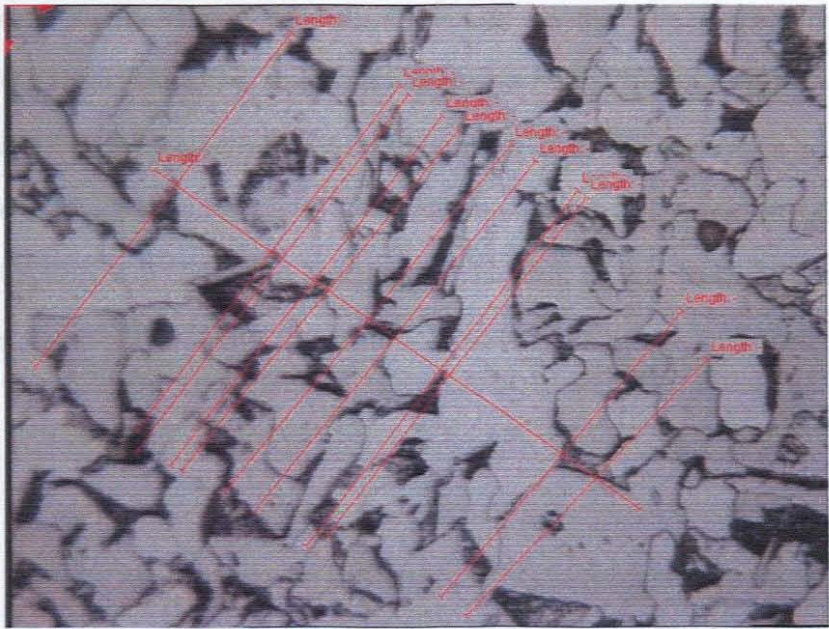


Figure 7.35: Depicts grain size measurement with a different line orientation.

The refinement of ferrite grain size provides an important strengthening tool in the heat treatment of steel. A close relationship exists between the grain diameter (d) and the yield stress (σ_y). The grain size has an effect on the yield stress and is explained by the assumption that a dislocation source operates within a crystal causing dislocations to move and subsequently pile up at the grain boundary. This pile-up results in stresses being generated in the adjacent grain and when it reaches a critical value, operates a new source within that grain. The yielding process is thus propagated from one grain to another.

The grain size determines the distance that dislocations have to move to form grain boundary pile-ups and in so doing determines the number of dislocations involved. The larger grain sizes results in larger numbers of dislocations in the pile-ups, causing higher stress concentrations in adjacent grains.

At the head of a dislocation pile up the shear stress is equal to the number of dislocations involved and the shear stress on the slip plane. Therefore the coarser the grain size, the easier it will be for dislocations to propagate. With a finer grain size, a resulting higher yield stress is achieved. While a coarse grain size of $d = 0.25\text{mm}$, gives a yield stress of approximately 100MPa, grain refinement to $d = 0.0025\text{mm}$ increases the yield stress to over 500MPa. Thus achieving grain sizes in the order of between 2 – 10 μm is extremely worthwhile [21].



Figure 7.36: Microstructure of the plate specimen 1 depicts a structure of equiaxed ferrite grains with pearlite islands as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

$$d = \frac{l}{n}$$

where : d = grain size

l = length of line

n = number of grain boundary intercepts

$$d_1 = \frac{153.80\mu\text{m}}{15} = d_1 = 10.25\mu\text{m} \quad 16 \text{ grains measured} \quad [7.15]$$

$$d_2 = \frac{134.25\mu\text{m}}{13} = d_1 = 10.33\mu\text{m} \quad 14 \text{ grains measured} \quad [7.16]$$

$$d_3 = \frac{139.80\mu\text{m}}{14} = d_3 = 9.99\mu\text{m} \quad 15 \text{ grains measured} \quad [7.17]$$

$$S = \frac{\sigma_d}{\sqrt{N}} = S = \frac{0.18}{\sqrt{45}} = 0.03 \quad [7.18]$$

where : σ_d = standard deviation of all measurements of d .

N = number of grains measured

S = error in measurements

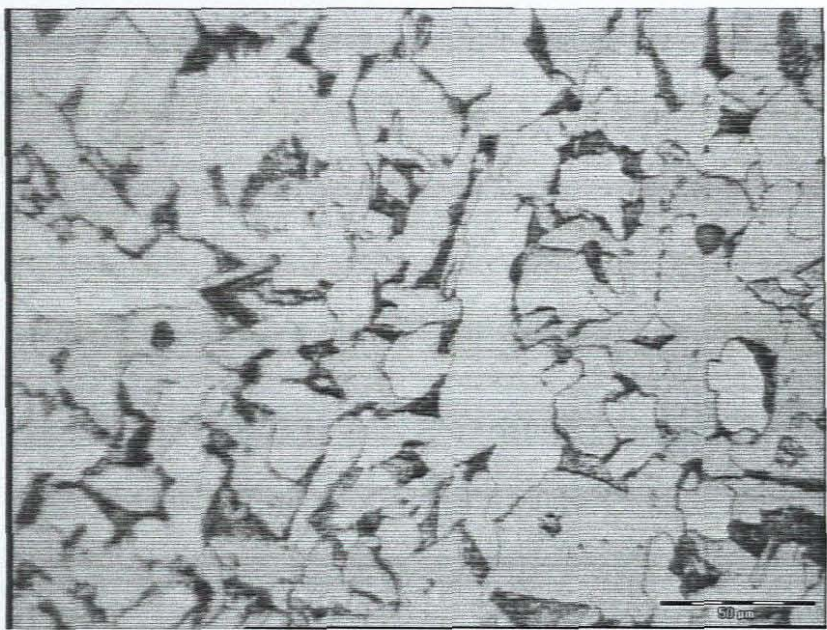


Figure 7.37: Microstructure of the HAZ specimen 1 depicts a structure of equiaxed ferrite grains with pearlite islands as seen at 50μm = 20mm ⇒ 400x.

$l_1 = 134.84\mu m$: $n_1 = 14$ $\therefore d_1 = 9.63\mu m$ 15 grains [7.19]

$l_2 = 128.63\mu m$: $n_2 = 14$ $\therefore d_2 = 9.19\mu m$ 15 grains [7.20]

$l_3 = 110.76\mu m$: $n_3 = 12$ $\therefore d_3 = 9.23\mu m$ 13 grains [7.21]

$S = \frac{0.24}{\sqrt{43}} = 0.04$ [7.22]



Figure 7.38: Microstructure of the weld specimen 1 depicts a structure of

acicular ferrite (Widmanstätten structure) with pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

Acicular ferrite nucleates from tiny non-metallic inclusions. These plates radiate from the point of nucleation sites, resulting in a less organised microstructure, which has a greater resistance to crack propagation. Acicular ferrite is most desirable because of its good mechanical properties [37].

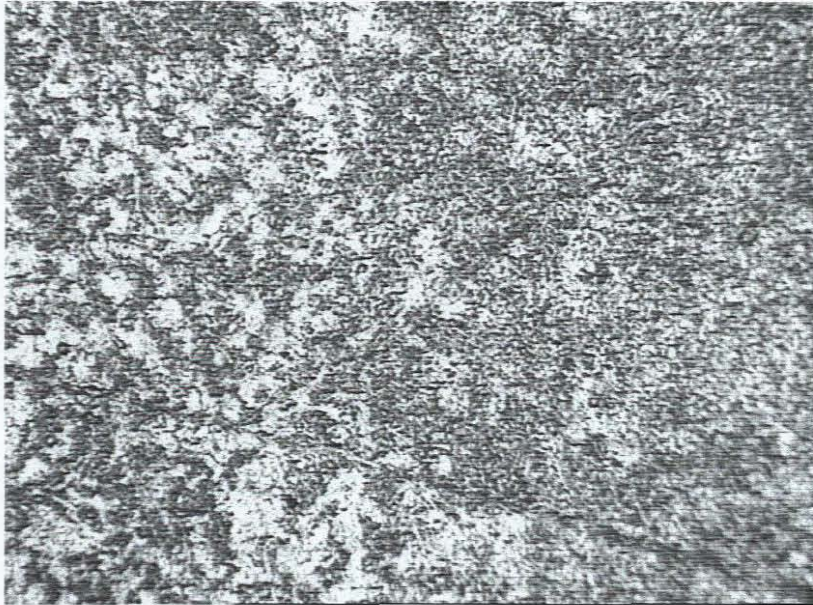


Figure 7.39: The microstructure of specimen 1 depicts a diffuse transition zone with the weld on the RHS as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\times$.



Figure 7.40: Microstructure of the plate specimen 2 depicts a structure of

equiaxed ferrite grains with pearlite islands as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

$$l_1 = 113.46\mu\text{m} \quad : n_1 = 13 \quad \therefore d_1 = 8.73\mu\text{m} \quad 14 \text{ grains} \quad [7.23]$$

$$l_2 = 155.49\mu\text{m} \quad : n_2 = 17 \quad \therefore d_2 = 9.15\mu\text{m} \quad 18 \text{ grains} \quad [7.24]$$

$$l_3 = 139.78\mu\text{m} \quad : n_3 = 16 \quad \therefore d_3 = 8.74\mu\text{m} \quad 17 \text{ grains} \quad [7.25]$$

$$S = \frac{0.24}{\sqrt{49}} = 0.03 \quad [7.26]$$

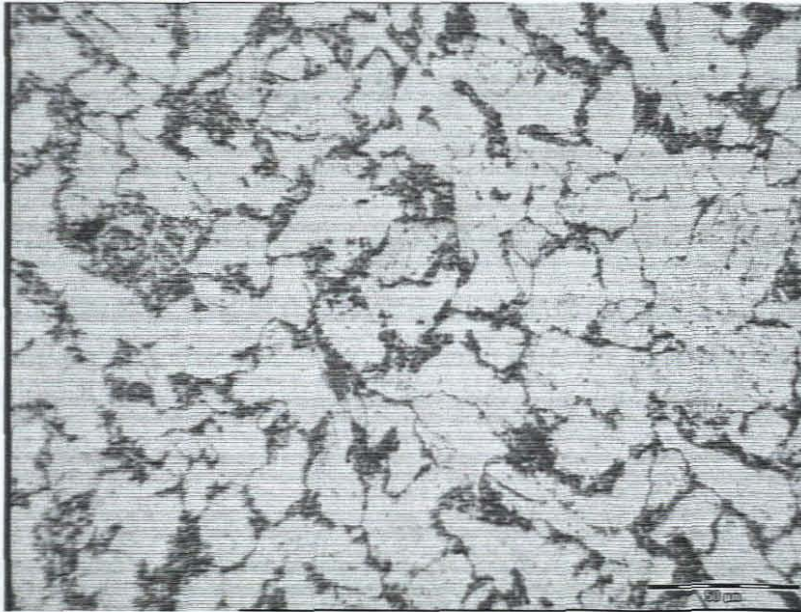


Figure 7.41: Microstructure of the HAZ specimen 2 depicts a structure of equiaxed ferrite grains with pearlite islands as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

$$l_1 = 133.46\mu\text{m} \quad : n_1 = 13 \quad \therefore d_1 = 10.27\mu\text{m} \quad 14 \text{ grains} \quad [7.27]$$

$$l_2 = 164.02\mu\text{m} \quad : n_2 = 15 \quad \therefore d_2 = 10.93\mu\text{m} \quad 16 \text{ grains} \quad [7.28]$$

$$l_3 = 148.73\mu\text{m} \quad : n_3 = 14 \quad \therefore d_3 = 10.62\mu\text{m} \quad 15 \text{ grains} \quad [7.29]$$

$$S = \frac{0.33}{\sqrt{45}} = 0.05 \quad [7.30]$$



Figure 7.42: Microstructure of the weld specimen 2 depicts a structure of acicular ferrite (Widmanstätten structure) with pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\text{x}$.

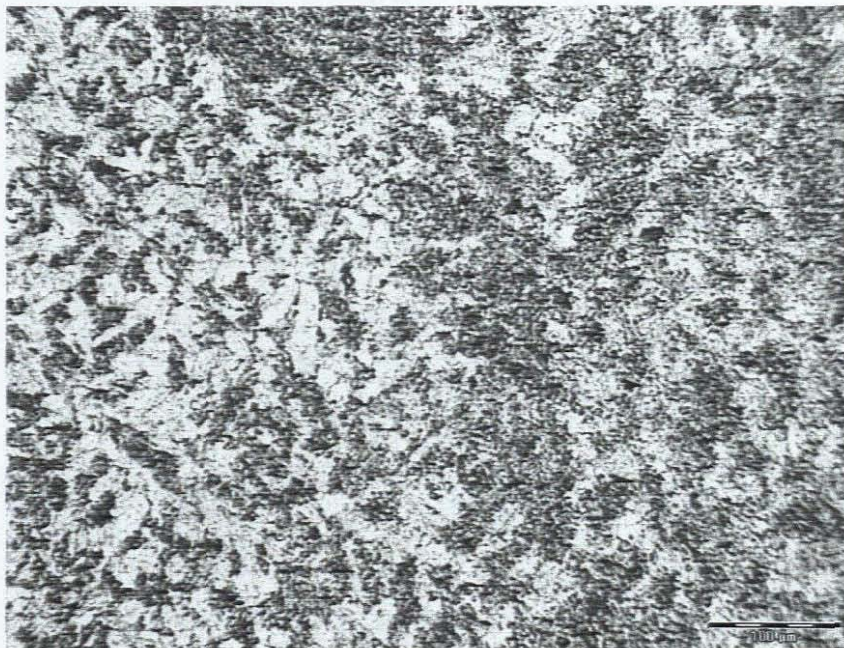


Figure 7.43: The microstructure of specimen 2 depicts a diffuse transition zone with the weld on the RHS as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\text{x}$.



Figure 7.44: Microstructure of the plate specimen 3 depicts a structure of equiaxed ferrite grains with pearlite islands as seen at 50μm = 20mm ⇒ 400x.

$$l_1 = 155.87\mu\text{m} \quad : n_1 = 16 \quad \therefore d_1 = 9.74\mu\text{m} \quad 16 \text{ grains} \quad [7.31]$$

$$l_2 = 133.14\mu\text{m} \quad : n_2 = 14 \quad \therefore d_2 = 9.51\mu\text{m} \quad 15 \text{ grains} \quad [7.32]$$

$$l_3 = 138.81\mu\text{m} \quad : n_3 = 15 \quad \therefore d_3 = 9.25\mu\text{m} \quad 16 \text{ grains} \quad [7.33]$$

$$S = \frac{0.25}{\sqrt{47}} = 0.04 \quad [7.34]$$



Figure 7.45 Microstructure of the HAZ specimen 3 depicts a structure of equiaxed ferrite grains with pearlite islands as seen at 50μm = 20mm ⇒ 400x.

$$l_1 = 120.35\mu\text{m} : n_1 = 15 \quad \therefore d_1 = 8.02\mu\text{m} \quad 16 \text{ grains} \quad [7.35]$$

$$l_2 = 138.83\mu\text{m} : n_2 = 16 \quad \therefore d_2 = 8.68\mu\text{m} \quad 17 \text{ grains} \quad [7.36]$$

$$l_3 = 118.82\mu\text{m} : n_3 = 14 \quad \therefore d_3 = 8.5\mu\text{m} \quad 15 \text{ grains} \quad [7.37]$$

$$S = \frac{0.34}{\sqrt{48}} = 0.05 \quad [7.38]$$



Figure 7.46: Microstructure of the weld specimen 3 depicts a structure of acicular ferrite with pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\text{x}$.

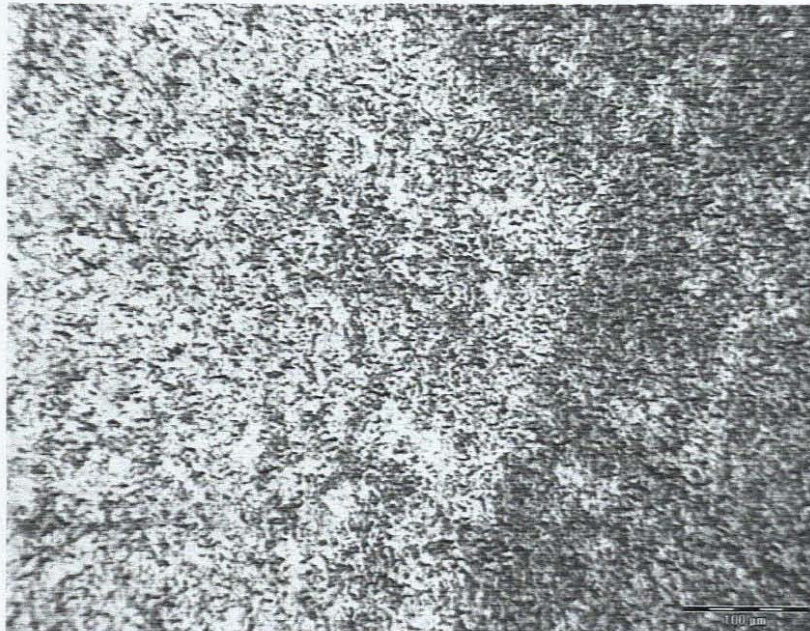


Figure 7.47: The microstructure of specimen 3 depicts a distinct diffuse transition zone with the weld on the RHS as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\text{x}$.



Figure 7.48: Microstructure of the plate specimen 4 depicts a structure of equiaxed ferrite grains with pearlite islands as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

$$l_1 = 128.29\mu\text{m} \quad : n_1 = 13 \quad \therefore d_1 = 9.87\mu\text{m} \quad 14 \text{ grains} \quad [7.39]$$

$$l_2 = 131.87\mu\text{m} \quad : n_2 = 14 \quad \therefore d_2 = 9.42\mu\text{m} \quad 15 \text{ grains} \quad [7.40]$$

$$l_3 = 121.36\mu\text{m} \quad : n_3 = 13 \quad \therefore d_3 = 9.34\mu\text{m} \quad 14 \text{ grains} \quad [7.41]$$

$$S = \frac{0.29}{\sqrt{43}} = 0.04 \quad [7.42]$$



Figure 7.49: Microstructure of the HAZ specimen 4 depicts a structure of equiaxed ferrite grains with pearlite islands as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

$$l_1 = 117.60\mu\text{m} \quad : n_1 = 13 \quad \therefore d_1 = 9.05\mu\text{m} \quad 14 \text{ grains} \quad [7.43]$$

$$l_2 = 147.48\mu\text{m} \quad : n_2 = 16 \quad \therefore d_2 = 9.22\mu\text{m} \quad 17 \text{ grains} \quad [7.44]$$

$$l_3 = 139.64\mu\text{m} \quad : n_3 = 15 \quad \therefore d_3 = 9.31\mu\text{m} \quad 16 \text{ grains} \quad [7.45]$$

$$S = \frac{0.13}{\sqrt{47}} = 0.2 \quad [7.46]$$

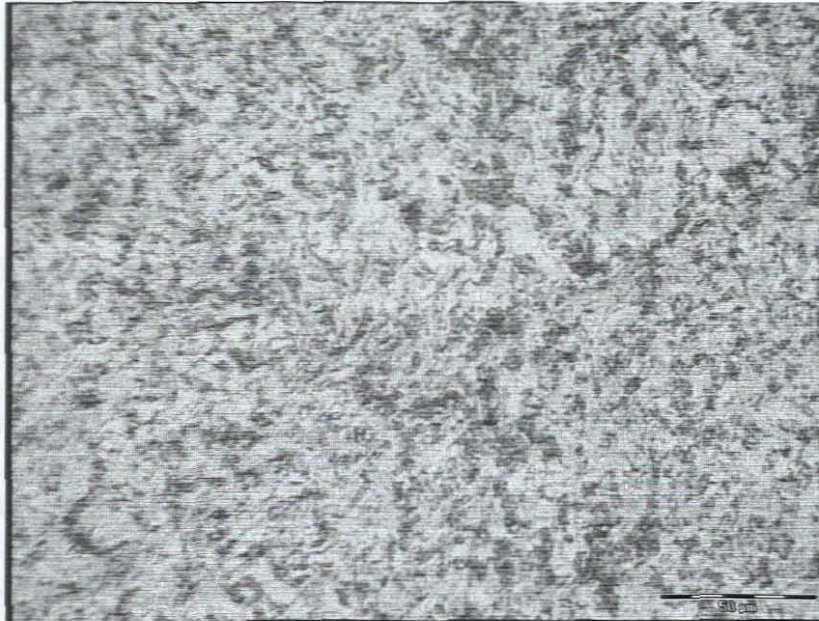


Figure 7.50: Microstructure of the weld specimen 4 depicts a structure of ferrite and pearlite islands as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

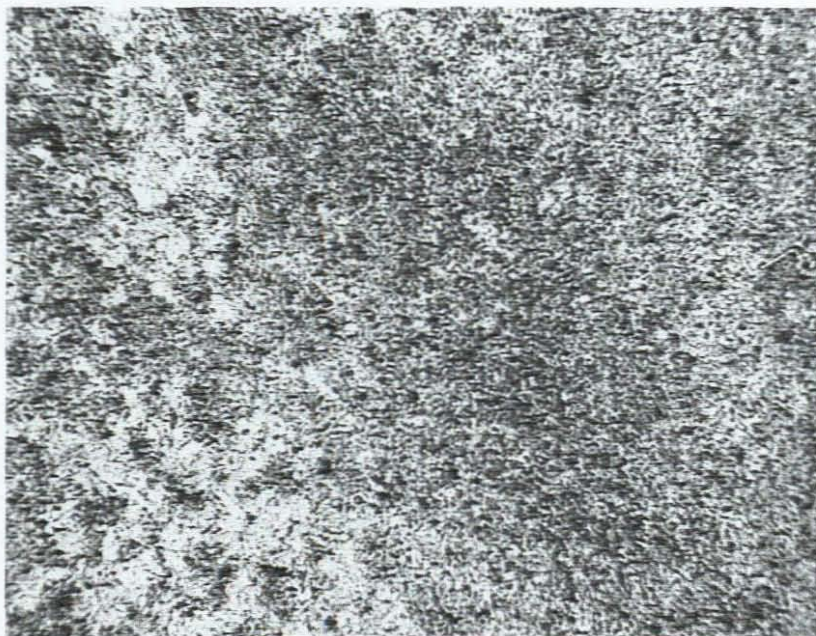


Figure 7.51: The microstructure of specimen 4 depicts a diffuse transition zone with the weld (RHS) as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\times$.

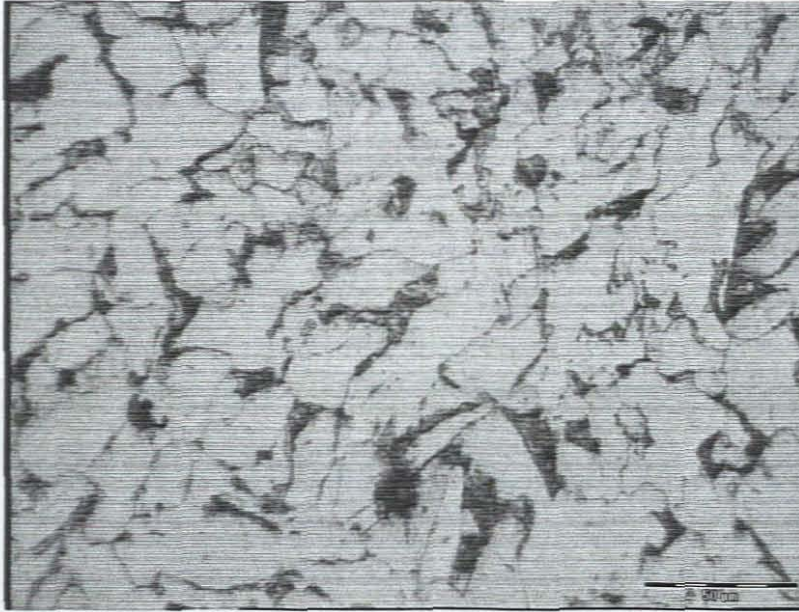


Figure 7.52: Microstructure of the plate specimen 5 depicts a structure of equiaxed ferrite grains with pearlite islands as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

$$l_1 = 160.36\mu\text{m} \quad : n_1 = 15 \quad \therefore d_1 = 10.69\mu\text{m} \quad 16 \text{ grains} \quad [7.47]$$

$$l_2 = 128.69\mu\text{m} \quad : n_2 = 13 \quad \therefore d_2 = 9.90\mu\text{m} \quad 14 \text{ grains} \quad [7.48]$$

$$l_3 = 185.58\mu\text{m} \quad : n_3 = 17 \quad \therefore d_3 = 10.92\mu\text{m} \quad 18 \text{ grains} \quad [7.49]$$

$$S = \frac{0.54}{\sqrt{48}} = 0.08 \quad [750]$$



Figure 7.53: Microstructure of the HAZ specimen 5 depicts a structure of equiaxed ferrite grains with pearlite islands as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

$$l_1 = 142.08\mu\text{m} \quad : n_1 = 15 \quad \therefore d_1 = 9.47\mu\text{m} \quad 16 \text{ grains} \quad [7.51]$$

$$l_2 = 140.25\mu\text{m} \quad : n_2 = 14 \quad \therefore d_2 = 9.35\mu\text{m} \quad 15 \text{ grains} \quad [7.52]$$

$$l_3 = 147.70\mu\text{m} \quad : n_3 = 16 \quad \therefore d_3 = 9.23\mu\text{m} \quad 17 \text{ grains} \quad [7.53]$$

$$S = \frac{0.12}{\sqrt{48}} = 0.02 \quad [7.54]$$

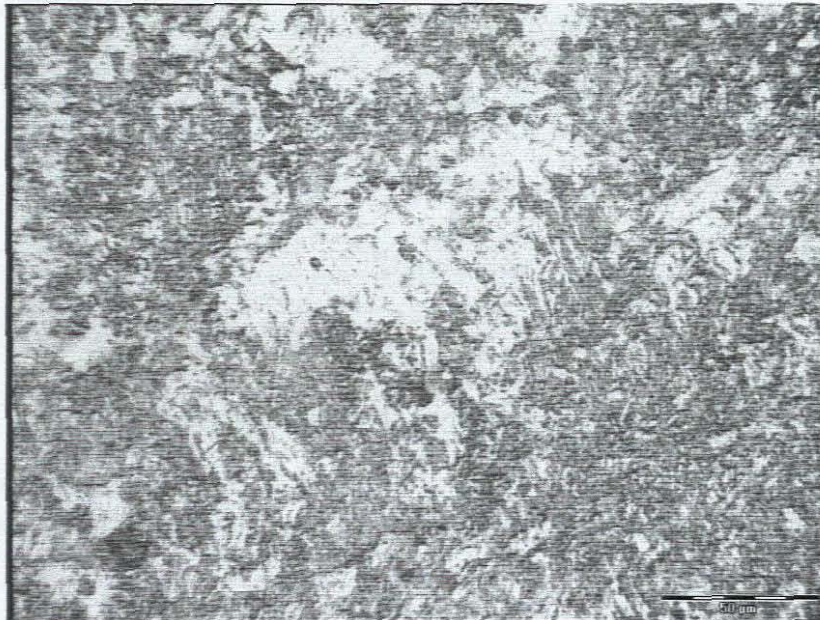


Figure 7.54: Microstructure of weld specimen 5 depicts a structure of acicular ferrite (Widmanstätten) with pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

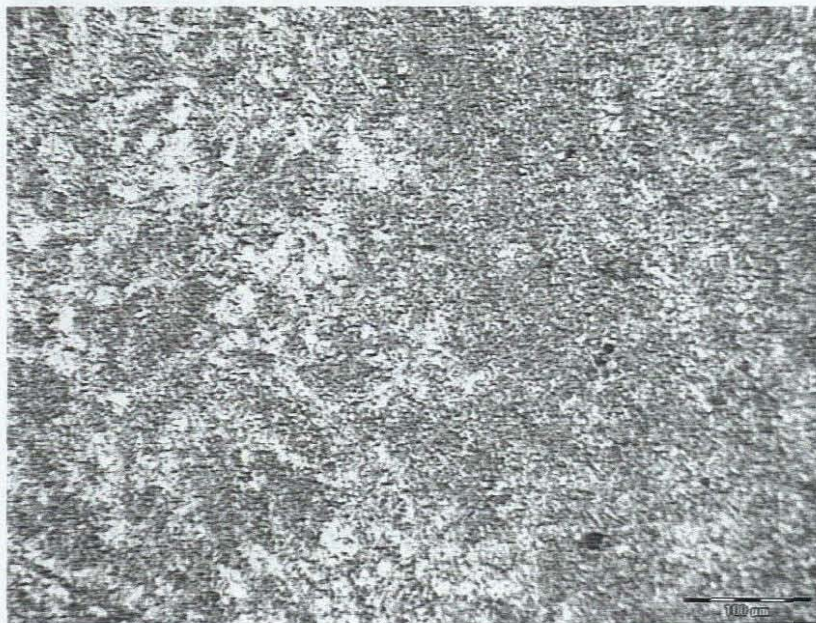


Figure 7.55: The microstructure of specimen 5 depicts a diffuse transition zone with the weld (RHS) displaying a finer grain structure than the HAZ as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\times$.

The figures below represent the results of specimens after fatigue testing and fracture.

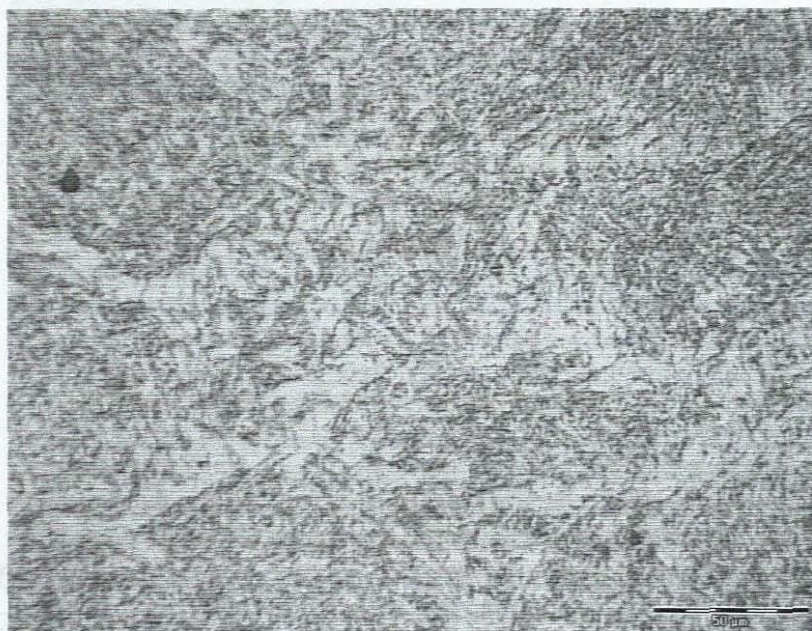


Figure 7.56: Microstructure of weld specimen 1 depicts a structure of acicular ferrite (Widmanstätten) with pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

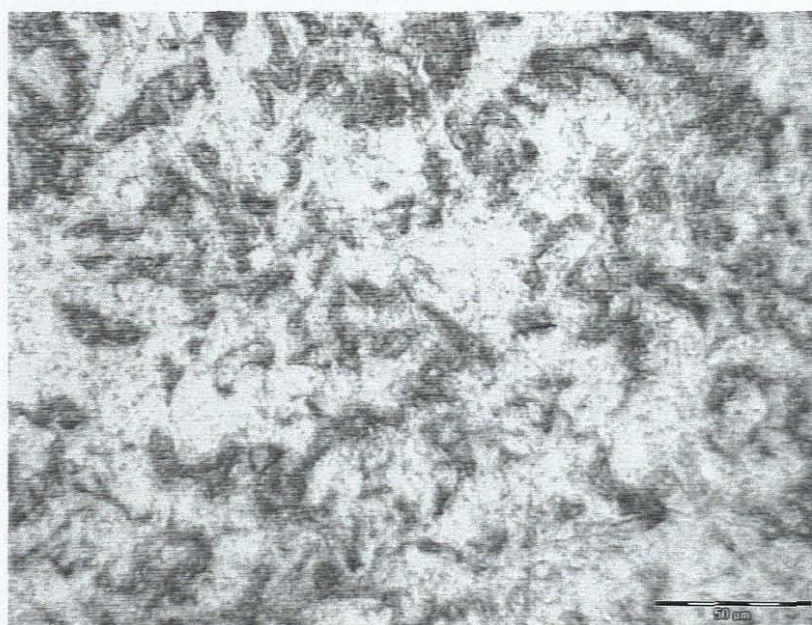


Figure 7.57: Microstructure of the HAZ specimen 1 depicts a structure of ferrite & pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

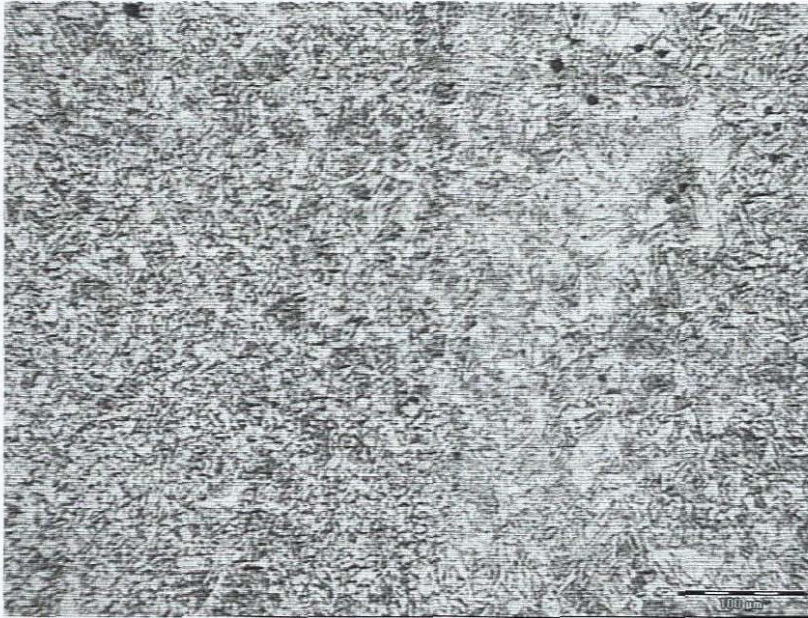


Figure 7.58: Microstructure of specimen 1 clearly depicting a change in microstructure distinguishing the weld (LHS) and the HAZ (RHS) as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\times$.



Figure 7.59: Microstructure of weld specimen 2 depicts a structure of acicular ferrite (Widmanstätten) with pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

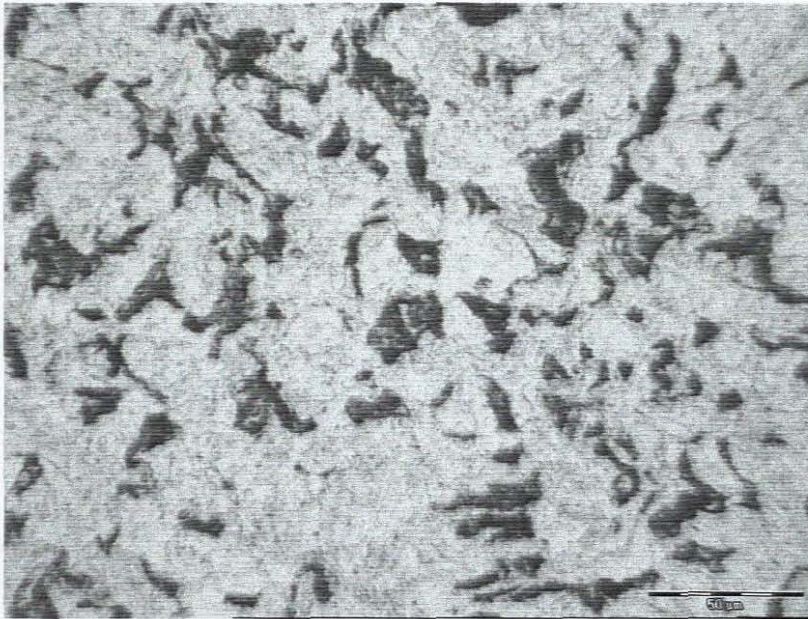


Figure 7.60: Microstructure of the HAZ specimen 2 depicts a structure of ferrite & pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.



Figure 7.61: Microstructure of specimen 2 clearly depicting a difference in microstructure between the weld (RHS) and the HAZ (LHS). Note the crack in the weld area as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\times$.

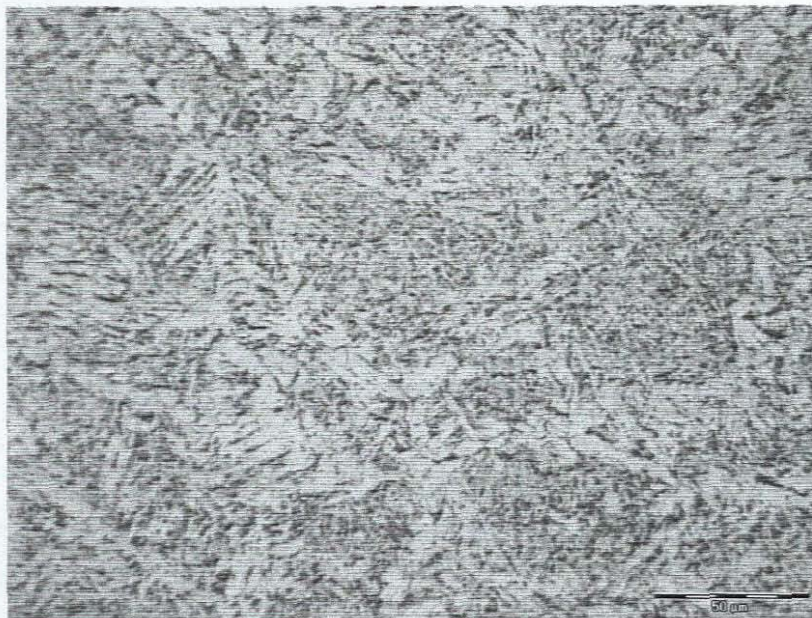


Figure 7.62 Microstructure of weld specimen 3 depicts a structure of acicular ferrite (Widmanstätten) with pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

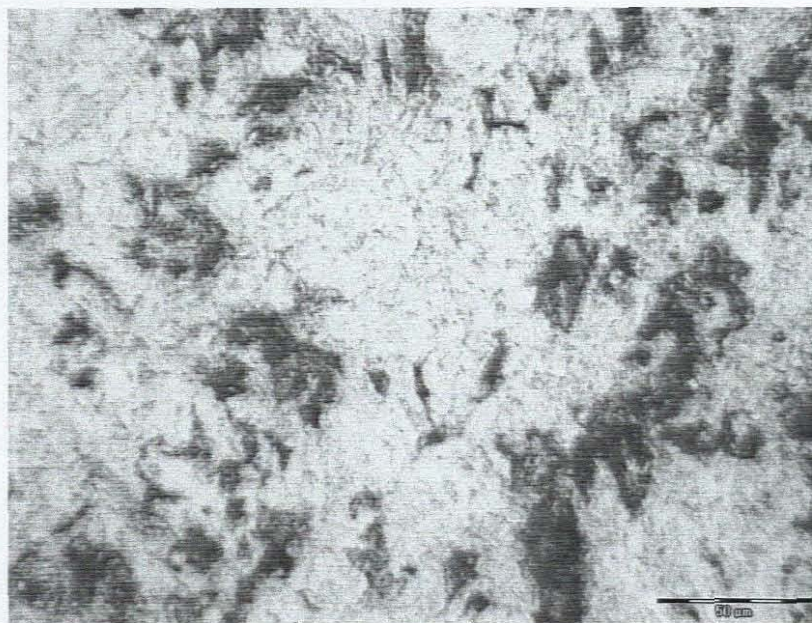


Figure 7.63: Microstructure of the HAZ specimen 3 depicts a structure of ferrite & pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

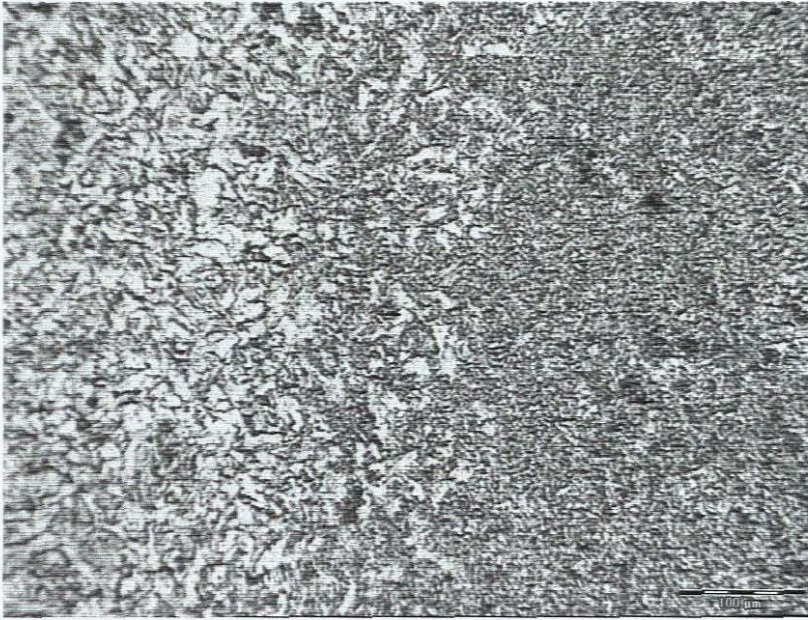


Figure 7.64: Microstructure depicting a phase change between the weld (RHS) and the HAZ (LHS) of specimen 3 as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\times$.



Figure 7.65 Microstructure of weld specimen 4 depicts a structure of acicular ferrite (Widmanstätten) with pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.

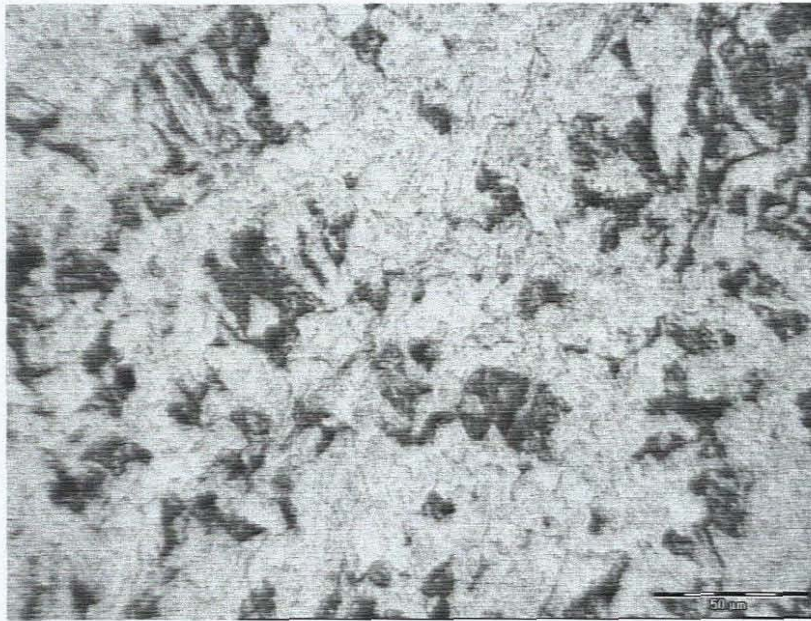


Figure 7.66: Microstructure of the HAZ specimen 4 depicts a structure of ferrite & pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.



Figure 7.67: Microstructure of weld (LHS) and the HAZ (RHS) of specimen 4 with a distinct difference in the microstructures as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\times$.



Figure 7.68: Microstructure of the weld specimen 5 depicts a structure of acicular ferrite (Widmanstätten) with pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.



Figure 7.69: Microstructure of the HAZ specimen 5 depicts a structure of ferrite & pearlite as seen at $50\mu\text{m} = 20\text{mm} \Rightarrow 400\times$.



Figure 7.70: Microstructure of weld (RHS) and the HAZ (LHS) of specimen 5. The weld displays ferrite grains in a pearlite matrix as seen at $100\mu\text{m} = 16.75\text{mm} \Rightarrow 167.5\times$.

Figures 7.36 – 7.55 depict metallurgical images of the weld, HAZ and the base plate captured before fatigue tests were performed. The remaining micrographs depict images captured after fatigue tests. There are no significant differences detected in the diffuse transition zones before and after fatigue testing. An insignificant amount of grain refinement has taken place when analysing the micrographs. Unfortunately no post-fatigue micrographs were captured for specimens 5.

Chapter 8

Conclusions

8.1 Analysis and Discussion

It is well known that weld geometry, weld imperfections and residual stresses are limiting factors in the expected life of a cyclically loaded weld.

As a result of high weld deposit rate the number of beads was significantly low, consequently the distribution of the high temperature in the weld was not uniform and changes rapidly as the weld progresses coupled with associated thermal strains and localised plastic deformation. High residual stresses were created. High temperatures from the weld, which heats up the bulk or the material also lessens the effect of self quenching, which results in less martensite formation, thus influencing the strength of the material. According to [41], the yield strength increases as the temperature decreases.

The initial ultrasonic stress measurements, recorded closest to the weld, were high (194MPa) and the minimum average recorded was 125MPa.

The rosette strain gauge measurement technique (hole drilling method) was also employed to measure the strains in the welded plate. These measured strains were converted into stresses and compared to the ultrasonic stress measurements previously obtained. The stresses that were converted from the strains measured using the hole-drilling method, yielded results that were significantly lower than the stresses first measured with the aid of the Debro-30. The Debro-30 machine was calibrated again as in 7.2.3.1 in order to determine

if the correct reference time of flight had been recorded previously. During the calibration process a strain gauge was connected to the tensile test specimen to record the strains in the loaded specimen. The strains recorded were then converted to stresses.

After the calibration process, the new reference time of flight, as well as the calculated acousto-elastic constant, were stored into the machine. Stresses were again measured in the same specimen using both techniques. This time similar measurements were obtained. This indicated that the stresses measured initially using the ultrasonic method on the welded specimens were incorrect and could no longer be relied upon. Stresses calculated from the hole drilling method, averaged about 52MPa closest to the weld and approximately 32MPa in the base plate.

The purpose of performing the tensile test for the calibration of the Debro-30 was to relate stress measurements at different strains on the tensile tester to the stress measurements on the Debro-30 by adjusting the time of flight parameters so that the stress measurement coincided. It was thus possible to compare the Debro-30 adjusted ultrasonic stress measurements with the values obtained by the strain gauge method.

The method to determine the parameters used in the ultrasonic stress measuring technique have now been recorded in this work and may be used to perform residual stress measurements on 300WA steel at a room temperature of 25°C with the same accuracy as the strain gauge measurement technique. In order to obtain accurate measurement using the Debro-30, careful attention must be given when fine adjustments are made to find the signal for the reference time of flight during the measuring cycles.

The welded plate also provided metallurgical test specimens. Microscopic images were analysed and compared. Metallurgical specimens analysed before the fatigue tests, exhibited equiaxed ferrite grains with pearlite islands in the HAZ and plate specimens. This is because during welding the various phases are formed with respect to temperature, time and carbon content of the steel. The temperature of the base plate does not exceed the A1 temperature on the carbon equilibrium diagram and thus no significant change takes place: here a mixture of ferrite and pearlite grains is evident. The HAZ, however, reaches well beyond that point where pearlite transforms to austenite, although not all ferrite transforms to austenite. During the cooling phase, austenite transforms to ferrite and particles usually precipitate as an interphase, which results in increased strength. In the HAZ the temperature is too low to cause melting yet high enough to cause a significant change in microstructure and hence affect the material properties through increased hardness, increased yield strength and increased fatigue life.

Grain sizes measured in the HAZ and the base plate averaged between 9 & 10 μm . According to [21], achieving grain sizes in the order of 2 – 10 μm is extremely beneficial. Due to a lack of equipment, grain sizes could not be measured accurately enough at the small scale so as to determine the expected relationship to hardness measurements especially at the weld.

Metallurgical images of the weld depict a microstructure widely desired, viz. acicular ferrite (fine grain size). It is desired because it improves the toughness of the weld metal. In figures 7.47, 7.58, 7, 7.61, 7.64, 7.67 & 7.70 the diffuse transition zone is evident. The acicular ferrite changes to ferrite/pearlite across the diffuse transition zone and this is because during the welding process, the fusion zone reaches a temperature in excess of 1400°C, the partially melted zone between $\pm 1450\text{-}1500^\circ\text{C}$ and the HAZ between $\pm 700\text{-}1450^\circ\text{C}$ as seen in figure 8.1.

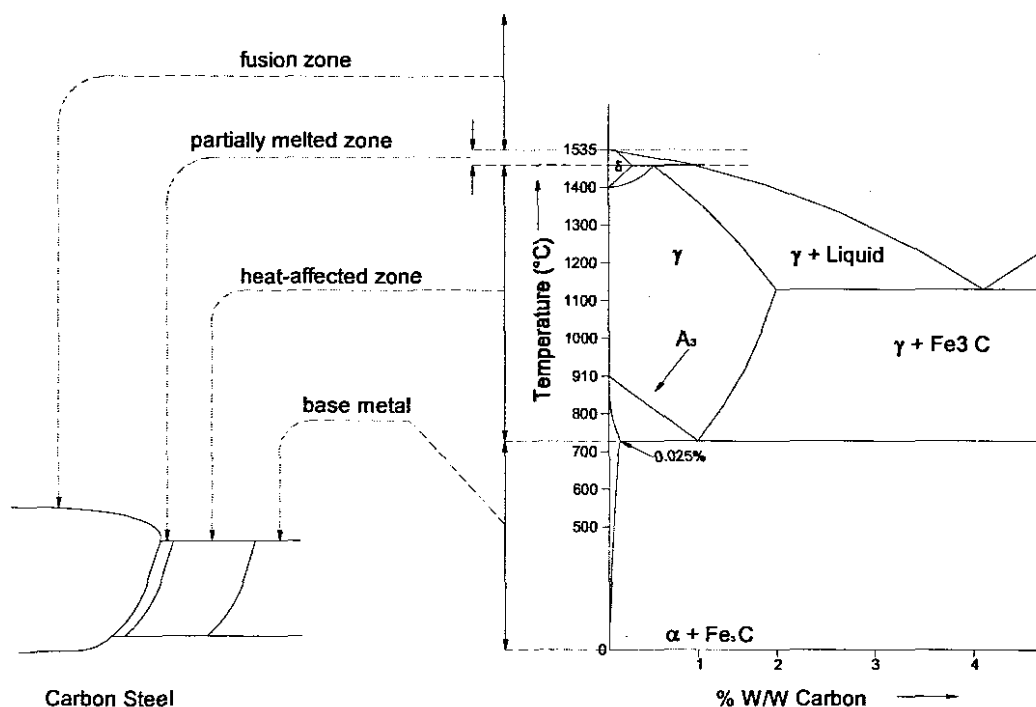


Figure 8.1: Carbon steel weld & phase diagram [24].

Figure 8.1 depicts the various regions for carbon steel welded specimens with a direct relation to the Fe-C phase diagram. When compared, metallurgical specimens analysed after the fatigue tests, exhibited the same microstructure as for all pre-fatigue test specimens. It was also rare to find any micro-cracks in the specimens, which indicates that damage was highly localised.

Tensile test specimens were obtained from the weld, HAZ and plate of one (1) of the remaining five (5) specimens that were originally prepared for the experiments. The tensile tests yielded expected results. The ultimate tensile stress as, well as the yield stress, were higher in the weld than in the HAZ and base plate. In this case the weld yield stress is fifty-three percent (52.5%) more than that of the base plate and thirteen percent (13%) more than that of the HAZ as seen in table 7.2. Three specimens were obtained from each welded specimen and they were subjected to fatigue tests. The results confirmed expectations that the proportion of cyclic life spent on initiating the crack is in the order of about ten percent (10%). The average life expectancy for the

welded specimen subjected to a load of 10kN is 40133 cycles with a crack initiation after 11833 cycles. From the data reflected in figure 7.19, the life cycles for the welded specimens were much higher than those of the base material as well as those of the HAZ. Even though the yield stress was higher in the HAZ than in the base plate, the HAZ seemed to be the most likely site for crack propagation, which is in accordance with what is generally observed in welding failures. This is evidenced by a number of specimens that revealed a crack growth path that was diverted to the diffuse transition zone. Figure 7.20 depicts a HAZ with a greater crack resistance than that of the base plate for the three specimens. In spite of this evidence the base plate has proven to have better toughness as displayed by the fatigue life.

The development of micro cracks in the fatigue specimen was also not observed other than in the region of ultimate failure. It was therefore not possible to estimate the damage in a specimen subjected to fatigue loading prior to failure.

Specimen 2.3 had its notch significantly close to the HAZ. At the earliest point of detection, the crack was in the process of propagating toward the HAZ.

Hardness tests were performed on the specimens prior to and after the fatigue tests. Hardness was measured in the weld, HAZ and the base plate to determine if there were any changes after the fatigue tests. No differences were noted in the hardness values obtained from the specimens. In figure 7.27 it is evident that a close relationship exists between the hardness and the yield stress of a material. The weld exhibits a hardness and stress value greater than that of the HAZ and the base plate coupled with an acicular ferrite microstructure. Although the HAZ shares a somewhat similar microstructure to that of the base plate, it has a higher hardness value and this is attributed primarily to increased temperatures during the welding process.

Fracture specimens reveal that plastic deformation has taken place due to the high welding temperatures supported by the fact that the crack growth path was along the diffuse transition zone. No differences were detected in the hardness values or the microstructures of the relevant regions after fatigue.

The experimental results presented in chapter 7, indicate that the welding process has a significant influence on the formation of residual stresses. The welding process in our experiments was identical for all specimens and hence a very close similarity existed between residual stress measurements for the various regions (weld, HAZ & parent metal). Stresses measured in the weld region were relatively close to the HAZ and parent plate material.

The micrographs of the welds displayed good structures viz. acicular ferrite. The weld, HAZ and parent metal have a respective declining hardness and yield stress. The HAZ and parent metal exhibited ferrite and pearlite structures with fine grain sizes.

In hindsight, a larger sample of fatigue specimens for the various loads could have been used in order for the weld metal, HAZ and base metal to be a more representative sample. Perhaps improved accuracy could have been obtained if a larger sample was used. Fatigue crack growth could have been monitored more accurately by connecting strain gauges and crack propagation gauges to the specimens during the fatigue testing process. In this respect, problems with the existing logging equipment hampered effective data collection.

A microscope fitted with a camera to capture images of crack initiation and crack growth has recently been purchased. This will enable automated continuous monitoring of crack initiation, and crack growth rates, especially when testing at the lower load cycles range.

The results from the experiments have revealed that residual stresses can be measured accurately either with the aid of the Debro-30 ultrasonic stress measuring device or when using the hole drilling method. Ultrasonic stress measurement is non-destructive and can be used in service, whereas the hole drilling method is semi-destructive.

Data in this research revealed that 300WA welded steel in operation, with an applied stress measurement of 69.5MPa and hardness value of 183HV in the weld region, would yield a life expectancy of about 40000cycles. The HAZ with respective values of 69.5MPa and HV168 would fracture at approximately 10600cycles and the parent metal with a similar stress measurement and hardness value of HV137 results in the material fracturing at 12500cycles.

As previously documented, a relationship exists between the hardness and the stress. However, even though higher stress and hardness values were measured, the life expectancy of the HAZ was shorter when compared to the plate. This is attributed to the region within the HAZ, being an area of weakness due to tempering during reheating in multi-pass welds. The microstructures in the various regions also differ and here the grain size determines the strength, with a finer grain in the weld than in the HAZ and plate displaying more strength.

In order to predict how close a welded material was to failure, it would be necessary to determine the applied stress as well as the hardness of the material. These parameters can be determined on site. However there is not enough information in this research to conclude that the life expectancy of 300WA welded steel can be predicted due to inadequate comparison between the weld regions with different stresses and hardness values. A number of welded specimens with varying stress measurements and hardness values should have been subjected to fatigue tests. This would have allowed for a data base of values to be recorded for future reference. A 300WA welded material in

service with given applied stress and hardness values could then be compared to stress and hardness values within the recorded data base. This information would then reveal the predicted life cycle of the in service material.

8.2 Recommendations

The following recommendations are suggested for further research in order to predict the life cycle of 300WA welded steel:

- A number of welded specimens with various applied stress and hardness values should be subjected to fatigue tests. The number of specimens should be enough in order to compare numerous varying stress and hardness values.
- Because of the relationship between crack initiation and ultimate fracture, close attention should be given to crack initiation.
- The grain sizes of the weld specimens should be measured in order to determine if a relationship exists between grain size and life expectancy.

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Gas Selection for Gas Metal Arc Welding [34]

Metal Type	Thickness	Transfer Mode Recommended Shielding Gas		Advantages/Description
		Transfer Mode	Recommended Shielding Gas	
Carbon Steel	Up to 14 gauge	Short Circuit	Argon + CO ₂ Argon + CO ₂ + O ₂	Good penetration and distortion control to reduce potential melt-through.
	14 gauge - 1/4 in	Short Circuit	Argon + 8 to 25% CO ₂ Argon + He CO ₂	Higher deposition rates without melt-through. Minimum distortion and spatter. Good weld control for out-of-position welds.
	More than 1/4 in.	Short Circuit	Carbon Dioxide. Argon + 15 to 25%CO ₂	High welding speeds. Good penetration and pool control. Applicable for out-of-position welds.
		Short Circuit Globular	Argon + 25% CO ₂	Suitable for high current high-speed welding.
		Short Circuit	Argon + 50% CO ₂	Deep penetration: low spatter; high travel speeds. Good out-of-position welding
		Short Circuit Globular (buried arc)	Carbon Dioxide	Deep penetration and fastest travel speeds but with higher melt-through potential. High-current mechanized welding
		Spray Transfer	Argon + 1 to 8% O ₂	Good arc stability: produces a more fluid weld pool as O ₂ increases; good coal-essence and bead contour. Good weld appearance and weld pool control.
		Spray Transfer	Argon + 5 to 20% CO ₂	Fluid weld pool and oxidizing to weld metal cause higher amounts of slag and scale as CO ₂ increases. Good arc stability, weld soundness and increasing width of fusion.
		Spray Transfer	Argon + CO ₂ + O ₂ Argon + He + CO ₂ Helium + Ar + CO ₂	Applicable to both short circuiting and spray transfer modes. Has wide welding current range and good arc performance. Weld pool has good control, which results in improved weld contour.
		High Current Density Rotational	Argon + He CO ₂ + O ₂ Helium + Ar + CO ₂	Used for high deposition rate welding where 15 to 30 lb/h (7 to 14 kg/h) is typical. Special welding equipment and techniques are sometimes required to achieve these deposition levels.
	More than 14 gauge	Pulsed Spray	Argon + 2 to 8% O ₂ Argon + 5 to 20% CO ₂ Argon + CO ₂ + O ₂ Argon + He + CO ₂	Used for both light-gauge heavy out-of-position weldments. Achieves good pulse spray stability over a wide range of arc characteristics and deposition ranges.

Metal Type	Thickness	Transfer Mode	Recommended Shielding Gas	Advantages/Description
Low and High-Alloy Steel	Up to $\frac{3}{4}$ in	Short Circuit	Argon + 8 to 20% CO ₂ Helium + Ar + CO ₂ Argon + CO ₂ + CO ₂	Good coalescence and bead contour. Good mechanical properties
		Short Circuit Globular	Argon + 20 to 50% CO ₂	High welding speeds Good Penetration and weld pool Control. Applicable for out-of-position welds. Suitable for high-current and high-speed welding.
	More than $\frac{3}{4}$ in	Spray Transfer (High Current Density & Rotational)	Argon + 2% O ₂ Argon + 5 to 10% CO ₂ Argon + CO ₂ + O ₂ Argon + He + CO ₂	Reduces undercutting Higher deposition rates and improved bead wetting. Deep penetration and good mechanical properties.
		Pulsed Spray	Argon + 2% O ₂ Argon + 5% CO ₂ Argon + CO ₂ + O ₂ Argon + He + CO ₂	Used for both light-gauge and heavy out-of-position weldments. Achieves good pulse spray stability over a wide range of arc characteristics and deposition ranges.
Steel Stainless, Nickel, Nickel Alloy	Up to 14 gauge	Short Circuit	Argon + 2 to 5% O ₂	Good control of melt-through and distortion. Used also for spray arc welding. Weld pool fluidity sometimes sluggish, depending on the base alloy.
	More than 14 gauge	Short Circuit	Helium + 7.5 Ar + 2.5 CO ₂ Argon + 2 % O ₂ Argon + He CO ₂ Helium + Ar + CO ₂	Low CO ₂ percentages in He mix minimizes carbon pickup, which can cause intergranular corrosion with some alloys. Helium improves wetting action and contour. CO ₂ percentages above 5% should be used with caution on some alloys. Applicable for all position welding.
		Spray Transfer	Argon + 1 to 2% O ₂ Argon + He + CO ₂ Helium + Ar + CO ₂	Good arc stability. Produces a fluid but controllable weld pool; good coalescence and bead contour. Minimizes undercutting on heavier thickness.
	More than 14 gauge	Pulsed Spray	Argon + 1 to 2% O ₂ Argon + He CO ₂ Helium + Ar + CO ₂ Argon + CO ₂ + H ₂	Used for both light-gauge and heavy out-of-position weldments. Achieves good pulse spray stability over a wide range of arc characteristics and deposition ranges.
Stainless Steel	Up to $\frac{1}{2}$ in	Spray Transfer Pulsed Spray	Argon	Best metal transfer, arc stability and plate cleaning. Little or no spatter. Remove oxides when used with CDE (Reverse polarity).
Aluminum	More than $\frac{3}{4}$ in.	Spray Transfer Pulsed Spray	Helium + 20 to 50% Argon Argon + Helium	High heat input. Produces fluid weld pool, flat bead contour and deep penetration. Minimizes porosity.

Rosette Strain Gauge Results

$$\epsilon_1 = \frac{\epsilon_1 + \epsilon_3}{4A} \pm \frac{1}{4B} \sqrt{(\epsilon_3 - \epsilon_1)^2 + (\epsilon_3 + \epsilon_1 - 2\epsilon_2)^2}$$

$$\epsilon_1 = 7.30E-05$$

$$\epsilon_3 = 1.60E-05$$

$$\sigma = \tan 2\alpha = \frac{\epsilon_1 - 2\epsilon_2 + \epsilon_3}{\epsilon_1 - \epsilon_3}$$

$$1.00E+08$$

$$A = 4.45E-13$$

$$B = 2.85E-13$$

Calculate the maximum and minimum principle stresses

Specimen 1	Gauge 1	Gauge 2	Gauge 3	Max Stress (Mpa)		Min Stress (Mpa)	
Rosette 1	4.70E-05	4.70E-05	4.70E-05	5.28E+07	52.8Mpa	5.28E+07	52.8Mpa
Rosette 2	4.80E-05	4.90E-05	4.80E-05	5.57E+07	55.7Mpa	5.22E+07	52.2Mpa
Rosette 3	2.80E-05	2.70E-05	2.70E-05	3.21E+07	32.1Mpa	2.97E+07	29.7Mpa

Specimen 2	Gauge 1	Gauge 2	Gauge 3	Max Stress (Mpa)		Min Stress (Mpa)	
Rosette 1	5.10E-05	4.90E-05	4.90E-05	5.87E+07	58.7Mpa	5.37E+07	53.7Mpa
Rosette 2	4.90E-05	5.00E-05	4.80E-05	5.73E+07	57.3Mpa	5.17E+07	51.7Mpa
Rosette 3	2.70E-05	2.70E-05	2.60E-05	3.10E+07	31.0Mpa	2.85E+07	28.5Mpa

Specimen 3	Gauge 1	Gauge 2	Gauge 3	Max Stress (Mpa)		Min Stress (Mpa)	
Rosette 1	4.70E-05	4.50E-05	4.60E-05	5.50E+07	55.0Mpa	4.95E+07	49.5Mpa
Rosette 2	4.60E-05	4.60E-05	4.70E-05	5.35E+07	53.5Mpa	5.10E+07	51.0Mpa
Rosette 3	2.60E-05	2.70E-05	2.70E-05	3.10E+07	31.0Mpa	2.85E+07	28.5Mpa

Specimen 4	Gauge 1	Gauge 2	Gauge 3	Max Stress (Mpa)		Min Stress (Mpa)	
Rosette 1	4.90E-05	4.70E-05	4.80E-05	5.73E+07	57.3Mpa	5.17E+07	51.7Mpa
Rosette 2	4.70E-05	4.70E-05	4.80E-05	5.46E+07	54.6Mpa	5.21E+07	52.1Mpa
Rosette 3	2.70E-05	2.60E-05	2.70E-05	3.21E+07	32.1Mpa	2.86E+07	28.6Mpa

Specimen 5	Gauge 1	Gauge 2	Gauge 3	Max Stress (Mpa)		Min Stress (Mpa)	
Rosette 1	4.80E-05	4.70E-05	4.70E-05	5.46E+07	54.6Mpa	5.21E+07	52.1Mpa
Rosette 2	4.70E-05	4.80E-05	4.70E-05	5.46E+07	54.6Mpa	5.11E+07	51.1Mpa
Rosette 3	2.90E-05	2.90E-05	2.80E-05	3.33E+07	33.3Mpa	3.08E+07	30.8Mpa

Rockwell Hardness Scales [13]

Scale	Indenter	Preliminary Load (kgf)	Additional Load (kgf)	Total Load (kgf)	Value of E
A	Diamond Cone	10	50	60	100
B	1/16" steel ball	10	90	100	130
C	Diamond Cone	10	140	150	100
D	Diamond Cone	10	90	100	100
E	1/8" steel ball	10	90	100	130
F	1/16" steel ball	10	50	60	130
G	1/16" steel ball	10	140	150	130
H	1/8" steel ball	10	50	60	130
K	1/16" steel ball	10	140	150	130
L	1/4" steel ball	10	50	60	130
M	1/4" steel ball	10	90	100	130
P	1/4" steel ball	10	140	150	130
R	1/2" steel ball	10	50	60	130
S	1/2" steel ball	10	90	100	130
V	1/2" steel ball	10	140	150	130

Typical applications of Rockwell hardness scales:

HRA : Cemented carbides, thin steel and shallow case hardened steel.

HRB : Copper alloys, soft steels, aluminium alloys, malleable irons, etc.

HRC : Steel, hard cast irons, case hardened steel and other materials harder than 100 HRB.

HRD : Thin steel and medium case hardened steel and pearlitic malleable iron.

HRE : Cast iron, aluminium and magnesium alloys, bearing metals.

HRF : Annealed copper alloys, thin soft sheet metals.

HRG : Phosphor bronze, beryllium, copper, malleable irons HRH.....Aluminium, zinc, lead

APPENDIX D
Results of Hardness Test

	Pre-Fatigue Test		Post-Fatigue Test	
Specimen 1.1	HRB	HV	HRB	HV
HAZ	82.5	168.2	86.7	171.1
Weld	93.7	203.5	93.5	202.5
Plate	72.8	131.6	77.5	142.5
Specimen 1.2	HRB	HV	HRB	HV
HAZ	81.9	155.7	84.1	162.3
Weld	94.6	208	96	216.6
Plate	70.5	126	76.4	139.8
Specimen 1.3	HRB	HV	HRB	HV
HAZ	86.5	170.5	84.7	164.1
Weld	94.1	205.5	87.8	175.2
Plate	70.6	126.2	68	121
Specimen 2.1	HRB	HV	HRB	HV
HAZ	84.7	164.1	83.5	160.5
Weld	93.6	203	93.7	203.5
Plate	71.3	127.9	74.7	136.4
Specimen 2.2	HRB	HV	HRB	HV
HAZ	86	170	85.4	166.6
Weld	88	176	85.7	167.8
Plate	77.5	142.5	75.1	137.2
Specimen 2.3	HRB	HV	HRB	HV
HAZ	82	156	84.9	164.7
Weld	82.5	157.5	83.6	160.8
Plate	77	141	79.1	147.3
Specimen 3.1	HRB	HV	HRB	HV
HAZ	83.8	161.4	81.8	155.4
Weld	85.4	166.6	85.8	168.2
Plate	73.9	134.7	73.3	132.9
Specimen 3.2	HRB	HV	HRB	HV
HAZ	87	172	82.9	158.7
Weld	86.6	170.8	85.9	168.6
Plate	76.4	139.8	68.8	122.6

	Pre-Fatigue Test		Post-Fatigue Test	
Specimen 3.3	HRB	HV	HRB	HV
HAZ	88.6	178.4	86.3	169.9
Weld	87.9	175.6	84.5	163.5
Plate	85.5	168.2	83.5	160.5
Specimen 4.1	HRB	HV	HRB	HV
HAZ	82.7	158.1	90.2	186
Weld	88.2	176.8	88.6	178.4
Plate	72.1	130.2	76.9	140.8
Specimen 4.2	HRB	HV	HRB	HV
HAZ	88	176	83.3	159.9
Weld	89.1	180.5	85.8	168.2
Plate	76.3	139.6	72.2	131.4
Specimen 4.3	HRB	HV	HRB	HV
HAZ	86.4	170.2	85.3	166.2
Weld	86.8	171.4	93.3	201.5
Plate	73.1	132.3	74	135
Specimen 5.1	HRB	HV	HRB	HV
HAZ	93.4	202	90.1	185.5
Weld	92.3	200.5	86	169
Plate	80.4	151.2	75.5	138
Specimen 5.2	HRB	HV	HRB	HV
HAZ	84.1	162.3	87.6	174.4
Weld	87.2	172.8	90.3	186.5
Plate	73.8	134.4	71.6	128.8
Specimen 5.3	HRB	HV	HRB	HV
HAZ	85.6	167.4	86.8	171.4
Weld	88.4	177.6	87	172
Plate	71.8	129.4	73.9	134.7
	Pre-Fatigue Test		Post-Fatigue Test	
	HRB	HV	HRB	HV
Average for HAZ	85.5	168.8	85.6	167.8
Average for Weld	89.2	183.1	88.5	180.2
Average for Plate	74.9	137.0	74.7	136.6

Debro-30 Stress Measurements

The Debro-30 stress measuring-device measures the stresses parallel to the weld. These stresses are measured in a cycle of four steps. Since the measuring cycle is dependant on a reference time of flight (T_L^0), constants have to be programmed into the device. These constants are obtained by experimental methods and are different for various materials. After a cycle of four steps, a stressed time of flight (T_L^σ) as well as a stress reading is recorded on the oscilloscope. From the recorded times of flight, an accousto-elastic constant was determined and stored in the device for stress measurements to be performed.

$$\beta_L = \frac{(T_L^0 - T_L^\sigma)}{\sigma_K}$$

where: T_L^0 = time of flight of a longitudinal wave for a stress which equals zero (0)
 T_L^σ = time of flight of a longitudinal wave for a stress which equals σ_K
 β_L = accousto-elastic constant

Specimen One - Side One : Measurement Taken 85mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress (Mpa)
5mm from edge of plate	24	7.5	24	7.5	-196	17759	17803	126
25mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17788	84
50mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17789	87
75mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17781	64
100mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17793	99
125mm from edge of plate	23.9	7.3	23.9	7.4	-196	17759	17782	66
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17759	59

Average Stress 84**Specimen One - Side One : Measurement Taken 75mm Away From Weld**

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17753	-16
25mm from edge of plate	23.8	7.4	24	7.5	-196	17759	17759	0
50mm from edge of plate	23.8	7.4	24	7.5	-196	17759	17756	-7
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17765	17
100mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17755	-10
125mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17755	-10
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17757	-4

Average Stress -4**Specimen One - Side One : Measurement Taken 65mm Away From Weld**

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17754	-12
25mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17753	-16
50mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17759	0
75mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17762	9
100mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17753	-15
125mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17759	1
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17760	4

Average Stress -4

Specimen One - Side One : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	24	7.5	-196	17759	17768	26
25mm from edge of plate	23.8	7.4	24	7.5	-196	17759	17765	18
50mm from edge of plate	23.8	7.4	24	7.5	-196	17759	17768	27
75mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17767	25
100mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17767	24
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17766	20
150mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17767	24

Average Stress 23

Specimen One - Side One : Measurement Taken 45mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17772	37
25mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17774	44
50mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17777	52
75mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17775	48
100mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17777	53
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17773	41
150mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17768	28

Average Stress 43

Specimen One - Side One : Measurement Taken 35mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17771	36
25mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17784	71
50mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17778	55
75mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17774	45
100mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17774	43
125mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17767	23
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17771	34

Average Stress 44

Specimen One - Side One : Measurement Taken 25mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17788	84
25mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17793	98
50mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17796	108
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17787	81
100mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17790	91
125mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17784	73
150mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17777	53

Average Stress 84

Specimen One - Side One : Measurement Taken 15mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17809	144
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17825	190
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17832	209
75mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17829	202
100mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17830	204
125mm from edge of plate	23.9	7.4	23.9	7.4	-196	17759	17819	171
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17812	154

Average Stress 182

APPENDIX E
Debro-30 Stress Measurements

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Specimen One - Side Two : Measurement Taken 85mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	24	7.4	-196	17759	17759	79
25mm from edge of plate	23.8	7.4	24	7.4	-196	17759	17797	111
50mm from edge of plate	23.8	7.4	24	7.4	-196	17759	17801	120
75mm from edge of plate	23.8	7.4	24	7.4	-196	17759	17797	111
100mm from edge of plate	23.8	7.4	24	7.4	-196	17759	17795	104
125mm from edge of plate	23.9	7.5	23.9	7.4	-196	17759	17797	110
150mm from edge of plate	23.9	7.5	23.9	7.4	-196	17759	17801	121

Average Stress 108

Specimen One - Side Two : Measurement Taken 75mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	23.9	7.4	-196	17759	17750	-25
25mm from edge of plate	23.9	7.5	23.9	7.4	-196	17759	17756	-6
50mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17756	-6
75mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17760	4
100mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17762	9
125mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17767	24
150mm from edge of plate	23.9	7.6	24	7.5	-196	17759	17771	35

Average Stress 5

Specimen One - Side Two : Measurement Taken 65mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24.2	7.4	24.3	7.8	-196	17759	17753	-17
25mm from edge of plate	24.2	7.4	24.3	7.7	-196	17759	17755	-10
50mm from edge of plate	24.1	7.5	24.2	7.4	-196	17759	17747	-33
75mm from edge of plate	24.1	7.5	24.2	7.4	-196	17759	17752	-18
100mm from edge of plate	24.1	7.5	24.1	7.4	-196	17759	17745	-38
125mm from edge of plate	24.1	7.5	24.1	7.4	-196	17759	17752	-17
150mm from edge of plate	24.1	7.5	24.1	7.5	-196	17759	17753	-14

Average Stress -21

Specimen One - Side Two : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24.1	7.5	24.2	7.6	-196	17759	17761	8
25mm from edge of plate	24.1	7.5	24.2	7.7	-196	17759	17764	14
50mm from edge of plate	24.1	7.5	24.2	7.6	-196	17759	17767	23
75mm from edge of plate	24.1	7.5	24.2	7.6	-196	17759	17763	13
100mm from edge of plate	24.1	7.5	24.1	7.5	-196	17759	17762	10
125mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17754	-11
150mm from edge of plate	24.1	7.5	24.1	7.6	-196	17759	17770	31

Average Stress 13

Specimen One - Side Two : Measurement Taken 45mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.4	24.1	7.6	-196	17759	17770	31
25mm from edge of plate	24	7.4	24.1	7.6	-196	17759	17769	30
50mm from edge of plate	24	7.4	24.1	7.5	-196	17759	17761	6
75mm from edge of plate	24	7.4	24	7.5	-196	17759	17763	12
100mm from edge of plate	24	7.4	24	7.4	-196	17759	17758	-1
125mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17764	14
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17764	16

Average Stress 15

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Debro-30 Stress Measurements

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Specimen One - Side Two : Measurement Taken 35mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24.1	7.6	-196	17759	17774	45
25mm from edge of plate	23.9	7.4	24.1	7.6	-196	17759	17775	48
50mm from edge of plate	23.9	7.4	24.1	7.5	-196	17759	17775	46
75mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17771	35
100mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17761	6
125mm from edge of plate	23.9	7.4	24.1	7.5	-196	17759	17773	40
150mm from edge of plate	23.9	7.4	24.1	7.5	-196	17759	17770	33

Average Stress 36

Specimen One - Side Two : Measurement Taken 25mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24.1	7.5	-196	17759	17778	55
25mm from edge of plate	23.9	7.4	24.1	7.5	-196	17759	17780	62
50mm from edge of plate	23.9	7.4	24.1	7.5	-196	17759	17784	74
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17778	55
100mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17771	36
125mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17775	46
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17763	12

Average Stress 49

Specimen One - Side Two : Measurement Taken 15mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24.1	7.6	-196	17759	17795	104
25mm from edge of plate	23.9	7.4	24.1	7.6	-196	17759	17816	164
50mm from edge of plate	23.9	7.4	24.1	7.6	-196	17759	17518	171
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17814	160
100mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17811	150
125mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17804	128
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17801	122

Average Stress 143

Specimen Two - Side One : Measurement Taken 85mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24.3	7.5	24.3	7.5	-196	17759	17789	86
25mm from edge of plate	24.3	7.6	24.4	7.5	-196	17759	17792	97
50mm from edge of plate	24.3	7.6	24.4	7.6	-196	17759	17792	94
75mm from edge of plate	24.3	7.6	24.4	7.6	-196	17759	17792	94
100mm from edge of plate	24.1	7.5	24.2	7.6	-196	17759	17800	119
125mm from edge of plate	24	7.5	24.2	7.5	-196	17759	17804	131
150mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17797	111

Average Stress 105

Specimen Two - Side One : Measurement Taken 75mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17759	0
25mm from edge of plate	24.1	7.7	24.1	7.5	-196	17759	17765	19
50mm from edge of plate	24.2	7.8	24.1	7.5	-196	17759	17765	17
75mm from edge of plate	24	7.5	24.1	7.6	-196	17759	17757	-5
100mm from edge of plate	23.9	7.5	24.1	7.6	-196	17759	17762	9
125mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17764	15
150mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17764	14

Average Stress 10

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Debro-30 Stress Measurements

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Specimen Two - Side One : Measurement Taken 65mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17753	-15
25mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17758	-1
50mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17759	1
75mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17754	-12
100mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17758	0
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17757	-5
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17766	20

Average Stress -2

Specimen Two - Side One : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	23.9	7.4	-196	17759	17768	26
25mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17769	29
50mm from edge of plate	23.9	7.6	24	7.6	-196	17759	17751	26
75mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17764	15
100mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17757	-4
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17767	24
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17773	41

Average Stress 22

Specimen Two - Side One : Measurement Taken 45mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17769	30
25mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17761	7
50mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17774	43
75mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17781	65
100mm from edge of plate	23.8	7.4	23.9	7.6	-196	17759	17769	31
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17773	40
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17780	60

Average Stress 39

Specimen Two - Side One : Measurement Taken 35mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17773	41
25mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17784	73
50mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17786	78
75mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17780	61
100mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17777	53
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17788	83
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17785	75

Average Stress 66

Specimen Two - Side One : Measurement Taken 25mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17792	97
25mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17791	92
50mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17787	80
75mm from edge of plate	23.8	7.5	24	7.6	-196	17759	17791	94
100mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17796	108
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17792	97
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17794	101

Average Stress 96

Debro-30 Stress Measurements

Specimen Two - Side One : Measurement Taken 15mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17805	132
25mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17809	143
50mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17824	186
75mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17822	181
100mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17818	170
125mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17818	169
150mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17816	164

Average Stress 164

Specimen Two - Side Two : Measurement Taken 85mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.6	23.9	7.5	-196	17759	17795	105
25mm from edge of plate	23.9	7.6	23.9	7.5	-196	17759	17785	75
50mm from edge of plate	23.9	7.6	24	7.6	-196	17759	17786	80
75mm from edge of plate	23.8	7.5	24	7.6	-196	17759	17783	68
100mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17787	81
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17796	108
150mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17799	117

Average Stress 91

Specimen Two - Side Two : Measurement Taken 75mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17771	37
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17788	85
50mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17792	94
75mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17778	55
100mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17788	84
125mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17794	101
150mm from edge of plate	23.8	7.5	23.9	7.4	-196	17759	17795	103

Average Stress 80

Specimen Two - Side Two : Measurement Taken 65mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.6	23.8	7.5	-196	17759	17775	47
25mm from edge of plate	23.8	7.6	23.9	7.5	-196	17759	17773	42
50mm from edge of plate	23.9	7.6	23.9	7.6	-196	17759	17774	43
75mm from edge of plate	23.8	7.4	23.9	7.6	-196	17759	17772	37
100mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17772	38
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17776	49
150mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17784	72

Average Stress 47

Specimen Two - Side Two : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17776	49
25mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17774	43
50mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17777	54
75mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17776	49
100mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17785	76
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17781	65
150mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17785	75

Average Stress 59

Debro-30 Stress Measurements

Specimen Two - Side Two : Measurement Taken 45mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17784	73
25mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17782	67
50mm from edge of plate	23.9	7.5	23.9	7.6	-196	17759	17781	64
75mm from edge of plate	23.8	7.4	23.9	7.6	-196	17759	17785	75
100mm from edge of plate	23.8	7.4	23.9	7.6	-196	17759	17788	83
125mm from edge of plate	23.8	7.4	23.9	7.6	-196	17759	17795	104
150mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17785	76

Average Stress 77

Specimen Two - Side Two : Measurement Taken 35mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17789	86
25mm from edge of plate	23.8	7.5	23.9	7.5	-196	17759	17785	76
50mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17790	90
75mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17793	98
100mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17790	91
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17794	102
150mm from edge of plate	23.7	7.4	23.8	7.4	-196	17759	17788	85

Average Stress 90

Specimen Two - Side Two : Measurement Taken 25mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	23.8	7.4	-196	17759	17784	72
25mm from edge of plate	23.9	7.7	24	7.5	-196	17759	17792	97
50mm from edge of plate	23.9	7.6	24	7.6	-196	17759	17803	128
75mm from edge of plate	23.8	7.4	24	7.7	-196	17759	17794	102
100mm from edge of plate	23.8	7.4	24	7.7	-196	17759	17798	111
125mm from edge of plate	23.8	7.3	23.9	7.6	-196	17759	17802	125
150mm from edge of plate	23.8	7.3	23.8	7.5	-196	17759	17790	91

Average Stress 104

Specimen Two - Side Two : Measurement Taken 15mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.6	23.9	7.5	-196	17759	17800	119
25mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17799	117
50mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17812	152
75mm from edge of plate	23.9	7.4	24.1	7.7	-196	17759	17820	175
100mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17817	167
125mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17820	175
150mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17822	182

Average Stress 155

Specimen Three - Side One : Measurement Taken 85mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24.2	7.5	24.3	7.6	-196	17759	17806	134
25mm from edge of plate	24.2	7.5	24.2	7.5	-196	17759	17787	81
50mm from edge of plate	24.2	7.5	24.2	7.5	-196	17759	17794	100
75mm from edge of plate	24.1	7.5	24.2	7.5	-196	17759	17782	67
100mm from edge of plate	24.1	7.5	24.2	7.5	-196	17759	17783	71
125mm from edge of plate	24.1	7.5	24.2	7.5	-196	17759	17796	108
150mm from edge of plate	24.1	7.5	24.2	7.5	-196	17759	17790	91

Average Stress 93

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Debro-30 Stress Measurements

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Specimen Three - Side One : Measurement Taken 75mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24.1	7.5	24.2	7.5	-196	17759	17761	8
25mm from edge of plate	24.1	7.5	24.2	7.5	-196	17759	17751	-21
50mm from edge of plate	24.1	7.5	24.2	7.5	-196	17759	17746	-35
75mm from edge of plate	24.1	7.5	24.2	7.5	-196	17759	17753	-16
100mm from edge of plate	24.1	7.5	24.1	7.5	-196	17759	17752	-17
125mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17747	-32
150mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17762	9

Average Stress -15

Specimen Three - Side One : Measurement Taken 65mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17753	-15
25mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17753	-15
50mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17752	-18
75mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17751	-20
100mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17750	-24
125mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17747	-34
150mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17757	-3

Average Stress -18

Specimen Three - Side One : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17762	8
25mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17759	2
50mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17760	2
75mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17757	-3
100mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17752	-19
125mm from edge of plate	24	7.5	24	7.5	-196	17759	17749	-28
150mm from edge of plate	24	7.4	24.1	7.5	-196	17759	17767	23

Average Stress -2

Specimen Three - Side One : Measurement Taken 45mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.4	24	7.5	-196	17759	17761	6
25mm from edge of plate	24	7.4	24	7.5	-196	17759	17766	20
50mm from edge of plate	24	7.4	24	7.5	-196	17759	17768	28
75mm from edge of plate	24	7.4	24	7.5	-196	17759	17764	16
100mm from edge of plate	24	7.4	24	7.5	-196	17759	17772	38
125mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17758	-1
150mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17763	13

Average Stress 17

Specimen Three - Side One : Measurement Taken 35mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17767	25
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17768	27
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17770	34
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17778	54
100mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17778	54
125mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17768	26
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17775	47

Average Stress 38

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Specimen Three - Side One : Measurement Taken 25mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17774	45
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17779	57
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17777	53
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17791	91
100mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17789	86
125mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17782	67
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17784	72

Average Stress 67

Specimen Three - Side One : Measurement Taken 15mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17792	97
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17804	131
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17808	142
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17807	139
100mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17806	136
125mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17803	127
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17795	103

Average Stress 125

Specimen Three - Side Two : Measurement Taken 85mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.4	24.1	7.7	-196	17759	17792	96
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17790	88
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17784	73
75mm from edge of plate	24	7.5	24	7.5	-196	17759	17787	82
100mm from edge of plate	24	7.5	24	7.5	-196	17759	17788	84
125mm from edge of plate	24	7.5	24	7.5	-196	17759	17787	81
150mm from edge of plate	24	7.5	24	7.5	-196	17759	17777	53

Average Stress 80

Specimen Three - Side Two : Measurement Taken 75mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24.1	7.7	-196	17759	17774	44
25mm from edge of plate	23.9	7.4	2.4	7.6	-196	17759	17762	8
50mm from edge of plate	23.9	7.4	2.4	7.5	-196	17759	17761	8
75mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17755	-10
100mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17753	-16
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17759	1
150mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17760	3

Average Stress 5

Specimen Three - Side Two : Measurement Taken 65mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.7	-196	17759	17772	37
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17765	17
50mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17764	15
75mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17763	12
100mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17767	24
125mm from edge of plate	24	7.6	24.1	7.6	-196	17759	17769	29
150mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17765	17

Average Stress 22

Specimen Three - Side Two : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17777	51
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17773	42
50mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17779	59
75mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17776	49
100mm from edge of plate	23.9	7.6	24	7.5	-196	17759	17776	51
125mm from edge of plate	23.9	7.6	24	7.5	-196	17759	17765	18
150mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17776	49

Average Stress 46

Specimen Three - Side Two : Measurement Taken 45mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.6	24	7.5	-196	17759	17775	47
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17790	91
50mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17779	59
75mm from edge of plate	23.9	7.5	24	7.4	-196	17759	17777	52
100mm from edge of plate	23.9	7.5	23.9	7.4	-196	17759	17769	30
125mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17777	53
150mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17772	39

Average Stress 53

Specimen Three - Side Two : Measurement Taken 35mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17771	36
25mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17780	62
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17778	56
75mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17787	82
100mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17773	41
125mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17781	63
150mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17771	35

Average Stress 54

Specimen Three - Side Two : Measurement Taken 25mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17781	65
25mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17775	47
50mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17785	75
75mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17790	89
100mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17778	56
125mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17790	91
150mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17780	60

Average Stress 69

Specimen Three - Side Two : Measurement Taken 15mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17815	162
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17822	182
50mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17817	166
75mm from edge of plate	24	7.5	24	7.6	-196	17759	17826	192
100mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17813	156
125mm from edge of plate	24	7.5	24	7.5	-196	17759	17816	163
150mm from edge of plate	24	7.5	24	7.5	-196	17759	17800	118

Average Stress 163

Specimen Four - Side One : Measurement Taken 85mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.5	24.1	7.4	-196	17759	17772	37
25mm from edge of plate	24	7.5	24.1	7.4	-196	17759	17780	60
50mm from edge of plate	24	7.5	24.1	7.4	-196	17759	17788	84
75mm from edge of plate	24	7.5	24.1	7.4	-196	17759	17785	75
100mm from edge of plate	24	7.5	24.1	7.4	-196	17759	17783	69
125mm from edge of plate	24	7.6	24.1	7.4	-196	17759	17788	85
150mm from edge of plate	24	7.6	24.1	7.5	-196	17759	17786	78

Average Stress 70

Specimen Four - Side One : Measurement Taken 75mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.5	24	7.5	-196	17759	17761	5
25mm from edge of plate	24	7.5	24	7.5	-196	17759	17759	1
50mm from edge of plate	24	7.5	24	7.5	-196	17759	17752	-17
75mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17750	-24
100mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17746	-36
125mm from edge of plate	23.9	7.6	24	7.4	-196	17759	17753	-16
150mm from edge of plate	24	7.5	24	7.5	-196	17759	17749	-27

Average Stress -16

Specimen Four - Side One : Measurement Taken 65mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24.1	7.5	-196	17759	17771	35
25mm from edge of plate	24	7.5	24	7.5	-196	17759	17763	13
50mm from edge of plate	24	7.4	24.1	7.7	-196	17759	17759	2
75mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17759	1
100mm from edge of plate	24	7.5	24.1	7.6	-196	17759	17767	22
125mm from edge of plate	24	7.7	24.1	7.6	-196	17759	17769	30
150mm from edge of plate	24	7.6	24.2	7.6	-196	17759	17765	17

Average Stress 17

Specimen Four - Side One : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17774	44
25mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17770	31
50mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17768	26
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17759	1
100mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17769	29
125mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17762	9
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17763	14

Average Stress 22

Specimen Four - Side One : Measurement Taken 45mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17781	63
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17778	55
50mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17782	67
75mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17763	14
100mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17767	22
125mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17762	9
150mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17768	25

Average Stress 36

Specimen Four - Side One : Measurement Taken 35mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17776	50
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17773	40
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17781	65
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17786	79
100mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17776	51
125mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17778	56
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17779	58

Average Stress 57

Specimen Four - Side One : Measurement Taken 25mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17782	65
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17789	87
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17787	81
75mm from edge of plate	23.9	7.5	24	7.4	-196	17759	17791	92
100mm from edge of plate	23.9	7.5	24	7.4	-196	17759	17791	93
125mm from edge of plate	23.9	7.5	24	7.4	-196	17759	17787	81
150mm from edge of plate	23.9	7.5	24	7.4	-196	17759	17778	57

Average Stress 79

Specimen Four - Side One : Measurement Taken 15mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24.1	7.6	24.1	7.6	-196	17759	17813	155
25mm from edge of plate	24	7.5	24.1	7.6	-196	17759	17824	186
50mm from edge of plate	24	7.5	24.1	7.6	-196	17759	177827	196
75mm from edge of plate	24	7.5	24.1	7.6	-196	17759	17827	194
100mm from edge of plate	24	7.5	24.1	7.6	-196	17759	177820	176
125mm from edge of plate	24	7.5	24.1	7.6	-196	17759	177816	165
150mm from edge of plate	24	7.5	24.1	7.6	-196	17759	177810	146

Average Stress 174

Specimen Four - Side Two : Measurement Taken 85mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.5	24	7.6	-196	17759	17781	64
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17779	57
50mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17796	106
75mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17790	89
100mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17782	66
125mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17787	80
150mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17792	97

Average Stress 80

Specimen Four - Side Two : Measurement Taken 75mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17772	38
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17767	24
50mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17762	10
75mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17764	16
100mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17762	10
125mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17767	24
150mm from edge of plate	24	7.6	24	7.5	-196	17759	17774	45

Average Stress 24

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Debro-30 Stress Measurements

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Specimen Four - Side Two : Measurement Taken 65mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.6	24	7.5	-196	17759	17776	49
25mm from edge of plate	24	7.6	24.1	7.7	-196	17759	17774	45
50mm from edge of plate	24	7.6	24.1	7.6	-196	17759	17776	51
75mm from edge of plate	24	7.6	24	7.5	-196	17759	17771	34
100mm from edge of plate	24	7.6	24	7.6	-196	17759	17767	23
125mm from edge of plate	24	7.6	24	7.5	-196	17759	17772	39
150mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17769	28

Average Stress 38

Specimen Four - Side Two : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17777	53
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17770	31
50mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17771	36
75mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17764	14
100mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17763	13
125mm from edge of plate	24	7.5	24	7.6	-196	17759	17765	17
150mm from edge of plate	23.9	7.5	24	7.6	-196	17759	17773	40

Average Stress 29

Specimen Four - Side Two : Measurement Taken 45mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17771	35
25mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17774	43
50mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17768	27
75mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17770	32
100mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17773	40
125mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17769	28
150mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17778	56

Average Stress 37

Specimen Four - Side Two : Measurement Taken 35mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17779	58
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17781	63
50mm from edge of plate	23.9	7.5	23.9	7.5	-196	17759	17778	55
75mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17777	51
100mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17776	51
125mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17762	8
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17759	2

Average Stress 41

Specimen Four - Side Two : Measurement Taken 25mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17776	49
25mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17773	40
50mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17782	67
75mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17781	64
100mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17774	45
125mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17772	38
150mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17778	56

Average Stress 51

Specimen Four - Side Two : Measurement Taken 15mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17815	162
25mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17823	185
50mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17828	198
75mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17835	217
100mm from edge of plate	23.9	7.5	24	7.5	-196	17759	17830	204
125mm from edge of plate	24	7.6	24	7.5	-196	17759	17832	210
150mm from edge of plate	24	7.7	24.1	7.5	-196	17759	17823	184

Average Stress **194**

Specimen Five - Side One : Measurement Taken 85mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24.2	7.5	24.2	7.5	-196	17759	17785	75
25mm from edge of plate	24.2	7.5	24.2	7.5	-196	17759	17792	96
50mm from edge of plate	24.2	7.5	24.2	7.5	-196	17759	17793	99
75mm from edge of plate	24.2	7.5	24.2	7.5	-196	17759	17794	101
100mm from edge of plate	24.2	7.5	24.2	7.5	-196	17759	17794	100
125mm from edge of plate	24.2	7.5	24.2	7.5	-196	17759	17797	110
150mm from edge of plate	24.1	7.5	24.2	7.5	-196	17759	17797	110

Average Stress **99**

Specimen Five - Side One : Measurement Taken 75mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24.1	7.5	24.1	7.5	-196	17759	17754	-14
25mm from edge of plate	24.1	7.5	24.1	7.5	-196	17759	17749	-27
50mm from edge of plate	24.1	7.5	24.1	7.5	-196	17759	17759	0
75mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17749	-27
100mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17754	-14
125mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17759	0
150mm from edge of plate	24	7.5	24.1	7.5	-196	17759	17762	9

Average Stress **-10**

Specimen Five - Side One : Measurement Taken 65mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Stress	T_L^0	T_L^σ	Stress
5mm from edge of plate	24	7.5	24.1	7.5	-21	17759	17751	-21
25mm from edge of plate	24	7.5	24.1	7.5	-23	17759	17750	-23
50mm from edge of plate	24	7.5	24	7.5	-31	17759	17748	-31
75mm from edge of plate	23.9	7.4	24	7.5	-36	17759	17746	-36
100mm from edge of plate	23.9	7.4	24	7.5	-20	17759	17751	-20
125mm from edge of plate	23.9	7.4	24	7.5	-25	17759	17750	-25
150mm from edge of plate	23.9	7.4	24	7.5	-7	17759	17756	-7

Average Stress -23

Specimen Five - Side One : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17761	6
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17759	0
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17763	12
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17759	1
100mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17761	6
125mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17756	-6
150mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17756	-8

Average Stress 2

Specimen Five - Side One : Measurement Taken 45mm Away From Weld								
Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17768	26
25mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17763	13
50mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17769	29
75mm from edge of plate	23.9	7.4	24	7.5	-196	17759	17766	20
100mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17763	12
125mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17763	12
150mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17764	16

Average Stress 18

Specimen Five - Side One : Measurement Taken 35mm Away From Weld								
Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17767	22
25mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17768	25
50mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17773	40
75mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17775	48
100mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17777	53
125mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17763	12
150mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17763	11

Average Stress 30

Specimen Five - Side One : Measurement Taken 25mm Away From Weld								
Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	24.1	7.5	24.2	7.9	-196	17759	17791	93
25mm from edge of plate	24.1	7.4	24.2	7.9	-196	17759	17795	103
50mm from edge of plate	24	7.4	24.1	7.6	-196	17759	17794	100
75mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17784	71
100mm from edge of plate	23.9	7.4	24	7.4	-196	17759	17786	78
125mm from edge of plate	23.9	7.4	23.9	7.4	-196	17759	17773	42
150mm from edge of plate	23.9	7.4	23.9	7.4	-196	17759		32

Average Stress 74

Specimen Five - Side One : Measurement Taken 15mm Away From Weld								
Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	23.9	7.4	-196	17759	17813	155
25mm from edge of plate	23.9	7.4	23.9	7.4	-196	17759	17827	197
50mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17830	204
75mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17834	215
100mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17832	210
125mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17828	197
150mm from edge of plate	23.9	7.4	23.9	7.5	-196	17759	17809	143

Average Stress 189

Specimen Five - Side Two : Measurement Taken 85mm Away From Weld								
Distance	Step 1	Step 2	Step 3	Step 4	Beta	R.T.O.F	F.T.O.F	Stress
5mm from edge of plate	23.9	7.4	24	7.5	-196	T_L^0	T_L^σ	113
25mm from edge of plate	23.8	7.4	24	7.5	-196	17759	17806	137
50mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17801	122
75mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17810	146
100mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17810	148
125mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17805	133
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17793	99

Average Stress 128

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Specimen Five - Side Two : Measurement Taken 75mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	R.T.O.F	F.T.O.F	Stress
5mm from edge of plate	23.8	7.4	23.9	7.5	-196	T_L^0	T_L^σ	34
25mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17771	36
50mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17766	22
75mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17766	21
100mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17760	4
125mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17760	3
150mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17759	0

Average Stress 17

Specimen Five - Side Two : Measurement Taken 65mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17771	35
25mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17767	25
50mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17764	16
75mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17767	24
100mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17760	3
125mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17756	-8
150mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17756	-6

Average Stress 13

Specimen Five - Side Two : Measurement Taken 55mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17769	30
25mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17776	48
50mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17766	20
75mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17766	22
100mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17767	23
125mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17766	21
150mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17768	27

Average Stress 27

Specimen Five - Side Two : Measurement Taken 45mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.9	7.4	24.1	7.7	-196	17759	17779	59
25mm from edge of plate	23.9	7.4	24	7.6	-196	17759	17785	75
50mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17784	72
75mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17778	55
100mm from edge of plate	23.8	7.4	23.8	7.5	-196	17759	17774	43
125mm from edge of plate	23.8	7.4	23.8	7.5	-196	17759	17775	48
150mm from edge of plate	23.8	7.4	23.8	7.5	-196	17759	17776	49

Average Stress 57

Specimen Five - Side Two : Measurement Taken 35mm Away From Weld

Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	23.9	7.6	-196	17759	17779	60
25mm from edge of plate	23.8	7.4	23.9	7.6	-196	17759	17785	69
50mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17784	73
75mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17778	59
100mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17774	65
125mm from edge of plate	23.8	7.4	23.8	7.5	-196	17759	17775	68
150mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17776	51

Average Stress 64

Specimen Five - Side Two : Measurement Taken 25mm Away From Weld								
Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17783	70
25mm from edge of plate	23.8	7.4	24	7.6	-196	17759	17788	84
50mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17788	83
75mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17792	95
100mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17789	88
125mm from edge of plate	23.8	7.4	23.8	7.4	-196	17759	17793	98
150mm from edge of plate	23.8	7.4	23.9	7.4	-196	17759	17790	89

Average Stress 87

Specimen Five - Side Two : Measurement Taken 15mm Away From Weld								
Distance	Step 1	Step 2	Step 3	Step 4	Beta	T_L^0	T_L^σ	Stress
5mm from edge of plate	23.8	7.4	23.9	7.6	-196	17759	17802	123
25mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17817	168
50mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17826	193
75mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17825	190
100mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17833	213
125mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17824	188
150mm from edge of plate	23.8	7.4	23.9	7.5	-196	17759	17813	154

Average Stress 176